Vowel Perception and Production in Adolescents with Reading Disabilities

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Perception and production of the vowels /ɪ/, /ɛ/, /æ/ in the words pit, pet *and* pat *were investigated in two groups of adolescents who differed significantly on measures of reading and phonological awareness. Perception performance was assessed using slope measurements between vowel categories. Duration measurements and a rating system based on first and second formant (F1 and F2) values were used to analyze production performance. As a group, the students with reading disabilities not only perceived but also produced less well-defined vowel categories than the control group of age-matched good readers. Perception and production performance, however, were not correlated. Results suggest that the speech processing difficulties of the students with reading disabilities include weak phonological coding for vowel sounds with similar phonetic characteristics. The implications of these findings for intervention are addressed.*

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Learning to read an alphabetic writing system such as English involves establishing sound-symbol correspondences. Although it is not clear exactly how this process takes place, it presumably involves several factors: for example, the ability to perceive and discriminate speech sounds, the capacity to form and store categories of speech sounds, and the ability to link these categories with specific orthographic symbols. Although each individual with a reading disability has a unique profile of strengths and weaknesses, it is generally accepted that phonological processing difficulties play a large role in the underlying problems of many of these individuals (Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Lyon, 1995; Rack, Snowling, & Olson, 1992; Snowling, 2000; Stanovich, 1986; Stone & Brady, 1995).

Well before children learn to read, they have established categories of speech sounds in memory. The later developing ability to analyze this phonological information in such tasks as segmenting and blending is an important prerequisite skill for acquiring literacy, and is referred to as phonological awareness (Adams, 1990; Ehri, Nunes, Willows, Schuster, Yaghoub-Zadeh, & Shanahan, 2001; Lundberg, Frost, & Petersen, 1988; Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001; Share & Stanovich, 1995; Wagner & Torgesen, 1987). Phonological awareness tasks often pose particular difficulty for students with reading disabilities. In considering the subskills needed in these tasks, it is clear that they require accurate perception and coding of phonological information, both for the formation of categories during early language development, and for on-line processing of sounds in a given task. Verbal working memory is also involved, as the phonological information must be held and manipulated in memory while the tasks are being performed (Hansen & Bowey, 1994; Brady, 1991; Brady, Shankweiler, & Mann, 1983). Without the ability to accurately discriminate and identify sounds, it would be difficult to establish useful phonemic categories for performing phonological awareness tasks or for pairing with graphemes in reading. Because phonological coding appears to play a fundamental role in the acquisition of literacy, the underlying ability to perceive and categorize speech sounds is a promising area for exploration in individuals with reading disabilities.

One experimental paradigm for studying these underlying phonological abilities is categorical perception, the ability to discriminate between categories of speech sounds along a continuum. Studies of categorical perception usually examine listeners' responses to synthetic stimuli from the continuum. (For a discussion of some alternative methodologies, see Nittrouer, 2002.) Categorical perception of stop consonants (/b/, /p/, /d/, /t/, /g/, /k/) has been studied extensively in individuals with reading disabilities (Brady, 1997).

Godfrey et al. (1981) provide an example of the methodology and findings typical of categorical perception research. Children with and without reading disabilities were asked to identify and discriminate synthetically created consonant-vowel (CV) syllables. The stimuli consisted of two series of CV syllables, one varying systematically from /ba/ to /da/, and the other from /da/ to /ga/. Children with reading disabilities displayed less distinct categorical boundaries than children in a control group. Although a few studies have failed to replicate these results (e.g., Brandt & Rosen, 1980), the overall trend has been toward individuals with reading disabilities displaying less well-defined speech categories. There may be, in fact, a subgroup of children with reading disabilities who exhibit a decreased ability to form distinct phonological categories (Adlard & Hazan, 1998; Joanisse, Manis, Keating, & Seidenberg, 2000; Manis, McBride-Chang, Seidenberg, Keating, Doi, Musson, & Petersen, 1997). A recent study suggests that part of the difficulty may lie in over-sensitivity to within-category variations, in addition to a weaker ability to make between-category distinctions (Serniclaes, Sprenger-Charolles, Carré, & Demonet, 2001).

It has been hypothesized that individuals with reading disabilities have particular difficulty discriminating *phonetically similar* phonological categories (Mody, Studdert-Kennedy, & Brady, 1997; Adlard & Hazan, 1998). For example, although two groups of second graders differed in reading ability and performance on discriminating phonetically similar consonants /ba/-/da/, Mody, et al. (1997) found that the groups did not differ on tasks involving phonetically less-similar stimuli (e.g., /ba/-/sa/). In addition to Mody et al.'s hypothesis, an alternative hypothesis implicates particular difficulties in processing brief, rapidly changing auditory information (e.g., Tallal, 1980; Tallal & Piercy, 1973, 1974; Tallal & Stark, 1981).

Phonetically similar categories are also found among vowels, and thus vowel perception tasks may be useful in examining the nature of speech perception deficits in individuals with reading disabilities. The vowels /ɪ/, /ɛ/ and /æ/ provide an example of three phonetically similar speech sounds (Ladefoged, 2001) that are often confused (Ehri, Wilce, & Taylor, 1987). Although vowels are perceived less categorically than stop consonants and have been found to be organized around a best representative or "prototype" (e.g., Kuhl, 1991), it is still possible to conduct identification tasks to see how consistently they are perceived. The /ɪ/-/ɛ/ pair was used by Pursell, Swanson, Hedrick, and Nabelek (2002) to investigate the influence of maturity on the perception of these vowels. The researchers tested the ability of adults, 10-year-olds and five- to six-year-olds to identify the synthetic vowels /ɪ/ and /ɛ/. Responses to a 14-token continuum revealed no differences among groups in boundaries between phonemes, but the steepness of the slope increased with age. That is, the vowel responses became more categorical with maturity.

While consonant perception in individuals with reading disabilities has been examined on numerous occasions, studies involving the perception of vowels are rare (cf. Brady, 1997). However, researchers often have considered vowel errors in reading aloud and spelling. Some studies indicate that vowel errors are more prevalent than consonant errors in reading English (e.g., Shankweiler & Liberman, 1972). This trend has been discovered in both individuals with reading disabilities and average readers, although individuals with reading disabilities make significantly more errors in each category (Bryson & Werker, 1989). In the case of spelling, similarly articulated vowels are often confused, and at all stages of development, vowels have been shown to produce more errors than consonants (Moats, 1995). In a recent study, Post, Swank, Hiscock, and Fowler (1999) found that second through fourth graders produced more spelling errors with short vowels than with long vowels; also, a relationship was found between vowel identification performance and vowel spelling errors.

Reading and spelling of vowels may be particularly difficult in English because the manner in which sounds map onto print is often ambiguous (in contrast with more transparent languages such as Spanish or Serbo-Croatian). In English, there are 15 vowel sounds and only six vowel letters with *r*, *y*, and *w* combining with these letters to create orthographic patterns to represent the sounds. For example, *ow* says /o/ in *snow* but /ou/ in *plow*, and the letter *a* can be pronounced in at least nine different ways (e.g., All the large baggage was put around the many crates with care). Similarly in spelling, the long "a" sound can be represented in at least eight different ways: *a, a-e, ai, ay, eigh, ei, ea, ey*. Therefore, because vowels are phonetically similar and pose particular problems in reading and spelling, it is important to explore vowel processing in children with reading disabilities.

Given that phonological categories are used in both the perception and production of speech, the question arises as to whether ill-defined categories stem from a perceptual deficit or subtle difficulties in production. Werker and Tees (1987) suggest that either explanation is possible, since perceptual abilities are necessary for constructing phonological categories, and oral production should help sharpen category boundaries. The relationship between perception and production is central to the motor theory of speech (e.g., Liberman, 1998). According to this theory, both perception and production activate a phonetic, rather than a purely auditory, modality of processing. This phonetic modality provides a direct route from articulatory gestures to meaning and could be a locus for the phonological problems that tend to occur in individuals with reading disabilities. The existence of such a phonetic modality suggests that speech perception and production are closely connected.

If students with reading disabilities tend to have less well-defined phonological categories as measured by perception tasks, it would be of interest to explore whether production of these categories shows a similar pattern. By analyzing the relationship between speech perception and production, insight may be gained into the nature of the underlying phonological impairment.

A study by Post, Foorman, and Hiscock (1997) examined speech perception and production of vowels by second and third grade "skilled" and "less skilled" readers. For the perception task, participants listened to natural voice recordings of two-syllable "created words" beginning with /d/ or /t/, followed by the vowel /ɪ/ or /i/ and ending with a syllable composed of a stop consonant plus /i/ (e.g., "dippy," "teepy"). Participants listened to the recordings twice, once for identification of the consonant and once for identification of the vowel. The groups performed equally on consonant identification, but the less skilled readers made significantly more vowel errors, particularly with short vowels. Post et al. (1997) also found an interaction between consonant voicing and vowel length in perception; consonant-vowel combinations with consonants and vowels of similar duration (e.g., dippy, teepy) were harder to discriminate than consonant-vowel pairings of mixed durations (e.g., tippy, deepy). It was concluded that vowels might be "less securely" represented than consonants by less skilled readers. For the production task, participants repeated the items from the perception task. Voice onset time was used to measure distinctions between /d/-/t/; vowel length (duration) was measured to distinguish productions of /ɪ/-/i/. No group differences were found on these production measures.

The current study also examined vowel perception and production in individuals with reading difficulties but used synthesized speech rather than recorded voice. The vowels /ɪ/, /ɛ/ and /æ/ ("short" *i, e, a,* respectively) were chosen because they are often misread and misspelled (e.g., Post, et al., 1999); they are also phonetically similar and can be synthesized to form a continuum varying only along the first and second formants (F1 and F2). Formants are resonances of the vocal tract, changing frequencies during speech production according to the shape of the vocal tract. F1 varies according to tongue height; the higher the tongue position, the lower the F1 value. F2 varies according to the front/back constriction of the tongue; the closer the constriction to the front of the mouth, the higher the F2. Moving along the continuum from /ɪ/ to /ɛ/ to /æ/ involves systematic changes in F1 (increasing) and F2 (decreasing).

Although naturally produced /ɪ/, /ɛ/, and /æ/ differ in additional acoustic parameters such as duration and formant bandwidth, it was possible to create synthetic vowels that were consistently heard as /ɪ/, /ɛ/, or /æ/. For these stimuli, naturally occurring differences other than the first and second formant frequencies were neutralized. Pictures were used to elicit productions and production targets were embedded in a simple carrier phrase in order to simulate natural vowel production.

The methods of data collection used in this study differ somewhat from those used by Post et al. (1997). The current study's use of synthetic voice recordings on the perception task allowed for precise control of speech input to the participants. Synthetic speech traditionally has been used instead of natural speech because a synthesized series can be generated in which the items vary systematically along a continuum in discrete steps. Also, the production task used by Post et al. involved speech repetition. The elicited production task in the current study avoids the potentially confounding effects of processing speech input. Finally, Post et al. examined vowel duration to distinguish between productions of /ɪ/ and /i/, while the current study measured formant frequency as well as duration.

As indicated earlier, the study of vowels may provide important information regarding the nature of the underlying perceptual difficulties found in individuals with reading disabilities. If individuals with reading disabilities differ from nondisabled readers in their ability to perceive /ɪ/, /ɛ/, /æ/, it would provide additional evidence supporting the hypothesis that poor readers have subtle phonological difficulties. This study explored both speech perception and production to investigate more fully the nature of any underlying phonological impairment. Further, it was of interest to determine whether or not proficiency of perception and production of the same vowel categories is related; such findings could have implications for theories of speech perception and production.

METHODS

PARTICIPANTS

Two groups participated in this study. One group was comprised of individuals with reading disabilities (subsequently referred to as reading disability [RD] group) recruited from a private school for children with language-based learning disabilities. Nineteen adolescents (17 boys, two girls) were selected for the RD group from a larger sample of 27 students who had been tested as part of a previous, unpublished study. Only students with a Word Identification standard score on the *Woodcock Reading Mastery Test, Revised* (Woodcock, 1987) of less than or equal to 90 were included in the current study. The mean age of this RD group was 16 years, 10 months (range: 15 years, 5 months to 18 years, 9 months).

Participants in the good reader (GR) group were recruited from honors English programs in two suburban school districts. Of the 20 students who volunteered, eight were chosen as controls for age (mean age: 16 years, 4 months; range: 15 years, 4 months to 17 years, 4 months) and gender; the ratio of males to females was similar for the two groups (8.5:1 for the RD group; 7:1 for the GR group). Matching groups by gender was important in order to prevent possible confounding effects of vocal-tract size differences between males and females. All participants were native speakers of English from the New England area, and were from similar socioeconomic backgrounds. They were required to pass a hearing screening at 25 dB.

Scores from the Word Identification subtest of the *Woodcock Reading Mastery Test, Revised* (Woodcock, 1987) and the Word Attack subtest on the *Woodcock-Johnson Psychoeducational Battery* (Woodcock & Johnson, 1987) were used as general indicators of the participants' single-word recognition and decoding abilities. Performance on these tests by the two groups is shown in table I. Six of the students in the RD group showed average performance (SS>90) on the Word Attack subtest. Given that these students were enrolled in a special school that provided systematic,

Table I. Group Means and Standard Deviations (*SD*) for the Reading and Phonological Awareness Measures.

	RD Group $n = 19$		GR Group $n = 8$	
Measure	**Mean**	***SD***	**Mean**	***SD***
Word Attack (standard score)	85.8	8.1	114.3	11.5
Word Identification (standard score)	72.5	13.1	111.4	7.3
Sound Deletion (raw score)	6.7	1.7	8.3	1.6
Pig Latin (raw score)	17.1	8.3	31.6	7.7

code-based, multisensory instruction in reading, it is to be expected that some of these students would have acquired basic decoding skills.

MATERIALS AND PROCEDURE

Participants were tested individually in a quiet room. Students in the RD group were tested during two 45-minute sessions as part of a larger study that included two other tests (Passage Comprehension and Listening Comprehension from the *Woodcock-Johnson Psychoeducational Battery*). Students in the GR group were tested in one 60-minute session. The following tasks were administered to all participants.

Word Attack. This test requires the participant to read a list of nonwords aloud until a ceiling level is reached. The nonwords follow regular phonetic patterns of English.

Word Identification. This test requires the participant to read a list of words until a ceiling level is reached. The words on this test include both phonetically regular (e.g., *boat*) and irregular (e.g., *yacht*) items.

Sound Deletion. (Adapted from the *Rosner Test of Auditory Analysis Skills*; Rosner, 1975). This test of phonological awareness consists of 10 words from which participants were required to delete sounds to formulate new words. Raw scores were used in the data analysis. See Appendix A for the Sound Deletion items.

Pig Latin. A pig latin task was used as an additional measure of phonological awareness. After being provided examples and sample tasks, participants were asked to manipulate words and sentences both from standard English into pig latin and vice versa. There were 21 words on this test worth a maximum of two points each. See Appendix A for a list of items.

Perception. The vowels /ɪ/, /ɛ/, and /æ/ were created using the Klatt synthesizer (Klatt & Klatt, 1990). Synthesizer parameter values were consistent with values collected from large numbers of children and adult female speakers in two vowel studies (Hillenbrand, Getty, Clark, & Wheeler, 1995; Peterson & Barney, 1952). The acoustic parameters F1 and F2 were manipulated in order to synthesize examples of each vowel according to the perceptual evaluation of two listeners trained in speech acoustics. The synthesizer parameters of duration, formant frequencies of the third and higher formants, formant bandwidths, and glottal source characteristics were identical for each synthesized vowel; these "identical" parameters were chosen by a process of iterative synthesis to yield a set of "three good exemplars" that differed only in frequencies of the lowest two formants. Figure 1 shows spectrograms of the stimuli for /ɪ/, /ɛ/, and /æ/. As shown in the figure, the frequencies of each formant follow trajectories typical of naturally produced speech. The fundamental frequency has a starting value of 180 Hz, falls to 160 Hz, and then to 150Hz near the end of the vowel. The values for /ɪ/, /ɛ/, and /æ/ were imbedded between the consonants /p/ and /t/ in order to form "endpoint" stimuli for *pit, pet, pat*. The p_t context was chosen in order to form a minimal triplet of words that could be represented pictorially. This factor was important given that the pop-

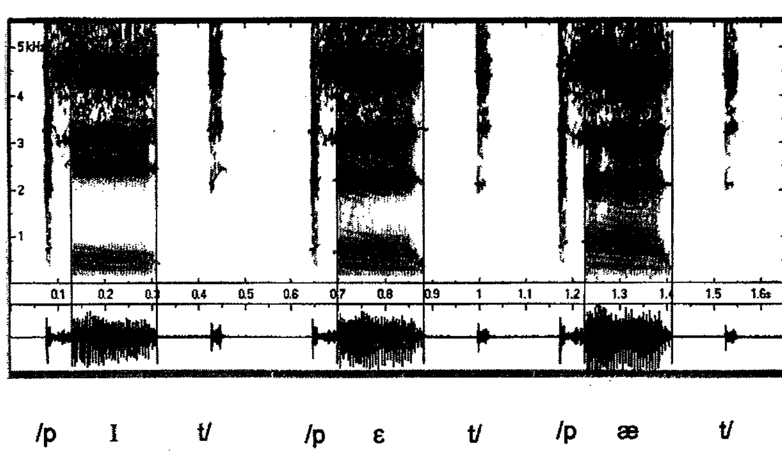

Figure 1: *Spectrogram of the words pit, pet, and pat created from the Klatt synthesizer (Klatt & Klatt, 1990). Time in seconds moves horizontally from left to right, and frequency is shown vertically. Formants of the vowel, shown by the dark horizontal bands, differ in their placement according to their frequency.*

ulation being studied had particular difficulty making sound-symbol associations. In each case, the initial /p/ and the final /t/ consonants were synthesized with the same parameters. Formant frequencies were interpolated at the vowel-consonant transitions by straight-line approximations. An audiotape with 15 trials (five repetitions of each item) was created with the items recorded in a random order. This set of the target vowels was played for 10 graduate students in speech-language pathology for identification. These listeners achieved 100 percent accuracy, confirming that the stimuli were suitable for use in this study.

Additional stimuli were then formed. Three stimuli were created between /ɪ/ and /ɛ/ and three between /ɛ/ and /æ/, yielding a continuum of nine stimuli that varied only in the frequencies of F1 and F2. Each of the nine stimuli were spaced evenly along a continuum of F1 and F2, based on the values used for the endpoint /ɪ/, /ɛ/, and /æ/ stimuli (see Appendix B for a table of values for each vowel). Values for F3 and F4 were the same for all vowels, as was duration (250 ms; the duration was typical of a style of clear, careful speech). For each stimulus, the formant frequency transitions between /p/ and the vowel (/ɪ/, /ɛ/, or /æ/) and between the vowel and /t/ were calculated according to the locus theory of Klatt (1987). An audiotape was created such that each stimulus occurred 11 times in a randomized order for a total of 99 stimuli. The items were presented at four-second intervals, with a pause of eight seconds after every 10th item.

Three line drawings were made to represent *pit*, *pet*, and *pat*. The drawings were explained and placed on a table in front of the participants in left-to-right order: *pit-pet-pat*. Stimuli were presented through headphones, and participants were asked to point to the picture representing the word they heard. Before the test began, a randomized list of 15 "endpoint" stimuli was presented to familiarize participants with synthetic speech and to ensure that participants were able to match the words with pictures. All participants achieved 100 percent accuracy on the endpoint stimuli. Pictures and explanations are given in Appendix C.

Production. Production data were gathered using a series of 15 pictures (five each for *pit*, *pet*, *pat* from the perception task). The pictures were presented one at a time in quasi-random order; the same picture did not occur more than twice in a row and the five trials for each stimulus were distributed fairly evenly across the task. The same order of presentation was used for each participant. Participants were asked to name the pictures of *pit*, *pet*, and *pat* in the carrier phrase, "Say _____ again." The productions were recorded on a DAT recorder using a Sony ECM-MS907 microphone placed approximately 12 inches from the speaker's lips.

ANALYSIS OF PERCEPTION DATA

For each student's perception data, the number of /ɪ/, /ɛ/, and /æ/ responses was measured at each of the nine vowel values along the continuum. A specific instance of the general normalizing transformation of proportions known as PROBIT analysis (SPSS, 2000) was used to "stretch the tails" in order to achieve a unit of measurement more nearly linearly related to other variables. The PROBIT analysis helped to determine the slopes of the regression lines transitioning from /ɪ/ to /ɛ/ (using number of /ɪ/ responses as the dependent measure) and transitioning from /ɛ/ to /æ/ (using number of /æ/ responses as the dependent measure). Each analysis included five data points: two endpoints and three stimuli between them. A steep slope indicates a sharp transition between adjacent vowels and a gradual slope reflects less distinct boundaries. The data from one student in the RD group was excluded from the slope analysis for /ɪ/-/ɛ/ because he perceived the first five stimuli as /ɪ/ and thus did not shift to /ɛ/ until after the endpoint stimulus.

ANALYSIS OF PRODUCTION DATA

Productions of the vowels were analyzed using Speech Station2 software (Sensimetrics Corporation, 1997–2000). Two kinds of measurements were made for each production: spectral measurements of the first and second formant frequencies (F1 and F2) plotted on a linear scale in Hz, and temporal measurements of the vowel duration. Spectrograms and formant tracks were generated by Speech Station 2, and F1 and F2 values were measured during the steady-state portion of the vowel, as close to the midpoint as possible. Measurement values were obtained by a second member of the research team with .96 interrater reliability. Vowel duration values were obtained by measuring the interval of voicing (see Post, et al., 1997).

The objective of the spectral analysis was to characterize the degree of distinction made by each individual in producing the vowel categories /ɪ/,/ɛ/ and /æ/. Each participant's performance was examined in relation to his or her own range of vowel productions, and the data were normalized to facilitate comparison. The range of frequency values produced by a single participant for all three vowels was first converted to a scale of 0.0 to 1.0 for both F1 and F2. In this way, each participant's individual production pattern was maintained, while also allowing for the development of a set of rules to classify and compare performance across participants.

The distance between normalized values for closest and farthest pairs of adjacent vowel categories (/ɪ/-/ɛ/ and /ɛ/-/æ/) was calculated, and participants were then rated according to the ratio of closest to farthest pairs. By considering the ratio of closest to farthest pairs, "distinctness" of categories is not characterized simply by distance between categories, but rather by distance relative to the consistency (spread) of productions. For example, tight categories with small distances between them may be just as "distinct" as widely spread categories with large distances separating them.

Ratios were used to classify the participants on a 3-point scale as follows: a ratio greater than 0.30 was rated 1 (distinct); a ratio less than or equal to 0.30 was rated 2 (close); and a participant who produced at least one member of a category within the vowel space of an adjacent category was rated 3 (overlapping). Two production ratings were determined for each participant, one for /ɪ/-/ɛ/ and another for /ɛ/-/æ/. Figures 2a, 2b, and 2c provide graphic examples of each rating.

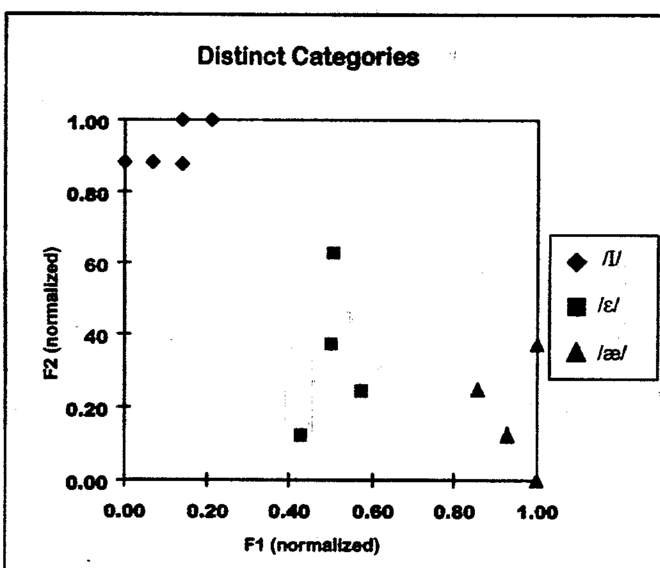

Figure 2a. Example of F1 x F2 scatterplot for production rating of 1.

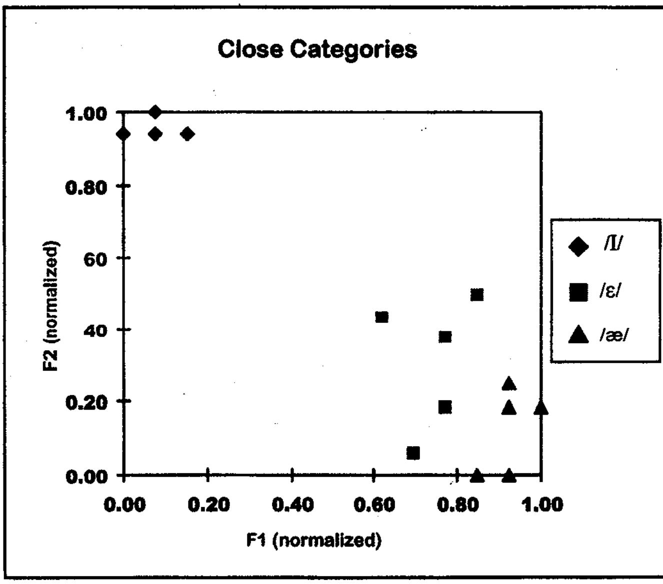

Figure 2b. Example of F1 x F2 scatterplot for production rating of 2.

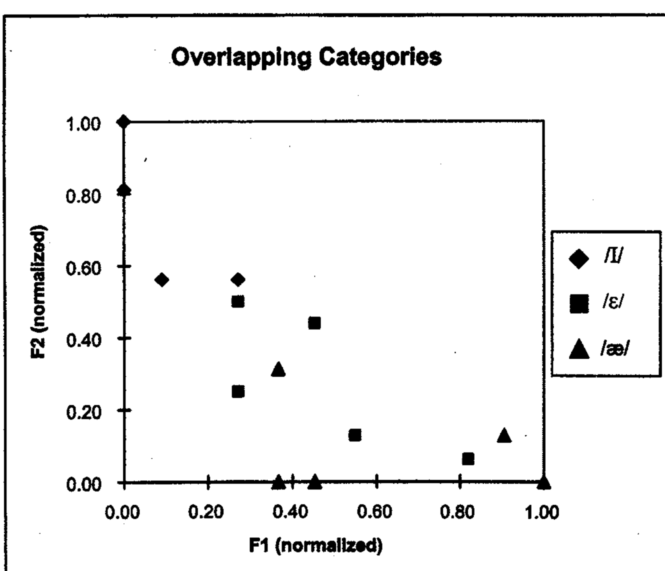

Figure 2c. Example of F1 x F2 scatterplot for production rating of 3.

RESULTS

In the first set of analyses, the RD and GR groups were compared on reading and phonological awareness measures. These analyses were followed by group comparisons of vowel perception and production measures. The last set of analyses examined correlations among perception, production, reading, and phonological awareness measures.

A MANOVA based on the five reading and phonological awareness measures resulted in a significant overall group difference ($F[5,21] = 15.82, p < .01$) (see table I). Subsequent analyses showed significantly higher performance by the GR group on each dependent measure: Word Attack ($F[1,25] = 54.11, p < .01$), Word Identification ($F[1,25] = 61.81, p < .01$), Sound Deletion ($F[1,25] = 5.10, p < .05$), and Pig Latin ($F([1,25] = 18.05, p < .01$).

Table II shows mean slopes based on vowel perception for the two groups. Significant differences between groups were obtained for both the /ɪ/-/ε/ slope (unequal variance ($t[18.6] = 2.84, p < .05$) and the /ε/-/æ/ slope ($t[25] = 2.62, p < .05$). In both cases, the mean slope for the GR group was steeper than for the RD group. Figures 3a and 3b present for each group the mean percentage of /ɪ/ responses for stimuli between /ɪ/ and /ε/ endpoints, and mean percentage of /æ/ responses for stimuli between /ε/ and /æ/ endpoints, respectively. Boundary differences between adjacent categories were noted for the two

Table II. Group Means and Standard Deviations (*SD*) for Slope, Vowel Duration, and Range of Vowel Duration.

	RD Group *n* = 19		GR Group *n* = 8	
Measure	**Mean**	***SD***	**Mean**	***SD***
Perception (regression coefficient)				
Slope /ɪ/ to /ε/*	2.34	.87	3.20	.63
Slope /ε/ to /æ/	1.87	.93	2.98	1.17
Production (in milliseconds)				
Vowel Duration pit	98	20	94	18
Vowel Duration pet	110	16	117	25
Vowel Duration pat	160	24	168	31
Range of Duration pit	27	16	23	12
Range of Duration pet	28	24	22	11
Range of Duration pat	36	31	27	21

*Note: For this analysis only, *N* for RD Group =18

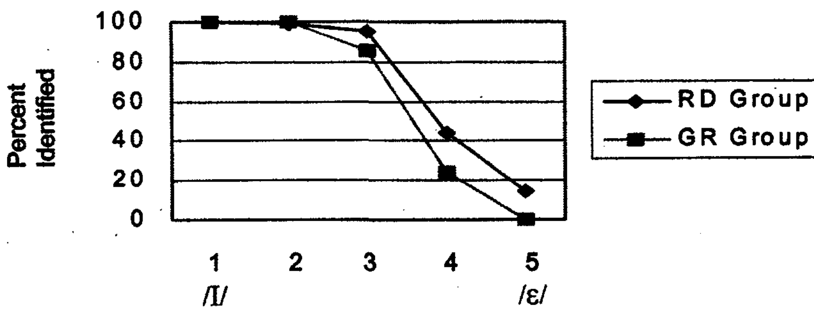

Figure 3a. Percent identified as /ɪ/. Data points 1–5 are on an /ɪ/ ←→ /ε/ continuum.

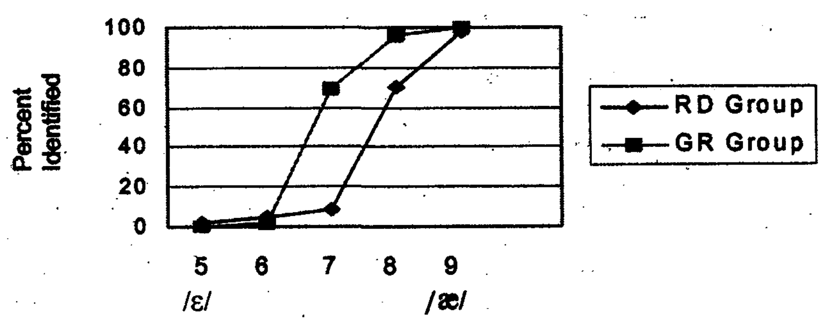

Figure 3b. Percent identified as /æ/. Data points 5–9 are on an /ε / ←→ /æ/ continuum.

groups. For the RD group the /ɪ/-/ε/ boundary was closer to the /ε/ endpoint and the /ε/-/æ/ boundary was closer to the /æ/ endpoint. In the case of /ε/-/æ/, there were significant group differences in percentage of /æ/ responses for stimuli 7 ($t[25] = 3.05$, $p < .01$) and 8 (unequal variance $t[22.1] = 3.54$, $p < .01$). No significant group differences were found for the percentage of /ɪ/ responses on the /ɪ/-/ε/ continuum.

Results for the spectral analyses based on vowel productions are shown in table III. In this case, no significant group differences were obtained for the vowel pair /ɪ/-/ε/ but significant differences were found for the pair /ε/-/æ/ (χ^2 (2) = 6.46, $p < .05$). For /ɪ/-/ε/, 100 percent and 79 percent of the responses were rated 1 (distinct) for the GR and RD group, respectively. In the case of /ε/-/æ/, only 26 percent of the responses were rated 1 for the RD group in comparison to 75 percent for the GR group; and 37 percent of the responses were rated 3 (overlapping) for the RD group in contrast to 0 percent for the GR group.

TABLE III. Frequency Counts of Production Ratings by Group.

	RD Group	GR Group
Production Rating /ɪ/-/ε/:		
1	15	8
2	3	0
3	1	0
	RD Group	GR Group
Production Rating /ε/-/æ/:		
1	5	6
2	7	2
3	7	0

Note: 1= distinct; 2 = close; 3 = overlapping

Results of the duration analysis indicate expected patterns of differences among vowels (/ɪ/ < /ε/ < /æ/) but no significant group differences. As an index of within participant variability, the range of durations for each participant was calculated and the mean range of durations was compared between groups. Again, no significant differences were found.

As expected, perception (slope) and production (ratings) correlated significantly with reading and phonological awareness performance when data for the two groups were combined. The following correlations were significant: Word Attack with slope /ɪ/-/ε/ (.39) and slope /ε/-/æ/ (.46); Word Identification with slope /ɪ/-/ε/ (.55) and slope /ε/-/æ/ (.53); Pig Latin with slope /ɪ/-/ε/ (.47) and slope /ε/-/æ/ (.42); and Word Identification with production ratings for /ε/-/æ/ (.44). However, correlations between the slopes and production ratings for /ɪ/-/ε/ and those for /ε/-/æ/ were not significant.

DISCUSSION

The purpose of this study was to examine the relationship between reading ability and vowel perception and production. The vowels /ɪ/, /ε/, and /æ/ were chosen for study because they often are misread and misspelled. Significant differences were found between good readers (GR group) and students with reading disabilities (RD group) in both vowel perception and production; the RD group displayed shallower slopes in the perception task (indicating less well-defined perceptual categories) and more overlapping and close categories (as measured by F1 and F2) when producing the vowels. No group differences were found in vowel durations on the production task.

The current study's results in the area of perception corroborate previous indications of weak phonemic categories in children with reading difficulties (e.g., de Gelder & Vroomen, 1998; Godfrey, et al., 1981; Joanisse, et al., 2000; Manis, et al., 1997; Werker & Tees, 1987). In contrast with those studies, which investigated perception of consonants, this study focused on vowels. The results concur with Post et al. (1997), showing that perception difficulties extend to tasks involving vowels. The vowels examined in the current study were phonetically similar, supporting the conclusions of Mody et al. (1997) that items with similar phonetic characteristics are particularly difficult for children with reading disabilities to perceive. Future studies could explore other vowels, including less similar pairs, to test the extent to which phonetic similarity poses difficulty for this population.

Although weak performance on the perception task could indicate less well-defined underlying categories, there are other possible explanations as well. For example, the use of computerized speech allows for controlled, consistent input; however, it also reduces the number of cues available to distinguish between categories. It may be that the students in the RD group were less able to use the particular cues that were varied in the stimuli (namely F1 and F2 values). It is also possible that they over-relied on their own stored categories, rather than adapting to the reference points for the given vowels. (See Kuhl [1991] for a discussion of the perceptual magnet effect.) The fact that the RD group demonstrated crossover points closer to /ɛ/ in the /ɪ/-/ɛ/ continuum and closer to /æ/ in the /ɛ/-/æ/ continuum may be evidence that the RD students were less able to use and remember the reference points. It could also be, however, that students' underlying categories for these vowels were broader and more diffuse. Whether the explanations for the shallower slopes and shifts in perception lie in weak and/or diffuse underlying categories or in difficulty extracting relevant speech cues, the results nevertheless suggest that some individuals with reading disabilities have difficulty using vowel information effectively.

The present study's finding of significant differences between groups in vowel production in single-syllable words is noteworthy. Previous research in production has focused on temporal ordering of phonemes or syllables in tasks requiring repetition of complex speech stimuli such as multisyllabic words or nonwords, tongue twisters, or phrases (e.g., Brady, Poggie, & Rapala, 1989; Catts, 1989; Snowling, 1981; Taylor, Lean, & Schwartz, 1989; Wolff, Michel, & Ovrut, 1990). The results of these studies have generally found differences between good readers and students with reading disabilities in both speed and accuracy of production. It has been hypothesized that these difficulties stem from weakly developed phonological categories, which lead to errors in selecting and ordering phonological segments during speech planning (e.g., Catts, 1989; Fowler, 1991; Snowling, 2000). Due to the complexity of the tasks involved, however, verbal working memory as well as motor timing control during articulation could affect performance. The current study's picture naming task, which employed monosyllabic, high frequency words, placed minimal demands on memory and motor planning. Thus, the finding of fine-grained production differences on this task supports the theory that some students with reading disabilities have weaker phonemic categories than good readers.

The group differences in vowel production occurred predominantly in the /ɛ/-/æ/ continuum, and not between /ɪ/-/ɛ/. Only 26 percent of the RD group produced distinct vowel categories for /ɛ/ and /æ/, whereas in 37 percent, these categories overlapped. In contrast, 75 percent of the GR group demonstrated distinct categories and none produced overlapping categories. The finding that /ɪ/ and /ɛ/ production categories were less likely to be close or overlapping may relate to the fact that while phonetically similar, the F1 and F2 values for /ɪ/ and /ɛ/ are generally farther apart than those for /ɛ/ and /æ/ (Hillenbrand, et al.,1995; Peterson & Barney, 1952).

Like Post et al. (1997), the current study did not find group differences in vowel production using measurements of duration. However, ratings based on formant frequency measurements did yield differences between groups. Another factor that may have contributed to the significant findings in this study was the use of a naming, rather than a repetition, task to elicit productions. The method of data collection and analysis may, therefore, have been more sensitive to individual differences in production performance than that used by Post et al. (1997).

Interestingly, weaknesses in perception did not correlate with weaknesses in production. This result implies either that perception and production do not share a single store of phonological codes, or that the difficulties may lie not with the phonological codes themselves but perhaps somewhere in perception and production processes that are not shared. These findings fail to provide support for the motor theory of speech perception (e.g. Liberman, 1998), which postulates an underlying phonetic module comprised of gestural codes (i.e., codes for changes in the vocal tract) that are referenced for both producing and perceiving phonemes. The current findings suggest, among other things, that precise gestural codes for vowel production are not necessarily tied to adequate codes for vowel perception. However, the present results may be limited by the measures used; perhaps the experimental tasks do not capture the essential linked characteristics. Additionally, due to the small number of participants tested, the findings should be considered preliminary. A larger study could look at these vowel perception and production issues in greater detail.

With respect to tasks employed, this study's perception and production measures differed in their overall processing demands. The production task simply required participants to name a series of familiar pictures one at a time. In contrast, the perception task required participants to compare a target stimulus with two endpoint stimuli in order to determine the target's identity. The latter task could, therefore, be considered more metalinguistic in nature. (See Nittrouer, 2002 for an in-depth discussion of the metalinguistic nature of categorical perception tasks.) While one might expect metalinguistic skills to be fully developed by adolescence, students in the RD group displayed specific deficits in phonological awareness, as noted earlier. Another factor that may have made the perception task more difficult than the production task for some students is that it involved listening to multiple auditory stimuli for an extended period of time and was, perhaps, more affected by attentional demands. Examination of history data for children in the RD group, however, indicated that only four students were diagnosed with attention deficit disorder (ADD) and all four were on medication at the time of the study.

The findings of weaknesses in vowel perception and production in adolescent students with reading disabilities have implications for remediation, in terms of both specific intervention techniques and age of intervention. Although the current study did not systematically assess the relationship of vowel processing to reading or spelling, the results are consistent with those of Post et al. (1999) who found a direct link between vowel perception and vowel spelling. Interestingly, they found that the correlation between vowel identification and vowel spelling was significant for the short vowels /ɪ/, /ɛ/ and /æ/, but not for /ʌ/ (as in "tub") nor for the long vowels /i/ (as in "deep"), /e/ (as in "tape"), and /u/ (as in "tube"). These findings highlight the importance of reading programs that focus on increasing students' awareness of the structure of the phonological system and how individual sounds map onto print. Because many students with reading disabilities demonstrate difficulty with consistent phoneme identification, they may need to be taught these skills systematically. These results suggest that vowels need particular instructional emphasis in intervention programs. In addition, the consonantal context in which vowels are found influences vowel discrimination and, therefore, should also be considered in remediation (see Post et al., 1999 for a discussion of specific techniques). The earlier that systematic sound-symbol intervention is implemented, the more successful the student can be in later attainment of fluent reading skills (Foorman, Francis, Shaywitz, Shaywitz, & Fletcher, 1997; Torgesen, Alexander, Wagner, Rashotte, Voeller, Conway, & Rose, 2001). The importance of training in phonemic awareness and phonics is also consistent with the conclusions of the National Reading Panel, which have found explicit instructional approaches to be particularly important for struggling readers (NICHD, 2000)

The results of the current study point to several potential areas for future research. Follow-up studies should explore more closely the links between vowel perception and production, and between vowel categorization and reading/spelling skills. The use of tasks that involve careful manipulation of /ɪ/, /ɛ/, and /æ/ for reading and spelling is recommended. As noted earlier, one could investigate different sets of vowels, both phonetically similar and those that are less similar. Also, given cross-sectional findings of developmental differences in vowel discrimination (e.g., Pursell, et al., 2002), it would be of interest to examine the relationships between vowel perception/production and reading abilities in different age groups. Through this type of investigation, one could also examine the differential effects of remediation on vowel categorization and reading abilities.

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References

Adams, M. J. (1990). *Beginning to read: Thinking and learning about print.* Cambridge, MA: The MIT Press.

Adlard, A., & Hazan, V. (1998). Speech perception in children with specific reading difficulties (dyslexia). *The Quarterly Journal of Experimental Psychology, 51A,* 153–177.

Bertucci, C. (1995). Vowel perception and its relationship to production, verbal memory and phonological processing in dyslexic participants: A small group case study. Unpublished masters thesis, MGH Institute of Health Professions, Boston.

Brady, S. (1991). The role of working memory in reading disability. In S. A. Brady & D. Shankweiler (Eds.). *Phonological processes in literacy: A tribute to Isabelle Y. Liberman* (pp. 129–151). Hillsdale, NJ: Lawrence Erlbaum Associates.

Brady, S. (1997). Ability to encode phonological representations: An underlying difficulty for poor readers. In B. Blachman (Ed.). *Foundations of reading acquisition and dyslexia: Implications for early intervention* (pp. 21–48). Mahwah, NJ: Lawrence Erlbaum Associates.

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.

Brandt, J., & Rosen, J. J. (1980). Auditory phonemic perception in dyslexia: Categorical identification and discrimination of stop consonants. *Brain and Language, 9,* 324–337.

Bryson, S. E., & Werker, J. F. (1989). Toward understanding the problem in severely disabled readers. Part I: Vowel errors. *Applied Psycholinguistics, 10,* 1–12.

Catts, H. (1989). Speech production deficits in developmental dyslexia. *Journal of Speech and Hearing Disorders, 54,* 422–428.

de Gelder, B., & Vroomen, J. (1998). Impaired speech perception in poor readers: Evidence from hearing and speech reading. *Brain and Language, 64*, 269–281.

Ehri, L., Wilce, L., & Taylor, B. (1987). Children's categorization of short vowels in words and the influence of spellings. *Merrill Palmer Quarterly, 33*, 393–421.

Ehri, L., Nunes, S., Willows, D., Schuster, B., Yaghoub-Zadeh, Z., & Shanahan, T. (2001). Phonemic awareness instruction helps children learn to read: Evidence from the National Reading Panel's meta-analysis. *Reading Research Quarterly, 36*, 250–287.

Foorman, B., Francis, D. J., Shaywitz, S. E., Shaywitz, B. A., & Fletcher, J. M. (1997). The case for early reading intervention. In B. Blachman (Ed.). *Foundations of reading acquisition and dyslexia: Implications for early intervention* (pp. 243–264). Mahwah, NJ: Lawrence Erlbaum Associates.

Fowler, A. E. (1991). How early phonological development might set the stage for phoneme awareness. In S. A. Brady & D. Shankweiler (Eds.). *Phonological processes in literacy: A tribute to Isabelle Y. Liberman* (pp. 97–117). Hillsdale, NJ: Lawrence Erlbaum Associates.

Godfrey, F. F., Syrdal-Lasky, A. K., Millay, K. K., & Knox, C. M. (1981). Performance of dyslexic children on speech perception tests. *Journal of Experimental Child Psychology, 32*, 401–424.

Hansen, J., & Bowey, J. A. (1994). Phonological analysis skills, verbal working memory, and reading ability in second-grade children. *Child Development, 65*, 938-950.

Hillenbrand, J., Getty, L., Clark, M., & Wheeler, K. (1995). Acoustic characteristics of American English vowels. *Journal of the Acoustical Society of America, 97*, 3099–3111.

Joanisse, M., Manis, F., Keating, P., & Seidenberg, M. (2000). Language deficits in dyslexic children: Speech perception, phonology, and morphology. *Journal of Experimental Child Psychology, 77*, 30–60.

Klatt, D. H. (1987). Review of text-to-speech conversion for English. *Journal of the Acoustical Society of America, 82*, 737–793.

Klatt, D. H., & Klatt, L. C. (1990). Analysis, synthesis, and perception of voice quality variations among female and male talkers. *Journal of the Acoustical Society of America, 87*, 820—857.

Kuhl, P. K. (1991). Human adults and human infants show a "perceptual magnet effect" for the prototypes of speech categories, monkeys do not. *Perception & Psychophysics, 50*, 93–107.

Ladefoged, P. (2001). *Vowels and consonants: An introduction to the sounds of languages.* Malden, MA: Blackwell Publishers.

Liberman, A. M. (1998). When theories of speech meet the real world. *Journal of Psycholinguistic Research, 27*, 111–122.

Lundberg, I., Frost, J., & Petersen, O. P. (1988). Effects of an extensive program for stimulating phonological awareness in pre-school children. *Reading Research Quarterly, 23*, 263–284.

Lyon, G. R. (1995). Research initiatives in learning disabilities: Contributions from scientists supported by the National Institute of Child Health and Human Development. *Journal of Child Neurology, 10*, 120–126.

Manis, F., McBride-Chang, C., Seidenberg, M., Keating, P., Doi, L., Munson, B., & Petersen, A. (1997). Are speech perception deficits associated with developmental dyslexia? *Journal of Experimental Child Psychology, 66*, 211–235.

Moats, L. (1995). *Spelling: Developmental disability and instruction.* Baltimore: York Press.

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.

National Institute of Child Health and Human Development (NICHD). (2000). Report of the National reading panel: Teaching children to read: An evidence-based assessment of the scientific research literature on reading and its implications for reading instruction: Report of the sub-groups. NIH Pub. No. 00-4754.

Nittrouer, S. (2002). From ear to cortex: A perspective on what clinicians need to understand about speech perception and language processing. *Language, Speech, and Hearing Services in Schools, 33*, 237–252.

Peterson, G. E., & Barney, H. L. (1952). Control methods used in a study of the vowels. *Journal of the Acoustical Society of America, 24*, 175–184.

Post, Y. V., Foorman, B. R., & Hiscock, M. (1997). Speech perception and speech production as indicators of reading difficulty. *Annals of Dyslexia, 47*, 3–27.

Post, Y. V., Swank, P. R., Hiscock, M., & Fowler, A. E. (1999). Identification of vowel speech sounds by skilled and less skilled readers and the relationship with vowel spelling. *Annals of Dyslexia, 49*, 161–194.

Pursell, S., Swanson, L., Hedrick, M., & Nabelek, A. (2002). Categorical labeling of synthetic /ɪ/ and /ɛ/ in adults and school-age children. *Journal of Phonetics, 30*, 131–137.

Rack, J. P., Snowling, M. J., & Olson, R. K. (1992). The nonword reading deficit in developmental dyslexia: A review. *Reading Research Quarterly, 27*, 29–53.

Rayner, K., Foorman, B. R., Perfetti, C. A., Pesetsky, D., & Seidenberg, M. S. (2001). How psychological science informs the teaching of reading. *Psychological Science in the Public Interest, 2*, 31–74.

Rosner, J. (1975). *Helping children overcome learning difficulties.* New York: Walker.

Sensimetrics Corporation. (1997–2000). SpeechStation2 Version 1.1. Somerville, MA: Sensimetrics Corporation.

Serniclaes, W., Sprenger-Charolles, L., Carré, R., & Demonet, J.-F. (2001). Perceptual discrimination of speech sounds in developmental dyslexia. *Journal of Speech, Language, and Hearing Research, 44*, 384–399.

Shankweiler, D., & Liberman, I. Y. (1972). Misreading: A search for causes. In J. F. Kavanagh & I. G. Mattingly (Eds.). *Language by ear and by eye* (pp. 293–317). Cambridge, MA: MIT Press.

Share, D., & Stanovich, K. (1995). Cognitive processes in early reading development: Accommodating individual differences into a model of acquisition. *Issues in Education: Contributions from Educational Psychology, 1*, 1–57.

Snowling, M. (1981). Phonemic deficits in developmntal dyslexia. *Psychological Research, 43*, 219–234.

Snowling, M. (2000). *Dyslexia.* Malden, MA: Blackwell Publishers.

SPSS. (2000). SPSS for Windows, Version 10.0.7. Chicago, IL: SPSS, Inc.

Stanovich, K. E. (1986). Explaining the variance in reading ability in terms of psychological processes: What have we learned? *Annals of Dyslexia, 35*, 67–96.

Stone, B., & Brady, S. (1995). Evidence for phonological processing deficits in less-skilled readers. *Annals of Dyslexia, 45*, 51–78.

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

Tallal, P., & Piercy, M. (1973). Developmental aphasia: Impaired rate of nonverbal 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., & Stark, R. (1981). Speech acoustic-cue discrimination abilities of normally developing and language-impaired children. *Journal of the Acoustical Society of America, 69*, 568–574.

Taylor, H., Lean, D., & Schwartz, S. (1989). Pseudoword repetition ability in learning disabled children. *Applied Psycholinguistics, 10*, 201–219.

Torgesen, J. K., Alexander, A. W., Wagner, R. K., Rashotte, C. A., Voeller, K., Conway, T., & Rose, E. (2001). Intensive remedial instruction for children with severe reading disabilities: Immediate and long-term outcomes from two instructional approaches. *Journal of Learning Disabilities, 34*, 33–58.

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

Werker, J. F., & Tees, R. C. (1987). Speech perception in severely disabled and average reading children. *Canadian Journal of Psychology, 41*, 48–61.

Wolff, P., Michel, G., & Ovrut, M. (1990). The timing of syllable repetitions in developmental dyslexia. *Journal of Speech and Hearing Research, 33*, 281–289.

Woodcock, R. W. (1987). *Woodcock reading mastery tests-Revised.* Circle Pines, MN: American Guidance Services.

Woodcock, R. W., & Johnson, M. B. (1987). *Woodcock-Johnson psychoeducational battery.* Circle Pines, MN: American Guidance Service.

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APPENDIX A

PHONOLOGICAL AWARENESS TASKS

Sound Deletion:

1.	Say *carwash* . . .	Now say it again but don't say *car*.	(wash)
2.	Say *time* . . .	Now say it again but don't say /*m*/.	(tie)
3.	Say *scold* . . .	Now say it again but don't say /*sk*/.	(old)
4.	Say *belt* . . .	Now say it again but don't say /*t*/.	(bell)
5.	Say *glow* . . .	Now say it again but don't say /*l*/.	(go)
6.	Say *desk* . . .	Now say it again but don't say /*s*/.	(deck)
7.	Say *block* . . .	Now say it again but don't say /*b*/.	(lock)
8.	Say *Germany* . . .	Now say it again but don't say /*ma*/.	(journey)
9.	Say *create* . . .	Now say it again but don't say /*ee*/.	(crate)
10.	Say *carpenter* . . .	Now say it again but don't say /*pen*/.	(carter)

Pig Latin:

Words to translate into pig latin:

bake

map

kite

rabbit

tumble

basket

Sentences to translate into pig latin:

Can you see me?

Put them by the table.

Comprehension (for translation into English):

atpo

occerso

eho anco unro astfo

APPENDIX B

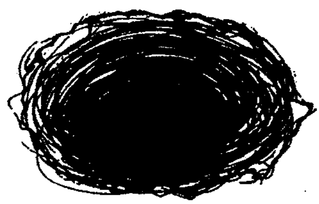
FORMANT VALUES FOR PIT-PET-PAT PERCEPTION TASK

Stimulus	F1(Hz)	F2(Hz)
1 = /ɪ/	550	2300
2	537	2241
3	575	2183
4	613	2124
5 = /ɛ/	650	2065
6	700	2048
7	750	2032
8	800	2016
9 = /æ/	850	2000

APPENDIX C

PIT, PET, PAT PICTURES AND EXPLANATIONS

Pit: a hole in the ground



Pet: examples of different pets you might have

Pat: as in a pat on the back