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## **Auditory Word Identification in Dyslexic and Normally Achieving Readers<sup>\*</sup>**

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### **Abstract**

The integrity of phonological representation/processing in dyslexic children was explored with a gating task in which children listened to successively longer segments (gates) of a word. At each gate, the task was to decide what the entire word was. Responses were scored for overall accuracy, as well as the child's sensitivity to coarticulation from the final consonant. As a group, dyslexic children were less able than normally achieving readers to detect coarticulation present in the vowel portion of the word, and primarily on the most difficult items, those ending in a nasal sound. Hierarchical regression and path analyses indicated that phonological awareness mediated the relationship of gating and general language ability to word and pseudoword reading ability.

Developmental dyslexia is characterized by difficulty with fluency and/or accuracy of reading in the absence of serious intellectual, sensory, emotional or experiential impediments to learning (Lyon, 1995). There is a strong consensus in the field that the proximal cause of the disorder involves phonological deficits (Brady, 1997; Fowler, 1991; Snowling, 2000; Stanovich & Siegel, 1994; Wagner & Torgesen, 1987). Phonological deficits are thought to underlie critical components of the reading process, such as the learning of spelling-sound correspondences and the development of efficient word recognition (Bruck, 1992; Rack, Snowling, & Olson, 1992; Share, 1995; Stanovich & Siegel, 1994). Phonological deficits may also be causally related to specific kinds of language processing difficulties outside the domain of reading, including poor phonological awareness (Bruck, 1992; Liberman & Shankweiler, 1985; Manis, Custodio, & Szeszulski, 1993; Pratt & Brady, 1988; Swan & Goswami, 1997), inefficient use of verbal working memory (Berninger, Abbott, Thomson, Wagner, Swanson, Wijsman, & Raskind, 2006; Brady, Shankweiler, & Mann, 1983; Griffiths & Snowling, 2002; McDougall, Hulme, Ellis, & Monk, 1994), and slow access to the mental lexicon as manifested in naming tasks (Denckla & Rudel, 1976; Wolf & Bowers, 1999).

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Many research studies have explored the relationship between phonological awareness and reading disability, yet the underlying cause of these phonological impairments remains ambiguous. Some have argued that poor phonological awareness reflects difficulties in analysis of the sound structure of words, particularly at the level of the phoneme. Such difficulties would lead directly to problems in learning spelling-sound correspondences in alphabetic languages (Liberman & Shankweiler, 1985; Share, 1995). A problem with this approach is that phonological awareness at the level of the phoneme appears not to develop actively until the onset of reading instruction, and it may be heavily influenced by the individual's experience with printed words in alphabetic languages (Morais, Cary, Alegria, & Bertelson, 1987; Perfetti, Bell, Beck, & Hughes, 1987; Ziegler & Goswami, 2005). Others have argued that poor performance on phonological awareness tasks may reflect incomplete or inaccurate phonological representations, rather than analytic problems per se (Boada & Pennington, 2006; Elbro, Borstrom, & Petersen, 1998; Fowler, 1991; Snowling & Hulme, 1989; Swan & Goswami, 1997). We will term this broad view the *phonological representations hypothesis* after Swan and Goswami (1997).

The primary goal of the present study was to investigate the integrity of underlying phonological representations among dyslexic individuals and normally-achieving readers. Additionally, we wanted to correlate the quality of phonological representations with phonological awareness and reading ability. Atypical phonological representations, if they do exist in dyslexic individuals, may be related to subtle problems in perceiving spoken words. Children with a speech perception problem would not succeed in accurate categorization of the phonemes in their language; therefore, they would have difficulty creating accurate representations for words in long-term memory. However, an isolated phoneme categorization problem alone is unlikely to be the sole explanation for reading problems among dyslexic children. Although several studies have reported categorical speech perception deficits in dyslexics as a group (Chiappe, Chiappe, & Siegel, 2001; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Maassen, Groenen, Crul, Assman-Hulsmans, & Gabreels, 2001; Reed, 1989; Serniclaes, Sprenger-Charolles, Carré, & Demonet, 2001; Werker & Tees, 1987), many individual dyslexics show normal speech perception (Adlard & Hazan, 1997; Joanisse, Manis, Keating & Seidenberg, 2000; Manis, McBride-Chang, Seidenberg, Keating, Doi, Munson, & Peterson, 1997; Manis & Keating, 2005; Pennington, van Orden, Smith, Green, & Haith, 1990; Ramus, Rosen, Dakin, Day, Castellote, White, & Frith, 2003).

In the Joanisse et al. (2000) and Manis & Keating (2005) studies, a subset of dyslexics with combined oral language and phonological awareness impairments performed poorly on tests of speech perception, but the remainder of the dyslexic sample did not. Several dyslexic children with the "classic" profile of normal oral language, low phonological awareness and low nonword reading performed normally on speech perception tasks, and some had better than expected discrimination ability (similar results were reported by Serniclaes et al., 2001), suggesting that their difficulty lies in categorization, rather than more general auditory processing. Thus, it is unlikely that general and extreme problems with speech perception are the cause of any representational problems that children with dyslexia may experience. Their difficulties are more likely to arise from poorly specified long-term representations of phonological entities, and/or an impairment in the process of comparing auditory input to long-term representations.

The results of speech perception studies, when looked at as a whole, are inconclusive at best. Either only a subset of dyslexics has speech perception difficulties, or studies finding null effects did not use a sensitive enough task. Categorical perception of consonants, a task typically used in speech perception studies, is not very demanding for school-age children, and therefore may not identify subtle speech perception deficits. Therefore, studies of speech perception are needed using methods that are more sensitive to subtle differences in performance and which are suitable for looking at the processing of the speech signal.

We designed a gating task, modeled after the one by Grosjean (1980) but scored as in Lahiri and Marslen-Wilson (1991) as a more sensitive measure of speech perception in dyslexic as compared to normally achieving readers. Gating tasks ask listeners to search their entire lexicons for matches to auditory inputs; both the long-term representations and processing must be robust to generate appropriate responses.

In a typical gating task a listener is presented with successively longer portions of the word (gates) beginning with the onset. At each gate, the listener is asked to guess the entire word. This type of task requires intact and highly integrated phonological representations because subjects must use limited acoustic information to identify a word by comparing the acoustic information to many possible stored representations (Salasoo & Pisoni, 1985). Adults require as little as 150 ms of the word (less than half the length of a typical spoken word) to identify highly familiar words (Grosjean, 1980; Salasoo & Pisoni, 1985; Tyler & Wessels, 1985). Children require more acoustic information than adults (Metsala, 1997a).

The gating task can be used as an index of the overall integrity of phonological representations and/or phonological processing because it does not depend on the ability to utilize phoneme-level segments to process spoken words, as is the case for certain tests of speech categorization or phonological awareness. Adequate performance on the gating task requires the ability to make comparisons to stored representations of entire words. There is no necessity that either the stored representations or the perceived fragments be encoded as a sequence of segments to perform this task (Griffiths & Snowling, 2001). Additionally, gating tasks minimize confounding factors often present in other tests of phonological processing. Because gating tasks require a single, un-timed response on each trial, they place a minimal load on working memory and on the speed of phonological retrieval, two processes that may be compromised in dyslexic children (e.g., Wagner & Torgesen, 1987; Wolf & Bowers, 1999). Finally, problems with phonological retrieval (e.g., as on confrontation naming tasks, found in some dyslexic children, e.g., Wolf & Bowers, 1999) are unlikely to interfere with gating performance, as the stimulus items are typically very common words. Thus gating is a task that is appropriate for children, yet is potentially more sensitive to problems with phonological representations and processing than is categorical perception, in that it places greater demands on lexical access.

Furthermore, we argue that the gating task can be made even more sensitive by scoring responses at a sub-lexical level, specifically at the level of phonetic features. Coarticulation, which occurs when the articulations associated with different speech segments overlap in time (e.g. Farnetani, 1997; Keating, 2002), facilitates performance on the gating task. Normally developing children as young as three years of age (Nitttrouer & Studdert-Kennedy, 1987; Repp, 1986) and even prelinguistic infants (Fowler, Best & McRoberts, 1990) are able to perceive coarticulatory influences in speech sounds. Crucially for our purposes, Warren & Marslen-Wilson (1987) showed

that adults can use the effect of anticipatory coarticulation on a vowel to identify spoken words in a gating task. In this study adults were able to identify the target word at the beginning of the final consonant, and more importantly, nasal responses were prevalent much earlier in the vowel; this effect was independent of the effect of the frequency of the target word. Coarticulatory nasalization of a vowel is extra, redundant information in the signal which listeners are clearly able to use to access lexical representations of nasal consonants. This ability is an indication that long-term lexical representations are specified below the level of the segment: either in terms of features, or with full acoustic detail. Edwards, Fourakis, Beckman & Fox (1999) have proposed that some children have “a weak cognitive representation of the redundant perceptual cues for speech sounds” (p. 184), which tasks like gating can reveal.

Relatively few studies have utilized the gating paradigm with children (Boada & Pennington, 2006; Dollaghan, 1998; Edwards et al. 1999; Elliot, Hammer, & Evan, 1987; Elliot, Scholl, Grant, & Hammer, 1990; Griffiths & Snowling, 2001; Metsala, 1997,a,b; Montgomery 1999; Munson, 2001); Walley 1988; Walley, Michela, & Wood, 1995; Wesseling & Reitsma, 2001). Performance is scored in terms of initial-consonant or whole-word matching. The findings are generally that children require more gates (a longer piece of the word) for identification than adults. For example, Metsala (1997a) assessed gating performance in 7-, 9-, and 11-year old children, as well as adults. The 7-year-olds required significantly more gates (i.e., more acoustic input) to identify target words, as well as initial phonemes of the target words, when compared to 11-year olds and adults. Both children and adults required fewer gates to identify high-frequency words, and words with a larger number of lexical neighbors (i.e., words that share more phonemic units with the target words in a “dense” lexical neighborhood). The results were interpreted in terms of the *lexical restructuring hypothesis* (Metsala 1993; Metsala & Walley, 1997a). According to this view, phonological representations of young children are initially holistic, but become more segmentally organized due to the pressure of vocabulary expansion; eventually the organization reaches the level of the phoneme. The denser a word’s neighborhood, the greater the pressure on the individual to restructure, and therefore the younger the age at which restructuring should occur. On this view, it must be the case that the adult participants do not have fully segmental representations for words in sparse neighborhoods, since adults as well as children required more gates to recognize these words. The finding that neighborhood density is facilitative rather than competitive for word recognition runs contrary to the pattern established for other word recognition tasks, and is perhaps surprising in terms of models of lexical competition (e.g. Dell and Gordon, 2003). At present, it appears that the interpretation of neighborhood effects in gating tasks requires further scrutiny.

A small number of gating studies have been conducted with dyslexic children. Metsala (1997b) administered a gating task to younger and older groups of dyslexic and age-matched normal readers (mean ages about 8 and 11 years). Stimuli in this study were grouped based on both frequency and lexical neighborhood density. High-frequency words, especially in sparse lexical neighborhoods, required fewer gates for identification. Furthermore, normally achieving readers needed fewer gates to identify words from sparse neighborhoods than dense neighborhoods. This result is more in accord with other word recognition studies (neighbors compete, not facilitate), but is the opposite of the result found by Metsala (1997a), and the opposite of the prediction made by the lexical restructuring hypothesis. Here, it would have to be the case that the normal readers had more segmental representations for words in sparse neighborhoods. The result for the

dyslexic children was that they needed more gates than normal readers to identify words in sparse neighborhoods, whereas the groups did not differ in gating performance on words in dense neighborhoods. That is, neighborhood density had no effect on the dyslexic children's performance; they performed as the normals did for words in dense neighborhoods. By itself this lack of an effect would accord with the restructuring hypothesis – none of the dyslexics' lexicons would have undergone restructuring – except for the fact that the normals' performance is in the wrong direction.

Griffiths & Snowling (2001), in contrast, found that not only dyslexic but also normally achieving readers (both age 8-12 years) required the same number of gates to identify words regardless of neighborhood density. The dyslexic sample in the Griffiths and Snowling study showed the commonly observed pattern of deficits in nonword pronunciation and rapid name retrieval. Therefore their null results could not be attributed to an unrepresentative dyslexic sample. They concluded, contrary to Metsala (1997b), that dyslexic children had segmentally organized phonological representations. They argued, based on null results for the gating task and the presence of rapid name retrieval difficulties, that phonological deficits in dyslexia involve problems in the generation of phonological output, rather than the adequacy of phonological representations per se. In sum, the evidence to date on the role of lexical neighborhood density in responses in the gating task, and its implications for the nature of lexical representations, is contradictory. However, it does appear that high frequency words are recognized with fewer gates, implying that representations are more intact or more easily accessed for highly familiar words

Boada & Pennington (2006) is a recent study that included a gating task. Their primary interest was recognition of the initial consonant; the children with dyslexia performed worse at this than the age-matched, but not the reading-level-matched, controls. However, when scored for whole-word matching, the children with dyslexia performed worse than both groups of controls. There were no differences between dyslexic groups with and without broader language impairments.

A methodological issue with the Metsala (1997b) and Boada and Pennington (2006), and especially the Griffiths & Snowling (2001) studies is the items themselves. The items chosen have a number of embedded words. For example, the word "weed" contains the word "we" and the word "fork" the word "for". For such items a correct whole word response would probably require a late gate because on earlier gates, one would have a tendency to guess the shorter word "we" simply because the earlier gate sounds identical to the intact word "we". It is possible that, for these items, listeners require stronger evidence of anticipatory information to impel them to select the longer response, and the test might lack sensitivity.

One aspect of these studies worth reconsideration is that responses were scored correct only when subjects named the exact target word for a given trial. According to this scoring method, if the target word was /kæt/ and a subject guessed /kæp/ that answer would be incorrect. However, both words end in a voiceless oral stop consonant. Stop consonants typically have relatively little influence on the articulation of the preceding vowel: the place of articulation difference between /t/ and /p/ is seen only in the formant transitions at the end of the vowel; the effect of their stop manner is likewise seen late in the vowel (in the speed of the first formant transition), and their voicelessness results in a shorter vowel with a different voice quality at its offset. Therefore, these two words sound quite similar until late in the vowel. For a listener to know that the final consonant is a voiceless oral stop (at any place of articulation) already shows sensitivity to a good

deal of acoustic phonetic information (Warren and Marslen-Wilson, 1988). Yet an incorrect response is not given partial credit, so to speak, for the strong resemblance of /kaet/ to /kaep/, as opposed to /kaen/ or /kaemp/, which would have substantially nasalized and lengthened vowels. An exact-match scoring procedure therefore might not be sensitive to subtle differences in listeners' ability to make full use of the acoustic phonetic information available in early portions of words.

The gating procedure used in the present study provided more direct information about the organization of phonological representations in dyslexic and non-dyslexic children. We made use of Warren and Marslen-Wilson's (1987) demonstration that listeners are sensitive to nasal coarticulation, and West's (1999) demonstration that listeners are sensitive to liquid coarticulation. Warren and Marslen-Wilson showed that listeners can detect and use nasalization by the middle of a vowel to anticipate an upcoming nasal consonant. West showed that listeners can detect an /l/ or /r/ a full syllable away, presumably on the basis of large and extensive perturbations in the third formant frequency. For purposes of the present study it was thus reasoned that if normally achieving readers possessed more fully specified phonological representations, they would be able to distinguish between words with nasals (or liquids, e.g. lateral /l/) and other types of words (e.g., with oral stops) at earlier gates than dyslexics. We have no hypotheses about reader ability group differences between these consonant categories, but included them all for completeness. We obtained two different scores for responses in the gating task, first, a category score, based on whether the child named a word in the correct category (nasal vs. lateral vs. oral stop), as in Lahiri & Marslen-Wilson (1991). For example, if the item was /kaet/, the response /kaep/ would receive a correct score in terms of category but the response /kaen/ would not. Secondly, a total score was given based on production of an exact match to the target word. In this case, if the target is /kaet/, the only correct response is /kaet/. We hypothesized that dyslexic children would perform more poorly than normal readers of the same age on both measures, but expected the category measure to be more sensitive. To our knowledge, our use of a category-match score is new in studies of children with or without dyslexia.

Although our primary goal was to explore group differences between dyslexic and non-dyslexic children on the gating task, we also investigated individual differences within the dyslexic sample. Two critical dimensions that may be important are the degree of phonological deficit, and the degree of language impairment (Gallagher, Frith, & Snowling, 2000; Griffiths & Snowling, 2002; Joanisse et al., 2000; Manis, Seidenberg, Doi, McBride-Chang, & Petersen, 1996; Stanovich, Siegel, & Gottardo, 1997). According to the phonological representations hypothesis, the degree of phonological impairment should be the primary variable affecting gating task performance. We obtained a measure of phonological awareness in order to explore this alternative.

Performance on the gating task may depend in part on the child's level of language development, with vocabulary perhaps assuming the most important role (Metsala & Walley, 1997; Walley, 1993). We obtained several measures of language ability, including measures of sentence memory, receptive vocabulary, expressive vocabulary and ability to follow oral directions. In addition to the overall comparison of dyslexic and non-dyslexic groups, multiple regression analyses were utilized to tease apart the relationships among gating performance, phonological awareness, language skill and reading.

## Method

### Participants

Children were recruited from elementary schools in a major metropolitan area in the state of California. The total number of participants was 46 (23 dyslexic individuals – 14 males and 10 females – and 23 normally achieving readers – 13 males and 13 females). Children ranged from 8 to 14 years of age (dyslexic individuals, 9-14 years and normally achieving readers, 8-14 years). Years of parental education were similar across groups: dyslexic individuals, 15.53 years and normally achieving readers, 15.59 years. Ethnic background (as assessed by parent report) of the dyslexic individuals was as follows: 43.5% Caucasian, 17.4% mixed decent, 4.3% Hispanic, 4.3% Asian; 34.8% of parents did not report ethnicity. For the normally achieving readers the ethnic background was as follows: 21.7% Caucasian, 21.7% mixed decent, 17.4% Hispanic, 8.7% African American, 8.7% Asian; 21.7% of parents did not report ethnicity. All children were fluent in English, three children (in the normally achieving reader group) were fluent in a language other than English and 4 children (also in the normally achieving reader group) were exposed to another language in the home, but were not fluent in any language other than English.

In order to be included in the study participants were required to have a scaled score greater than 7 (corresponding to a standard score of 85) on either the verbal (average of Vocabulary and Similarities subtests) or performance (average of Block Design and Picture Completion subtests) estimate of WISC-III IQ (Wechsler, 1992). This criterion was used to avoid participants who would likely have poor reading ability due to general cognitive impairments, while not overly restricting the range of oral language ability within the dyslexic sample. Children were excluded from the study based on the following criteria as determined from parent report: neurological problems, uncorrected hearing or vision problems, serious emotional or behavioral problems including Attention Deficit Hyperactivity Disorder (ADHD). According to parent report 5 children (4 in the dyslexic reader group and 1 in the normally achieving reader group) were currently taking medication for ADHD and were well-controlled enough to participate in the testing.

**Dyslexic children.** Dyslexic children were defined by a score at or below the 25<sup>th</sup> percentile (SS=90) on either of two subtests (Word Identification or Word Attack) of the Woodcock-Johnson Reading Mastery Test-Revised (Form G) (Woodcock, 1987). Both subtests are standardized measures of reading level. Word Identification contains a series of increasingly difficult English words and Word Attack contains orthographically regular nonwords whose pronunciations are scored based on common spelling-sound correspondence patterns in English. Norms updated in 1993 were used to calculate percentile scores (Woodcock, 1998).

**Normally achieving readers:** To be classified as a normally achieving reader a child was required to score at or above the 40<sup>th</sup> percentile on both Woodcock Word Identification and Word Attack. All other criteria for inclusion in the sample as a whole applied (e.g., estimated IQ criteria, absence of attention or neurological problems, etc.).

### Test of Phonological Abilities

The Elision task from the Comprehensive Test of Phonological Processing (Wagner, Torgesen, & Rashotte, 1999) was administered in the standard format. The Elision task requires children to delete syllables or phonemes from words spoken by the examiner.



The test mostly taps phoneme awareness, as only the first three items involve syllable deletion. The remaining 17 of the 20 test items involve the deletion of a single phoneme (from the word onset, middle or end, including blends at the beginnings of the words). The test is terminated if the child misses three in a row. The test manual reports Cronbach's Alpha reliability at age 10 of 0.91.

### **Oral Language Tasks**

Language ability was assessed by means of the following standardized tests: Concepts and Directions and Recalling Sentences from the Clinical Evaluation of Language Fundamentals- Revised (CELF-R) (Semel, Wiig & Secord, 1995), and the Receptive OneWord Picture Vocabulary Test (ROWPVT) (Brownell, 2000). Concepts and Directions requires subjects to listen to a short sentence and carry out the action by pointing to black and white geometric forms (e.g., "Point to the small, white square after you point to the large triangles."). Recalling Sentences requires subjects to listen to sentences of varying lengths and repeat each one back verbatim.

### **Gating Task**

All test items were monosyllabic English words. Approximately half the words were low (mean = 116.45; e.g., *cone*) and half were high (mean = 2052.45; e.g., *cat*) in printed word frequency in a corpus of approximately 5.1 million words (Carroll, Davies & Richman, 1971). Low and high are relative to the present study; all words were chosen because they were readily available in a third grader's vocabulary (according to Carroll et al.). Groups of words that have CVC or CCVC structures but differed in their final consonant were constructed, and printed word frequency was matched across these sets of items. The final consonant varied in terms of manner of articulation: nasal, lateral, or oral stop (*/kod/*). Most of the stimuli were constructed as minimal pairs (e.g. *sweat/swell*) but 2 sets were minimal triples (*cone/coal/code*, *bone/bowl/boat*). The effect of neighborhood density on children's word recognition is not clear (see Garlock, Walley & Metsala, 2001) therefore, stimuli were chosen to have a moderate N (range = 2-19; mean = 12.59; SD = 7.42) and neighborhood density was matched across based on final consonant class and frequency (high or low). The nasal items were: *clown, cone, rang, dawn, pan, bone, scene, and can*. The lateral items were: *swell, bowl, coal, feel*. The stop items were: *rag, pad, sweat, code, dot, cloud, seat, cat, boat, and feet*.

The listener was presented (via headphones) partial word segments of varying durations and asked to identify the words. There were a total of 25 words (3 practice, 22 test items) and each word was divided into 6 gates. The gates were not of equal durations but rather were keyed to important acoustic properties of the words (see Figure 1), as follows. The first gate was just the initial consonant(s), until the beginning of a voiced vowel. This gate was not played in the experiment. The second gate added the initial 25 msec of the vowel, that is, most or all of the CV formant transition interval. From this gate the initial consonant(s) can generally be fully perceived, along with partial information about the vowel. It is unlikely that much information about nasality or laterality of the final consonant is available in this gate. The third gate gave an additional 25 ms of the vowel and, at 50 msec total, generally included the entire CV formant transition interval; from this gate the initial consonant(s) plus the vowel should ordinarily be perceived, and some information about the final consonant's manner should already be available. The fourth gate presented the entire vowel *except* for its last 25 msec, making the vowel even more likely to be correctly perceived. Nasalization and lateralization of

vowels should be quite obvious in the fourth gate, and some place of articulation information as well. The fifth gate added the last 25 msec of the vowel, that is, the remaining VC formant transition interval. From this gate the entire word is likely to be correctly perceived. Gate 6 added the final consonant, and hence was the full presentation of an intact, complete word. Gates 3 and 4 provide the crucial comparison with respect to anticipatory information about final consonant manner: a listener who is better able to make use of coarticulation should be able to perceive the consonant manner in gate 3, while other listeners will need the much greater amount of information in gate 4. Similarly, gates 4 and 5 provide the crucial comparison with respect to identifying the exact final consonant: gate 5 provides more of the VC formant transitions that reflect the consonant's place of articulation, but a listener who is better able to make use of more minimal formant transition information should be able to perceive the consonant from gate 4.

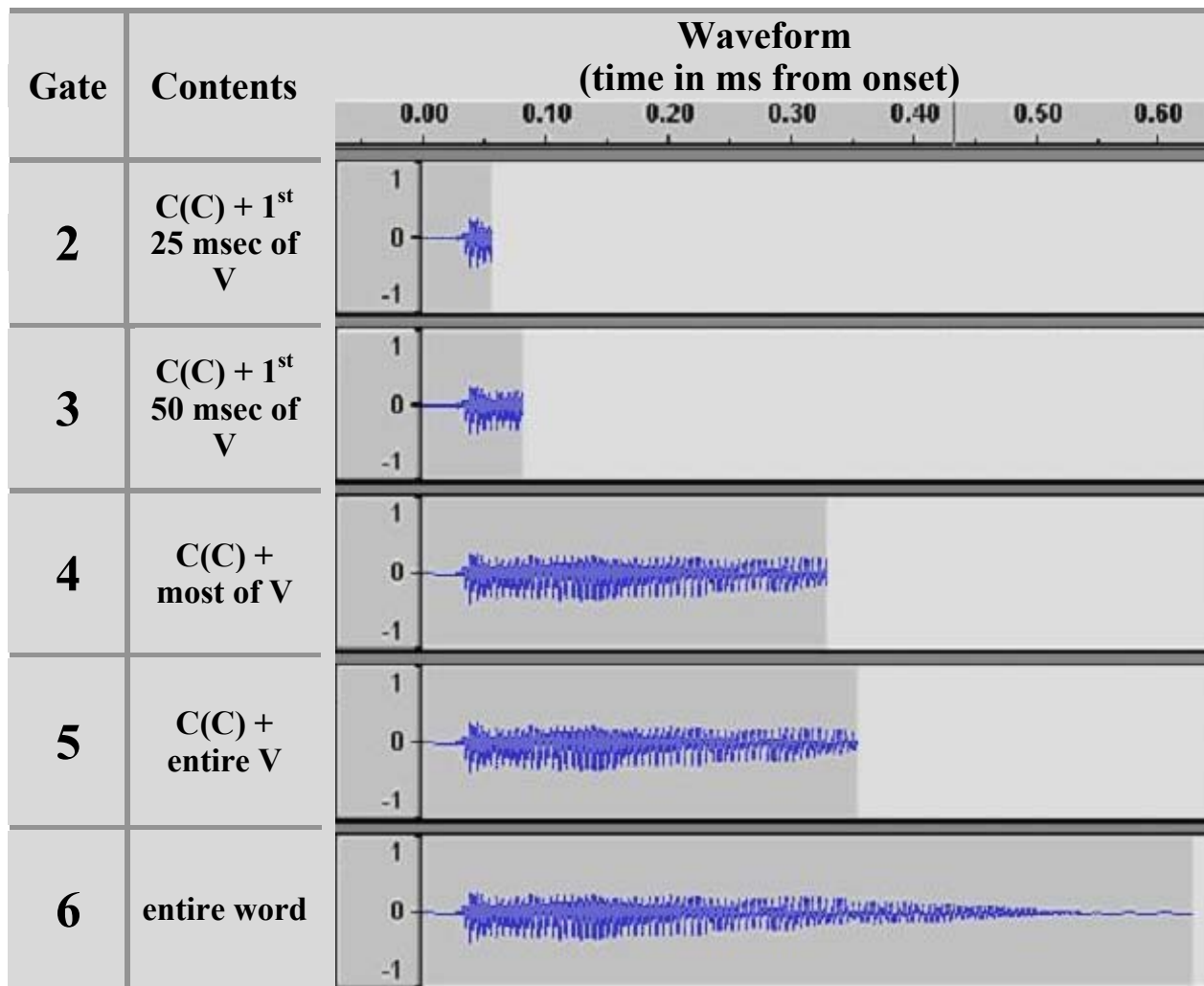
Since the word sets contained different vowels which inherently differ in duration, and since the final consonant affects vowel duration, words differed in their total vowel durations within and across sets but no one class (stop, lateral or nasal) was significantly different from another by ANOVA test. The durations of gates 4 and 5 were very similar across words with final nasals, laterals, and orals; they were particularly closely matched for final nasals vs. laterals. Gate 6, the original complete recording of each word, varied in duration as a function of the final consonant durations. In contrast, the first three gates differed in duration as a function of their initial consonant durations, since gate 1 was just the consonant(s), gate 2 was the consonant(s) plus 25 msec, and gate 3 was the consonant(s) plus 50 msec. As a result of initial consonant differences, the third gates for the nasal-final words happened to be much shorter in total duration (including the consonant). Total length of the words did not differ significantly as a function of item class.

For the practice trials, each of three practice items was played four times (gates 3 through 6) to familiarize subjects with the gating task. For the experimental trials, the presentation of the 22 test items was duration blocked as in (Walley et al. 1995 ) where each successive block contained only one duration of gate. Presentation began with gate two. Gate 1 was not used because pilot testing determined that children were not able to guess the correct word or category of the ending sound (nasal, lateral, stop) based on such limited acoustic information, and many children said they heard only a piece of static, and therefore, refused to guess the word. The order of items was randomized within each block. All 5 blocks corresponding to gates 2 through 6 were presented. Responses were recorded via audio cassette for later transcription by linguistics students with phonetic training.

Children were encouraged to make a guess on each item regardless of confidence level. If a child refused to give a response at a particular gate, the response was removed from subsequent analyses. No feedback was given at any time except during administration of the practice items. One concern with gating tasks in the study of children in general, and dyslexia in particular is that children with higher verbal ability may perform better because they are better at guessing words from partial information. Although this is indeed a limitation of gating tasks, it is less of a problem with the current design, for two reasons. First, all of the items were of relatively high frequency. Second, the categorical scoring method reduces the accuracy with which children have to guess. If children detect nasalization for example, they are given credit for "being in the ballpark" (i.e., guessing a word ending in a nasal).

The set of words was recorded by a female who was selected because her pronunciations were typical of Californian speakers. The recording was made in a sound booth to DAT, which was then transferred to a computer disk and edited using Praat (Boersma & Weenink, 2002). The stimuli were presented using software written in MATLAB 7 (MathWorks, Natick, MA); stimuli and experimental script are available for download from: <http://www.linguistics.ucla.edu/people/keating/dyslexia/dysweb2.htm>. Gates were produced by cutting at zero-crossings, but the amplitude of the end of the gate was not ramped. Because gates were cut at zero-crossings, the nominal 25-msec increments between gates could not be exact, but rather to the closest zero-crossing. Amplitudes were not normalized during the experiment, but the recorded levels of the items were similar.

**Figure 1. Waveform representation of gates 2-6 of the word *boat*. Gate lengths for each word vary due to different lengths of onsets, etc. Amplitude is shown in arbitrary units.**



### **Gating Task Scoring**

One dependent measure for the gating task was the first gate at which the child was able to name a word that was within the correct category of consonant ending (nasal, lateral or oral stop) as the target word (*category score*). For example, if the word was /kon/, responses of /kon/ and /kom/ would be accepted as correct because both words have a nasal consonant following the vowel . A response of /kot/ would be incorrect in this case because /kot/ ends in an oral stop (/t/) and /kon/ ends in a nasal (/n/). The gate at which a subject first correctly identified the category of the final consonant was used as his/her score even if the child later changed his/her answer. Analyses by Griffiths & Snowling (2001) supported this last scoring procedure, as they found a similar pattern of results whether counting the first correct response or counting only consistently correct responses. A second dependent measure was the first gate at which a subject was able to produce an exact identification of the target word (*exact match score*). This measure is the one used in previous gating studies with child listeners. Once again, changes in responses at later gates were ignored in the analyses.

All words were divided into 6 gates as described in the previous section, and since subjects were presented with gates 2-6, therefore the lowest and best possible score for each word was 2. Success at gates 2, 3, or 4 meant that a subject used anticipatory acoustic information; in general this was expected to be very unlikely for gate 2 and quite likely for gate 4. If a subject never correctly identified a word, a score of 7 was assigned for that word (largest gate plus 1). In such a case it was assumed the subject would be able to correctly identify the word if it was repeated or presented in context. This part of the scoring method was also used in the two previous gating studies with dyslexic children (Griffiths & Snowling, 2001; Metsala, 1997b). We also report alternative analyses in which subjects' responses were excluded from analyses if they made an error in identifying either the category or the exact word on the 6<sup>th</sup> gate (which represented an intact word.)

Reliability (Cronbach's Alpha) was calculated for the 22 test items in terms of gating scores for all subjects. Cronbach's Alpha for category scores was .689. Removing any one of the test items resulted in minor shift in Cronbach's Alpha (values ranged from .643 to .699 with removal of any one item). Cronbach's Alpha for exact match scores was .795. Again, removing any one of the items resulted in only minor shifts in Cronbach's alpha (values ranged from .773 to .796 with removal of any one item).

### **Procedure**

Testing was conducted in a quiet room at a University laboratory or at the children's schools. The entire battery of tests was completed in approximately 2 hours (including breaks) and took place within a period of time that did not exceed three weeks for any given child.

## **Results**

### **Descriptive Data**

Mean scores on the standardized tests for dyslexic and normally achieving readers are shown in Table 1. There was no group difference in general cognitive ability as measured by the WISC-III Performance estimate. The mean Verbal estimate of WISC-III

was significantly higher for normally achieving readers than dyslexic individuals as a group,  $F(1, 44) = 17.38$ ,  $p < .001$ ,  $\Sigma^2 = .28$ . The dyslexic group performed worse on all three language tasks, and on Elision (see Table 1 for F-values).

### **Gating Task Group Results**

The results, shown in Table 2, revealed that children were able to identify the correct category of consonant somewhere between the 3<sup>rd</sup> and 4<sup>th</sup> gate, on the average. This means that many children were able to detect the category of consonant prior to the end of the vowel. Fewer gates were required for identification of words ending in stop consonants, followed by words ending in laterals and then words ending in nasals. Exact matches required more gates on average (between 4 and 5) than category identification (between 3 and 4). Planned comparisons of the groups on each item type revealed a group difference favoring the normally achieving readers on the word-final-nasal category,  $F(1, 44) = 10.93$ ,  $p < .01$ , and a trend on the word-final-lateral category,  $F(1, 44) = 3.93$ ,  $p = .054$ . A two-way ANOVA with group and category as the factors revealed a main effect of group,  $F(1, 44) = 8.55$ ,  $p < .01$ . The overall group difference was about 0.3 of a gate. There was also a main effect of category of word ending,  $F(1, 44) = 7.160$ ,  $p < .002$ . Nasal-ending words were significantly more difficult to identify than words ending in a stop consonant (Tukey's procedure,  $p < .001$ ) but laterals were not more difficult than nasals or stops. The interaction of group with category was not significant.

The category score was hypothesized to be a more sensitive measure than the exact match measure used in previous studies. The data bore this out. The exact match measure did not produce significant group differences pooling across stimulus types. When analyzing individual categories, the word-final nasal category was the only one for which dyslexics showed a significant deficit on the exact match measure (about .4 of a gate),  $F(1, 44) = 4.659$ ,  $p < .05$ . It is possible that more extreme deficits in the integrity of phonological representation/processing on the gating task would only be found for a subset of dyslexics. Accordingly, we turned to individual differences analyses.

In order to confirm the validity of stimuli used in the gating task error rates were examined for identification of each item at the 6<sup>th</sup> gate. No single item was missed by more than 1/3 of the subjects. This indicated that there were no problems with the recording or playback of any particular item. Most subjects made 1 or fewer of these errors. There were four subjects, three dyslexic children and one normal reader, who made 5 or more errors (out of 22 items). We reanalyzed the data, excluding individual subjects' data when an error was made in identifying a word at the 6<sup>th</sup> gate. Excluding errors lowered all of the gating scores slightly (by about 1/10 of a gate for the composite categorization score and about 1/5 of a gate for the composite exact match score). The group comparisons described here remained unchanged. Analyses were repeated removing children who were bilingual with no significant difference in results.

### **Correlation and Regression Analyses**

Significant group differences on the gating task support the phonological representations hypothesis; however, the nature of the relationships among these variables was not clear. Conducting hierarchical regression analyses allows us to determine to what extent gating performance was related to reading ability because of its overlap with phonological awareness, or whether there were other factors (such as age, language ability and estimated IQ) that mediated the relationship between gating and word reading.

Bivariate correlations among the measures are shown in Table 3. Category identification scores were moderately correlated with standard score measures of Word Identification, Word Attack, Performance IQ estimate, Concepts and Directions, ROWPVT, Recalling Sentences, and Elision. The exact match score correlated only with category identification and was excluded from further analyses.

We conducted hierarchical regressions predicting standard scores for Word Identification and Word Attack from the three theoretically important variables in the study (gating category score, composite language ability, and phonological awareness), with age and IQ as control variables (see Table 4). We collapsed the verbal and performance IQ estimates into a single estimated IQ measure. We entered three variables on the first three steps of the analyses, age, estimated IQ, and average language score. On the 4<sup>th</sup> and 5<sup>th</sup> steps we entered either category identification score (pooling across item types) first or Elision first, to determine the unique contribution of these variables to reading.

**Table 1. Means and standard deviations on standardized tasks for the undifferentiated groups.**

Measures	Dyslexic (N=23)		Normal Achievers (N=23)		F-value; sign.
	Mean	SD	Mean	SD	
Age in months	142.75	16.13	134.04	17.19	3.13, p < .05
Word Ident. SS	78.43	8.09	107.04	7.10	162.5, p < .001
Word Attack SS	86.83	9.61	107.43	7.73	64.21, p < .001
WISC-III Verbal Est.	8.67	2.55	11.52	2.06	17.39, p < .001
WISC-III Perf. Est.	9.98	2.18	11.09	2.23	2.91
Recalling Sent. SS	6.74	3.39	11.13	2.44	25.47, p < .001
ROWPVT SS	97.57	9.64	105.70	12.81	5.92, p < .05
Con and Dir. SS	7.39	3.33	11.39	2.90	18.87, p < .001
Elision SS	7.04	3.01	10.91	2.56	22.10, p < .001

Word Ident. and Word Attack: Woodcock Reading Mastery Word Identification and Word Attack; WISC-III Verbal Est.: WISC-III mean scaled score on Vocabulary and Similarities; WISC-III Perf. Est.: WISC-III mean scaled score on Block Design and Picture Completion; ROWPVT: Receptive One-Word Picture Vocabulary Test; Concept and Dir.: CELF-R Concepts and Directions scaled score; Elision: CTOPP Elision;

**Table 2. Means on the gating measures by group.**

Measures	Dyslexic (N=23)		Normal Achievers (N=23)		F-value; sign.
	Mean	SD	Mean	SD	
Mean category score	3.55	0.46	3.23	0.25	8.55, p<.01
Category – Stops	2.87	0.84	2.79	0.47	.17
Category – Laterals	3.57	0.53	3.22	0.65	3.93, p = .054
Category – Nasals	4.20	0.55	3.68	0.53	10.93, p < .005
Mean exact match	4.70	0.71	4.45	0.47	1.89
Exact – Stops	4.35	0.81	4.27	0.60	.17
Exact – Laterals	4.65	.76	4.47	0.77	.68
Exact – Nasal	5.08	0.81	4.62	0.63	4.66, p < .05

Category score = first gate at which correct identification of consonant category was achieved (maximum score: 7); exact match = first gate at which an exact match to the target word was achieved (maximum score: 7)

Elision accounted for 10.5% and 12.4% unique variance (i.e., when it was entered last in the equation) but category identification accounted for less than 1% unique variance in Word Identification or Word Attack scores when entered on the last step. In an additional analysis (not shown in Table 4), we entered just age and the performance estimate of IQ along with the gating measure. The contribution of the gating variable remained significant. This demonstrates that it is some combination of the verbal ability measures (estimated verbal IQ and average language score) and the phonological awareness measure (Elision) that reduced the contribution of the gating measure to non-significance. In other words, the common variance between gating and the reading measures is shared with the verbal ability, language and phonological measures, but gating performance did not account for unique variance in reading beyond these measures.

The effect of one variable, Elision, in reducing the contribution of gating performance to variability in reading scores was particularly strong. Accordingly, we ran a hierarchical regression (shown in the bottom section of Table 4) controlling for age, average IQ and average language ability, exploring the contribution of gating to Elision performance. Category score accounted for 9.1% unique variance in Elision, when entered on the fourth step, after Age, estimated IQ and average language ability. Composite language ability accounted for 5.7% of the variance in Elision. Age and estimated IQ did not account for unique independent variance in Elision.

**Table 3. Correlations.**

	AGE	WID	WAT	IQ-V	IQ-P	C&D	ROWPVT	RECAL	ELISIO	Category
WID	-.30*									
WAT	-.29*	.90***								
IQ-V	-.12	.56***	.52***							
IQ-P	.01	.42**	.38**	.61***						
C&D	-.12	.61***	.54***	.64***	.54***					
ROWPVT	-.05	.45**	.42 <sup>2</sup>	.73***	.55***	.66***				
RS	-.20	.62***	.63***	.75***	.49***	.73***				
ELISIO	-.24	.69***	.70***	.46***	.40**	.59***	.36			
Category	.02	-.36*	-.39**	-.26	-.45**	-.43**	-.33*	-.39**	-.53***	
Exact	-.17	-.16	-.28	-.20	-.17	-.20	-.08	-.24	-.27	.66***

\*  $p < .05$ ; \*\*  $p < .01$ ; \*\*\*  $p < .001$

AGE: Age in months, All test data were standard scores. WID: Woodcock Word Identification, WAT: Word Attack, IQ-V: WISC-III Verbal estimate, IQ-P: WISC -III Performance estimate, C&D: Concepts & Directions, RS: Recalling Sentences, ROWPVT: Receptive one word picture vocabulary test, ELISIO: Elision, Category: first gate correct category identification was achieved; Exact: first gate an exact match to the target word was achieved



**Table 4. Hierarchical Regression Analyses for Three Criterion Variables**

**Word Identification:**

Variable	R <sup>2</sup>	Change in R <sup>2</sup>	Final Beta Weight
1. Age (in months)	.090	.05*	-.141
2. IQ Estimate	.381	.291***	.143
3. Language Ave.	.487	.106**	.289
4. Category Score.	.493	.006	.061
5. Phoneme Elision	.598	.105**	.446**
-----	-----	-----	-----
4. Phoneme Elision	.596	.109**	.446**
5. Category score	.598	.002	.061

\* p < .05                      \*\* p < .01                      \*\*\* p < .001

**Word Attack:**

Variable	R <sup>2</sup>	Change in R <sup>2</sup>	Final Beta Weights
1. Age (in months)	.085	.085*	-.124
2. IQ Estimate	.320	.235***	.071
3. Language Ave.	.433	.113**	.272
4. Category Score	.450	.017	.022
5. Phoneme Elision	.574	.124**	.486***
-----	-----	-----	-----
4. Phoneme Elision	.574	.141***	.486***
5. Category Score	.574	.000	.022

\* p < .05                      \*\* p < .01                      \*\*\* p < .001

**Phoneme Elision:**

Variable	R <sup>2</sup>	Change in R <sup>2</sup>	Final Beta Weights
1. Age (in months)	.056	.056	.161
2. IQ Estimate	.273	.217***	.068
3. Language Ave.	.381	.108**	.369*
4. Category Score	.472	.091*	-.340*

\* p < .05                      \*\* p < .01                      \*\*\* p < .001

The path analysis diagram shown in Figure 2 at the end of the paper summarizes the series of regression analyses. It illustrates a proposed set of relationships among the variables. The relationships cannot be considered to be true causal relationships or even to be directional, as the data are not longitudinal. The beta weights shown in the diagram represent each variable's unique contribution to the dependent variable to which the arrow points. All relationships among variables that were not significant (e.g., between age and phonological awareness, or between IQ and reading), are not shown in the diagram. Beta weights for each variable's unique contribution to phonological awareness (Elision), and to reading ability (Word Identification and Word Attack) were obtained by rotating each variable into the final position in the sets of hierarchical regressions discussed above. These values are shown along with the percent unique variance accounted for in parentheses. Average language ability and gating category scores made indirect contributions to Word Identification and Word Attack, mediated by their

relationship with Elision. The overall model accounted for 59.8% of the variance in Word Identification, and 57.4% of the variation in Word Attack.

One caution in interpreting the path analyses is that the data were concurrent, and hence we cannot determine the direction of the relationship over time. It is possible that prior reading development has an impact on phoneme awareness or gating performance, but this cannot be determined without longitudinal analyses.

## **Discussion**

The purpose of the study was to compare the amount of auditory input necessary to identify spoken words in dyslexic children and normally achieving readers using a gating task. We found that dyslexic children required more gates to generate a word response in the correct category for words ending in nasals, indicating they were less sensitive to anticipatory co-articulation. There was a statistically non-significant trend toward poorer performance by dyslexic children on the laterals. For the exact match measure, commonly used in previous studies, the only significant group difference was on nasals.

In previous work on gating with dyslexic samples, overall group differences were not always observed. Metsala (1997b) found a group difference only for sparse neighborhoods, and Griffiths & Snowling (2001) found no group differences. Boada & Pennington (2006)'s groups did differ, both on whole word matching and on initial consonant identification. Our study found an overall group difference for final consonant category identification, but differences were less pronounced for whole word matching.

One direct implication of our data is that measures of anticipatory coarticulation, like initial consonant identification, may be more sensitive than the whole word matching measures used in previous studies. More importantly, because of the nature of how listeners represent and process co-articulation, poorer performance by dyslexics on this task implies that their phonological representations for common words are less well integrated than those of normal readers. This finding extends previous results obtained with gating tasks in dyslexic samples (Boada & Pennington, 2006; Griffiths & Snowling, 2001; Metsala, 1997b), and supports the growing literature suggesting that dyslexics have less complete phonological representations of printed words (Elbro, et al., 1998; Swan & Goswami, 1997; Wesseling & Reitsma, 2001).

A series of regression analyses was employed as a group (another term for this process is path analysis) to provide a more detailed picture of the relationships among the variables than could be obtained with subgroup comparisons. The measure of sensitivity to co-articulation (the category score) contributed unique variance to the phonological awareness task, which, in turn accounted for unique variability in word and nonsense word reading (see Figure 2). Gating scores did not make direct contributions to the reading tasks, once age, estimated IQ, language ability and particularly, phonological awareness, were taken into account. The inference is that gating scores made indirect contributions to the reading variables, mediated by phonological awareness. The path analyses revealed a similar pattern of results for a composite language measure consisting of receptive and expressive subtests. Gating and language ability were correlated, but made partially independent contributions to phonological awareness.

There are at least two theoretical interpretations of the pattern of group differences and regression findings. First, as we have argued, the gating task may index

fundamental qualities of the phonological representation and processing of spoken words. Even subtle deficiencies at this level may interfere with the development of phonological awareness, which in turn interferes with the learning of spelling-sound correspondences, and hence reading progress in general. This would mean that dyslexic children have separable deficits in phonological representations and in the development of phonological awareness. It is possible that dyslexic children approach the reading task with a deficit in phonological representation or access to these representations (Ziegler & Goswami, 2004) and acquire the phonological awareness deficit in the process of learning to read, partly as a consequence of attempting to apply inadequate phonological representations to the demanding task of learning spelling-to-sound correspondences. Evidence of early auditory/phonetic processing and speech categorization difficulties in infants at risk for dyslexia has been reported (Leppanen, Richardson, Pihko, Eklund, Guttorm,, Aro, & Lyytinen, 2002; Molfese, 2000; Richardson, Leppanen, Leiwo, & Lyytinen, 2003).

A second interpretation of our group differences and regression findings is that dyslexic children have intact, perhaps even high-quality, holistic representations of spoken words, but fail to organize their phonological representations at the segmental level, particularly phonemic segments, which make lexical access easier (Metsala, 1997b, Garlock et al. , 2001). Earlier, we described our reservations about this line of argument, attractive though it is, due to the range of conflicting findings in the literature concerning neighborhood density effects, and the difficulty in interpreting gating as reflecting the segmental nature of lexical representations.

It is important to point out that, while there is a general consensus among developmentalists that segmentation of the speech stream into phoneme-sized units is a developmental process, it is somewhat controversial whether normal adult phonological representations are necessarily segmental (Walley, 1993). One view is that such representations arise only under the influence of alphabetic orthography (Morais et al., 1979). On this view, learners of languages with non-alphabetic writing systems, or no writing system, will generally not form segmental representations. Another view is that segmental representations will arise normally (or “emerge”) from the pressure of a crowded lexicon (Walley, 1993). However, some phoneticians, including Browman and Goldstein (1989), have rejected the traditional segment in favor of other kinds of discrete units of representation. Goldsmith (1976)’s Autosegmental Phonology hypothesis states that mature phonological representations are only partly segmental. Derwing et al. (1986) provide an overview of arguments for and against the phoneme-sized segment in adult representations. It would be prudent to investigate alternatives to segmental representations in the quest to understand phonological deficits in dyslexia.

One particular finding of the study deserves additional scrutiny. We found that words ending in nasalization were the most difficult items for all subjects, regardless of group membership, and words ending in oral stops were the easiest. That orals should be easiest was unexpected relative to Lahiri & Marslen-Wilson’s (1991) study of adults, but it suggests that the children in our study were able to use the non-nasal, non-lateralized quality of vowels as a positive cue about the upcoming consonant. In contrast, the literature provides no a priori expectations about whether nasals or laterals should be hardest, and it may well be a function of the particular degrees of nasal vs lateral coarticulation used by a given speaker. In addition, dyslexics as a group showed the most impaired performance on nasals compared to normally achieving readers. This could indicate that phonological representations for words ending in nasalization (or more specifically for nasal phonemes) are particularly impaired among dyslexic children for

some reason. Alternatively, nasals were more difficult to identify for both subject groups, suggesting that we were simply seeing greater group differences on the more demanding task (a measurement characteristic). To distinguish between these two possibilities dyslexic and non-dyslexic readers would need to be tested on a wider range of stimuli, incorporating anticipatory features of pronunciation that are equal to or greater in difficulty than nasalization and lateralization. If dyslexics have an overall impairment in phonological representations, it should be present on an appropriate and demanding spoken word perception task.

The study is limited in several respects. First, we did not include reading-level matched younger normal readers, as is often the case in studies of phonological processing in dyslexics. The typical argument for this group is that the task in question (in this case, gating performance) might vary as a function of reading experience, as indexed by reading level. A strong test of the hypothesis that the gating deficit is a core deficit in dyslexia would be the observation of differences favoring reading level-matched younger normal readers. However, given the lack of group differences even between chronological-age matched normal readers and dyslexics in some conditions or age levels in past studies (Griffiths & Snowling, 2002; Metsala, 1997b), it was important first to establish that such group differences existed. Our sample had 5 younger normal readers who could be equated to a subset of the dyslexic sample (15 dyslexic children) based on the mean and range of raw scores on the Word Identification test, and thus could serve as a reading level comparison group. When these two groups were compared on the gating task, group differences failed to emerge. However, there are obvious power limitations for such an analysis. Future studies utilizing sensitive measures of spoken word perception will need to include a reading level comparison group.

A second limitation is that the dyslexic sample did not have the same overall IQ as the normal reader sample, as is often the case in traditional studies of dyslexia. This was primarily due to the fact that we allowed the sample to include dyslexic children with low oral language scores (this tends to deflate the verbal portion of the IQ-estimate). Language ability accounted for some variance in Word Identification and Elision scores for the sample as a whole, and it did reduce the contribution of gating to word reading to non-significance, even when gating scores were entered at a step prior to Elision in the regression equation (see the top two sections of Table 4). However, language ability did not detract from the relationship of gating to Elision. In fact, language ability and gating made independent contributions to Elision scores (see Figure 2). Nevertheless, caution must be observed in generalizing our findings to other dyslexic samples. It is possible that differences would be difficult to observe if only dyslexic children with average oral language ability were tested, or conversely, that differences in gating would be more pronounced in a sample with more severe language impairments.

To conclude, the use of a gating task enabled us to explore the integrity of phonological representation and processing in dyslexic children by means of a novel method for the dyslexia literature (sensitivity to anticipatory coarticulation). Our more sensitive gating paradigm detected group differences whereas past studies using the gating paradigm did not consistently find group differences. In addition, we found that gating performance was not directly related to word reading and decoding skills, but appeared to be related indirectly through its relationship with phonological awareness. The results join the findings of other investigations utilizing different techniques (e.g., Elbro et al., 1998; Swan & Goswami, 1997) in pointing to a basic deficit in phonological representation and processing in dyslexic children.

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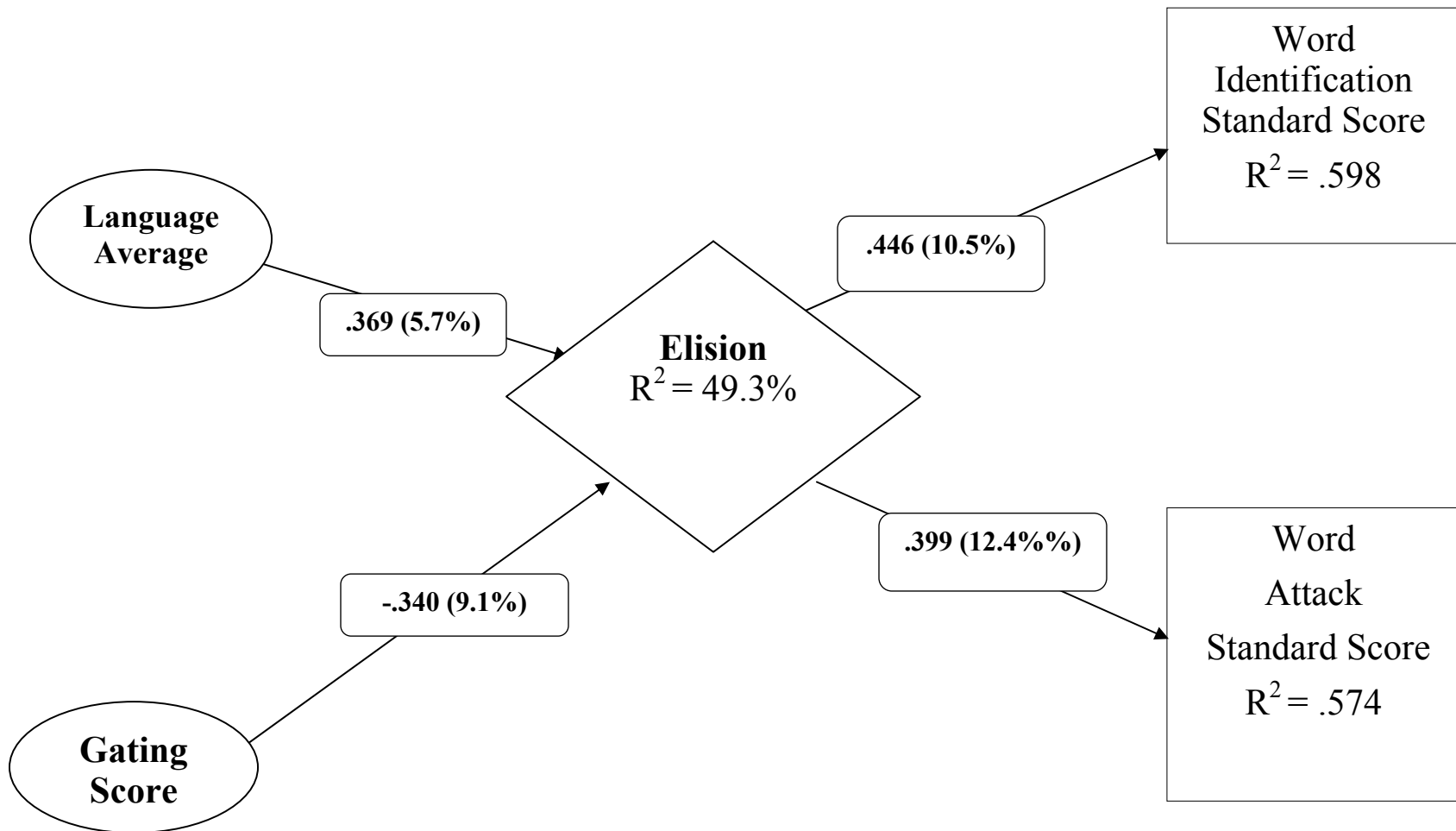


Figure 2.  
 Path analysis with standardized beta weights and percent unique variance accounted for in parentheses. Gating score is the mean gate at which a word in the correct category of consonant (stop, lateral, nasal) was first identified.