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Cognition 100 (2006) B32–B42
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Brief article

# Specific phonological impairments in dyslexia revealed by eyetracking

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Received 9 June 2005; revised 5 September 2005; accepted 7 September 2005

**Abstract**

Phonological deficits in dyslexia are typically assessed using metalinguistic tasks vulnerable to extraneous factors such as attention and memory. The present work takes the novel approach of measuring phonology using eyetracking. Eye movements of dyslexic children were monitored during an auditory word recognition task in which target items in a display (e.g., *candle*) were accompanied by distractors sharing a cohort (*candy*) or rhyme (*sandal*). Like controls, dyslexics showed slower recognition times when a cohort distractor was present than in a baseline condition with only phonologically unrelated distractors. However, unlike controls, dyslexic children did not show slowed recognition of targets with a rhyme distractor, suggesting they had not encoded rhyme relationships. This was further explored in an overt phonological awareness test of cohort and rhyme. Surprisingly, dyslexics showed normal rhyme performance but poorer judgment of initial sounds on these overt tests. The results implicate impaired knowledge of rhyme information in dyslexia; however they also indicate that testing methodology plays a critical role in how such problems are identified.


*Keywords:* Dyslexia; Phonological awareness; Eyetracking; Auditory word recognition; Phonological development

Children with developmental dyslexia have significant difficulties acquiring reading skills in spite of apparently normal cognitive, emotional, and neurological profiles (Snowling, 1987). There is a growing consensus that phonological deficits play a key role in dyslexics' reading problems (Wagner & Torgesen, 1987). Studies of this sort typically

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doi:10.1016/j.cognition.2005.09.001

focus on phonological awareness, the ability to identify and manipulate individual phonemes in words. Learning to read relies heavily on translating printed words into sound. Thus, poorer phonological awareness skills appear to contribute to poorer reading development (e.g. Bradley & Bryant, 1983).

In spite of these findings, the precise nature of the phonological impairment in dyslexia remains elusive (Bryant, 1998; Stanovich, 2000). Critically, phonological knowledge spans phonetic and acoustic features, segmental knowledge such as phonemes, and suprasegmental knowledge such as rhymes and prosody (Morais, 2003). Thus, there is considerable debate about the level at which phonological processing is impaired in dyslexia. While some have argued that this deficit is at the level of how they represent individual segments, others suggest the deficit lies in how they represent higher-level structure such as rhymes (Goswami, 1999; Muter, Hulme, Snowling, & Taylor, 1998). On the former account, children's ability to represent segmental information is essential to reading development (Fowler, 1991; Nation & Hulme, 1997). For instance, Muter et al. (1998) have found that whereas rhyming and segmentation skill both appear to be independent factors in dyslexia, only segmental knowledge is predictive of later reading skill. The competing account holds that dyslexics' reading deficits are related to their ability to use suprasegmental information such as rhymes in generalizing spelling-sound correspondences across words (Goswami, 1999). These studies emphasize that children with reading difficulties make less use of rhyme analogy cues in reading, compared to normal readers (e.g. being able to read *peak* when cued with *beak*, Goswami, 1999).

This disagreement might stem from the types of tasks that are used to measure phonology in children. Overt metalinguistic tasks such as phoneme deletion, phoneme segmentation and rhyme judgment involve many extraneous factors such as short-term memory and attention that can weigh heavily on performance (Gathercole & Baddeley, 1993; McDougall, Hulme, Ellis, & Monk, 1994; Stanovich, 2000). In addition, the child must have a proper understanding of the task in order to perform it correctly; for instance, a rhyme judgment task requires the explicit understanding of what constitutes a 'rhyme', which might be appreciably different from having adequate implicit phonological representations of rhymes. This is further complicated by the finding that younger dyslexic children have significant problems with rhyme awareness and rhyme generation, these difficulties tend to resolve by ages 8 or 9 (Swan & Goswami, 1997), possibly due to compensatory mechanisms that mask an underlying impairment. The potential discrepancy between implicit and overt phonological awareness raises the need for a different approach to assessing phonology that minimizes extraneous factors and focuses on processing.

One approach is to use a purely perceptual task. Many studies have used perception tasks to identify abnormal categorical perception in dyslexia (Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Joanisse, Manis, Keating, & Seidenberg, 2000; Werker & Tees, 1987). Such measures are appealing because they minimize demands on working memory, attention and overt metalinguistic awareness. However, perception studies have so far been limited to measuring auditory and phonetic processing in dyslexia. In this study, we present a novel approach to testing children's segmental and suprasegmental phonological knowledge using an auditory word recognition task and eyetracking. Eyetracking is well established as a measure of linguistic processing of an uninterrupted speech stream in adults (Allopenna, Magnuson, & Tanenhaus, 1998; Altmann & Kamide, 1999) and children (Arnold, Novick, Brown-Schmidt, & Trueswell, 2001). The present study extends this technique to studying speech processing in dyslexia.

In our study, children heard instructions to look at named items that were presented in a visual display (Fig. 1). In addition to the target item (e.g. *candle*), some displays contained a cohort competitor (e.g. *candy*), and/or a rhyme competitor (e.g. *sandal*), embedded among phonologically unrelated distractors (e.g. *flower*). The study builds on the hypothesis that eye movements are linked to lexical processing such that fixations to a target over time reflect a word's lexical activation (Tanenhaus, Magnuson, Dahan, & Chambers, 2000). For instance, individuals are slower to fixate to a target picture when a rhyme or cohort distractor is present, compared to when only phonologically unrelated distractors are present (Allopenna et al., 1998; Dahan, Magnuson, & Tanenhaus, 2001). This phenomenon was used to examine the organization rhymes and onsets in children with developmental dyslexia. It was hypothesized that the eyetracking task would reveal differences in the time course of auditory word recognition in these children, compared to children who are normal readers. We were also interested in the degree to which task

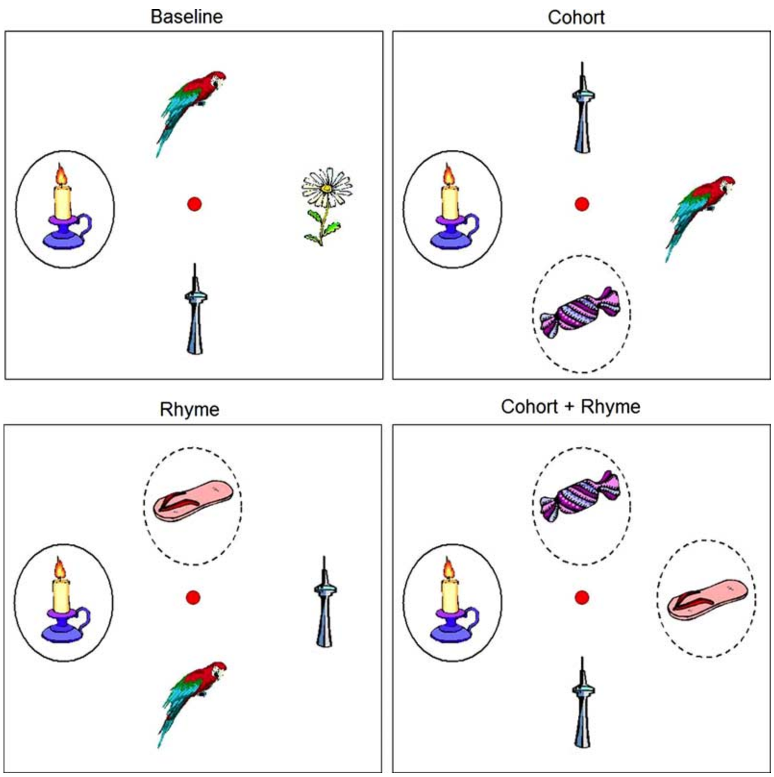


Fig. 1. Sample stimuli from the eyetracking experiment. Children were presented with arrays of four objects and were instructed to look at a target item (e.g. *candle*). On some trials, the distractor images included a cohort distractor, a rhyme distractor, or both a cohort and rhyme distractor. (A) Baseline: **CANDLE**, PARROT, FLOWER, TOWER; (B) Cohort: **CANDLE**, *CANDY*, PARROT, TOWER; (C) Rhyme: **CANDLE**, *SANDAL*, PARROT, TOWER; (D) Cohort + Rhyme: **CANDLE**, *CANDY*, *SANDAL*, TOWER.

characteristics can influence measures of phonological skill, which we assessed by also testing children using traditional overt phonological awareness tasks.

## 1. Method

### 1.1. Participants

School-age children were recruited from schools in the London, Ontario area. Recruitment and testing procedures were approved by the University of Western Ontario office of Research Ethics. Eight dyslexic children in the third and fourth grades were tested (age $M = 8;9$, range 8;1–9;5); one additional child was unable to complete the eyetracking task and was excluded from analyses. Children in the dyslexic group scored below the 25th percentile ($M = 15.63$, $SD = 7.58$) on the Word Identification subtask of the Woodcock Reading Mastery Test-Revised (WRMT-R; Woodcock, 1989), and had standard scores within normal ranges on a verbal and nonverbal subtask of the Wechsler Intelligence Scale for Children (WISC-III, vocabulary $M = 11.00$, $SD = 2.62$; block design, $M = 11.63$, $SD = 1.92$; Wechsler, 1992). None of these children had pervasive neurological, emotional, social, cognitive or sensory impairments. This cognitive/reading skill discrepancy diagnosis is typical of how dyslexia is identified in school-aged children of this age (Snowling, 1987).

Dyslexic children were compared to a control group consisting of nine normally-developing readers of the same age as the dyslexics ($M = 9;1$, range 8;7–10;3). These children scored at or above the 40th percentile on the WRMT-R Word Reading task ($M = 69.11$, $SD = 7.80$) and scored in the normal range on the two WISC-III subtasks (vocabulary: $M = 13.11$, $SD = 3.33$; block design: $M = 11.44$, $SD = 1.94$). To confirm the identification of the dyslexic and control groups, all children also completed a nonword reading test (WRMT-R Word Attack), and a phoneme deletion test (see Section 2.1).

### 1.2. Eyetracking procedures

Children performed an auditory–visual word identification task in which we manipulated the phonological relationship between a target word (e.g. *candle*) and a set of visual distractors (e.g. *candy, sandal, tower*; Fig. 1). Visual stimuli were presented on an LCD monitor located 50–60 cm away. Children saw a series of displays, each comprised of four pictures oriented around a central fixation point (see Fig. 1). Auditory stimuli consisted of one- and two-syllable words spoken by an adult female English speaker that were digitally recorded (16-bits, 48,828 Hz) and presented over loudspeakers. During each block of trials, children were given 3000 ms to inspect the display before hearing a fixation prompt ("*Look at the red circle*") followed by a target cue (e.g. "*Now look at the candle*"). Eye movements were recorded at 60 Hz using an remote infrared eyetracker (SMI, Inc.; Cambridge, USA).

In each trial, children saw the target item (e.g. *candle*) and three distractor pictures. As illustrated in Fig. 1, the experimental manipulation consisted of the types of distractors that were included: only phonologically unrelated items (the baseline condition); only a rhyme distractor (e.g. *sandal*); only a cohort distractor (which had the same initial CV for monosyllables, or initial syllable for two syllable words, e.g. *candy*); or both rhyme and cohort distractors. Stimuli were adapted from Allopenna et al. (1998). Items in each display set were balanced for frequency (Zeno, 1995, see Appendix A). As much as possible, the same targets in the baseline condition were also used in rhyme, cohort and rhyme + cohort conditions. Prior to testing, children were presented with each picture in the experiment and asked to name them, to assure that they could accurately identify all of them. On occasions when a child provided a different name for a target (e.g. saying *buggy* for *carriage*), they were told, “that’s right, but in this activity we are going to call it a carriage”. When prompted, all children acknowledged that they were familiar with the word that was being used to correspond to each picture.

Each child performed 216 trials, with an equal the probability of presentation for each condition. Trials containing eye blinks and head movements were excluded from analyses. The dependent measure consisted of the cumulative proportion of eye movements to the correct visual stimulus following auditory word onset. These were calculated as the proportion of valid fixations to the target at 50 ms time steps for each participant on each condition (baseline, cohort distractor, rhyme distractor and rhyme + cohort distractors). We next computed the sum of these proportions from 400 to 1500 ms post-stimulus-onset (Figs. 2 and 3). This provided us with an estimate of the area below the fixation curve for

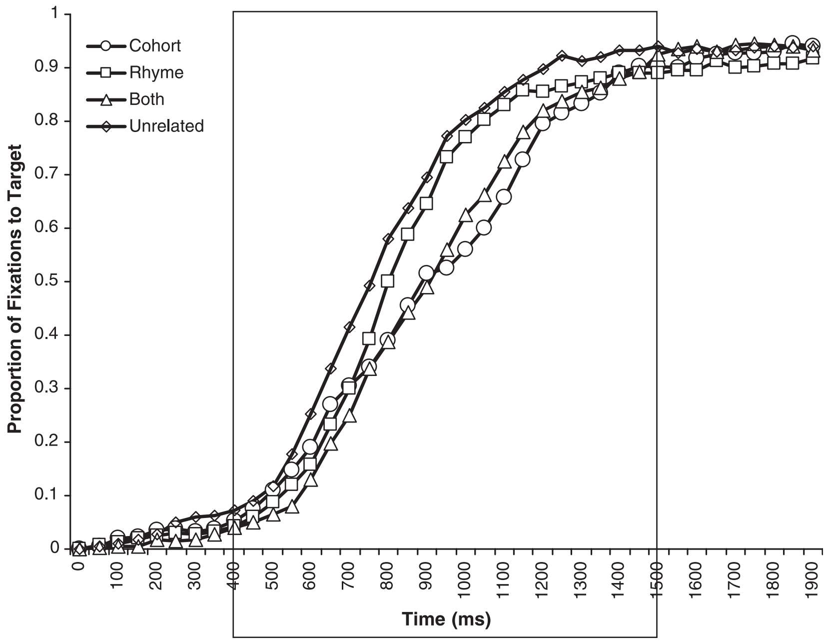


Fig. 2. Eyetracking data from normally developing children in an auditory word recognition task. Proportion of eye movements to the target item are plotted over time, relative to the onset of the target word. Speed of recognition is reflected in the time to asymptote. The data show significant cohort and rhyme interference effects reflected in slower fixation rates for the cohort, rhyme and cohort + rhyme conditions, compared to the baseline condition.

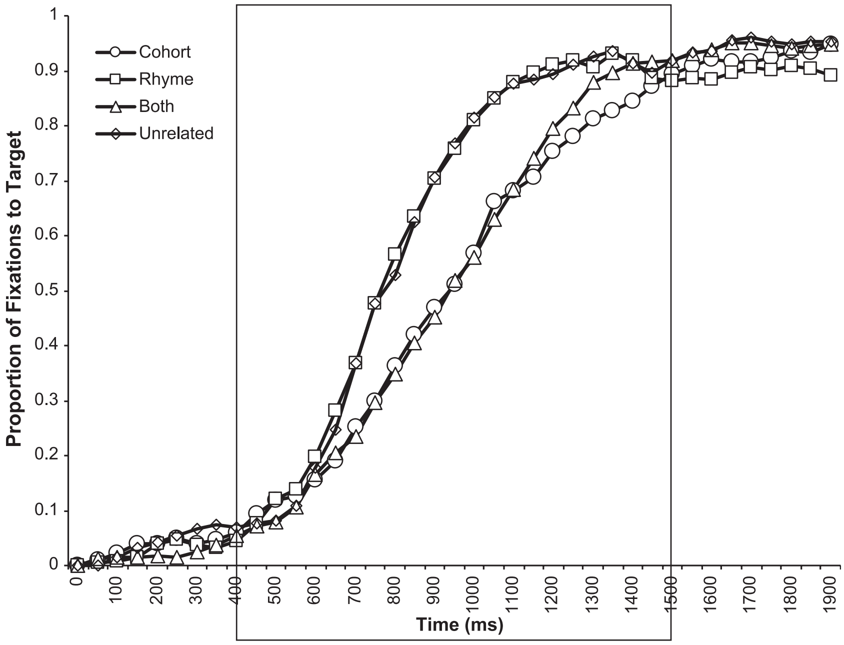


Fig. 3. Performance of dyslexic children on eyetracking task. These children showed expected delay in fixation times for the cohort and cohort + rhyme conditions compared to baseline, but no effect in the rhyme condition.

each participant on each condition (Altmann & Kamide, 1999). These fixation rates were then compared using within-group statistical comparisons of the four trial types.

### *1.3. Phonological awareness tests*

In a different session, children also performed two phonological awareness tests: rhyme judgment and initial sounds judgment. The two tasks used the same visual and word stimuli as the eyetracking task in order to keep them as similar as possible. In the rhyme judgment task, children were shown eight pairs of pictures. As each pair was presented, the experimenter named each item aloud and asked whether the two words rhymed. Half the items rhymed (*candle-sandal*), a quarter shared the same initial CV or syllable (*candle-candy*) and the balance were phonologically unrelated (*candle-flower*). In the initial sounds judgment test, children were again presented with eight word pairs and asked if the words began with the same sounds. In this task, half the items began with the same CV or syllable, a quarter were rhymes, and a quarter were phonologically unrelated. No word pair was repeated in either list. Task order was randomized across subjects, and half the children completed the eyetracking task first, and the other half performed the phonological awareness tasks first. One of the children in the control group who was included in the eyetracking analyses was not available for the phonological awareness tests.

## 2. Results

### 2.1. Reading and IQ measures

As expected, dyslexic children scored lower than controls on word reading ability (WRMT-R Word Identification), $t(15)=14.30$, $P<.001$, nonword reading (percentile rank: controls, $M=55.11$, $SD=17.82$; dyslexics, $M=10.00$, $SD=7.43$; $t(15)=6.95$, $P<.001$) and phoneme deletion (grade level: controls, $M=3.93$, $SD=.95$; dyslexics, $M=2.44$, $SD=.44$; $t(15)=4.23$, $P<.001$). However, the dyslexic and control groups did not differ on the WISC-III measures (Block Design: $t(15)=-.19$, ns; Vocabulary $t(15)=1.44$, ns).

### 2.2. Eyetracking

Mean fixation rates for the control group are plotted in Fig. 2. Using a single factor within-subjects ANOVA we found a main effect of condition, $F(3, 24)=19.46$, $P<.001$. Post hoc tests with a Bonferroni adjustment revealed significant differences between the baseline and cohort conditions ($t(8)=6.81$, $P<.001$), baseline and rhyme + cohort conditions ($t(8)=6.84$, $P<.001$), and baseline and rhyme conditions ($t(8)=3.20$, $P<.001$). These results are similar to what has been found in adults (Allopenna et al., 1998) and indicate that the control children were sensitive to both rhyme and cohort interference effects, marked by slower fixation rates when these types of distractors are present.

Fixation rates for the dyslexic group are plotted in Fig. 3. A single factor within-subjects ANOVA also revealed a main effect of condition type for this group, $F(3, 21)=16.20$. As was found with the control children, post hoc tests revealed significant differences between the baseline and cohort conditions ($t(7)=5.05$, $P<.001$) and baseline vs. rhyme + cohort conditions ($t(7)=4.59$, $P<.001$); however, there was no significant difference between the baseline and rhyme conditions ($t(7)=.20$, ns). These results indicated that although dyslexic children showed clear cohort competitor effects, they did not demonstrate delayed eye movements due to the presence of rhyme competitors.

We also tested whether dyslexic children had generally slower lexical access by comparing their fixation rates on the baseline condition to those of the control group. A planned comparison *t*-test revealed that the two groups did not differ significantly on this condition, $t(15)=.44$, ns. This suggests that both groups had similar speed and accuracy of auditory word recognition.

### 2.3. Phonological awareness

The two phonological awareness tasks assessed children's explicit use of concepts such as onsets and rhymes. Mean correct items on the rhyme and word onset judgment tasks are plotted in Fig. 4. *T*-tests were used to compare the two groups on both tasks. The dyslexic children were significantly less accurate than controls on the initial sounds judgment task, $t(15)=2.34$, $P<.05$; however, they did not differ on the rhyme judgment task, $t(15)=1.23$, ns.

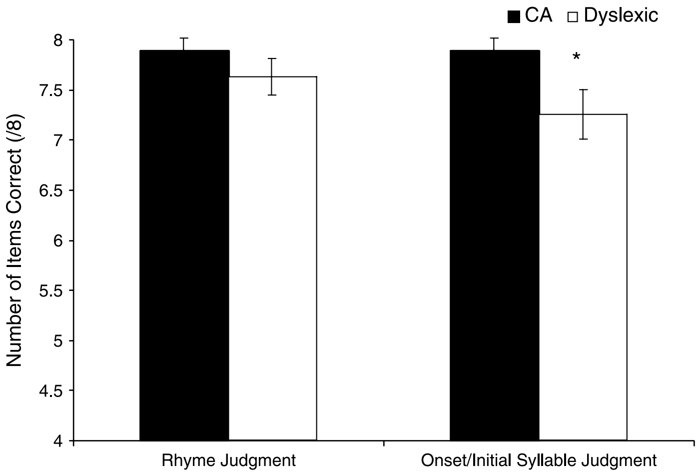


Fig. 4. Control children compared to dyslexic children on the two phonological awareness tasks. Asterisks indicate significant differences from the control group, $P < .05$.

## 3. Discussion

We compared phonological processing abilities of children with dyslexia to those of normally developing same-aged controls. Previous studies have tended to rely on phonological awareness tests to assess phonology in dyslexia, which can be undermined by attendant factors related to children's difficulty understanding instructions as well as attention and memory limitations. Results of the eyetracking task indicated that under normal circumstances, auditory word identification in dyslexic children was not appreciably different from that of same-age controls. Both groups showed the same speed of eye movements when only unrelated competitors were present (the baseline condition), suggesting that the ability to identify auditory words in isolation is similar across groups. Moreover, both the dyslexic and control children showed slower fixation rates when a cohort competitor was present, indicating that both groups were sensitive to this type of phonological overlap in words, similar to what has previously been found in adults both with eyetracking and a variety of other tasks (Allopenna et al., 1998; Marslen-Wilson & Tyler, 1980). However, while the control group also showed slower recognition when a rhyme distractor was present, the dyslexic group did not; instead, their performance on rhymes was similar to their baseline performance. This finding suggests that dyslexic children can perceive segmental information about words in sufficient detail to rapidly identify spoken words; however, they are much less sensitive to higher-order rhyming relationships among words. This supports the findings of previous studies indicating that while normally developing children naturally categorize auditory stimuli based on both segmental and suprasegmental properties, reading disabled children tend to be more sensitive to segmental information (Kirtley, Bryant, MacLean, & Bradley, 1989).

It is worth mentioning that dyslexics' faster-than-normal performance in the rhyme condition of the eyetracking task does not indicate that they were simply failing to attend to the ends of words. If this were the case, their performance would have been much worse on the cohort competitor task, where word-final information was critical to recognizing the target (e.g. discriminating *candle* and *candy*). Instead, this finding suggests a fundamental divergence in how dyslexic and normally developing children process the phonological structure of rhyme relationships in words.

We were also interested in the comparability of eyetracking data with more traditional phonological awareness tests. It was hypothesized that even if dyslexic children's eye movements revealed impaired perceptual processing, their performance might not be congruent with how they make explicit decisions about segmental and rhyme information. Consistent with this, we observed conflicting results between the eyetracking task, which measured phonology in an automatic and online way, and the overt judgment tasks, which measured more explicit phonological knowledge. While dyslexic children showed evidence of abnormal rhyme processing on the eyetracking task, their performance on the overt rhyme judgment task was similar to that of controls. Similarly, while the initial-sounds test suggested dyslexic children have difficulty identifying words that are cohorts, a similar effect was not present in the eyetracking task.

The findings with respect to rhymes suggest a clear strength of eyetracking: the ability to identify subtle processing deficits that are not detectable using off-line methods. The eyetracking measure revealed problems with rhyme relationships that were not detectable using overt phonological awareness tests. It is also interesting that dyslexics scored below controls on an initial sounds judgment test whereas they demonstrated normal cohort effects in an on-line eyetracking measure. It is possible that their problems judging the initial sounds of words are due to difficulty explicitly applying phonological knowledge, rather than an on-line processing deficit. If this is the case, we predict that such meta-phonological problems are peripheral to the phonological processing deficits that actually play a causal role in dyslexia.

## 4. Conclusion

Phonological awareness tests have long been an important source of information about the underlying nature of phonological deficits in dyslexia (Ball & Blachman, 1991; Bradley & Bryant, 1983). Indeed, considerable debate has focused on whether the locus of this problem is in their representation of individual segments (Fowler, 1991; Muter et al., 1998; Nation & Hulme, 1997) or at the level of rhymes (Bryant, 1997; Goswami, 1999; Kirtley et al., 1989). The present results suggest some caution in how phonological awareness tests are interpreted. We found appreciable differences in how children performed in an on-line word recognition task, versus overt phonological awareness tests. The purpose of the eyetracking task was to directly assess how different types of phonological knowledge are used during online auditory word recognition. The use of eyetracking shows significant promise for revealing characteristics of phonological ability and disability that are not detectable using traditional measures.

## Acknowledgements

This research was supported by grants from the Natural Sciences and Engineering Research Council, the Canada Foundation for Innovation and the Canadian Institutes for Health Research to MFJ and the Ontario Graduate Scholarships for Science and Technology to ASD.

## Appendix A

Stimulus sets and frequencies (Zeno, 1995) by competitor type

| Type of competitors | | | |
|---|---|---|---|
| Baseline (no competitor) | Rhyme | Cohort | Rhyme + Cohort |
| bowl (420) | cat (772) | hand (5538) | hat (1001) |
| hat (1001) | bone (538) | comb (118) | cone (118) |
| lock (243) | coat (791) | bowl (420) | boat (1589) |
| bone (538) | sock (39) | log (397) | lock (243) |
| log (397) | ghost (309) | toes (247) | toast (106) |
| carriage (183) | flower (562) | towel (119) | tower (305) |
| parrot (76) | candle (213) | sandwich (176) | sandal (30) |
| tower (305) | sandal (30) | candy (374) | candle (213) |
| sandal (30) | parrot (76) | carriage (182) | carrot (42) |

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