Article

Hammill Institute on Disabilities

Journal of Learning Disabilities
2017, Vol. 50(3) 275–285

DOI: 10.1177/0022219415618502
journaloflearningdisabilities.sagepub.com
SAGE

# Eye Movements and Articulations During a Letter Naming Speed Task: Children With and Without Dyslexia

**Noor Z. Al Dahhan, MSc[1], John R. Kirby, PhD[1,2], Donald C. Brien, MSc[1], and Douglas P. Munoz, PhD[1,3]**

**Abstract**

Naming speed (NS) refers to how quickly and accurately participants name a set of familiar stimuli (e.g., letters). NS is an established predictor of reading ability, but controversy remains over why it is related to reading. We used three techniques (stimulus manipulations to emphasize phonological and/or visual aspects, decomposition of NS times into pause and articulation components, and analysis of eye movements during task performance) with three groups of participants (children with dyslexia, ages 9–10; chronological-age [CA] controls, ages 9–10; reading-level [RL] controls, ages 6–7) to examine NS and the NS–reading relationship. Results indicated (a) for all groups, increasing visual similarity of the letters decreased letter naming efficiency and increased naming errors, saccades, regressions (rapid eye movements back to letters already fixated), pause times, and fixation durations; (b) children with dyslexia performed like RL controls and were less efficient, had longer articulation times, pause times, fixation durations, and made more errors and regressions than CA controls; and (c) pause time and fixation duration were the most powerful predictors of reading. We conclude that NS is related to reading via fixation durations and pause times: Longer fixation durations and pause times reflect the greater amount of time needed to acquire visual/orthographic information from stimuli and prepare the correct response.

**Keywords**

naming speed, phonological processing, orthography, dyslexia, eye movements, articulations

Despite decades of research conducted to explain the etiology of reading disabilities, it remains unclear why some individuals develop dyslexia whereas others do not. Currently, the most established theory is the phonological deficit hypothesis, which proposes that dyslexia is caused by a deficit in the consolidation and/or retrieval of phonological or sound based codes (Stanovich, 1988). A second factor that has accounted for variability in reading achievement is naming speed (NS) or rapid automatized naming (RAN; Kirby, Georgiou, Martinussen, & Parrila, 2010; Norton & Wolf, 2012). NS tasks measure how quickly and accurately participants can name highly familiar stimuli (e.g., letters) presented in a visual display. Performance on these tasks has been shown to be an independent source of variance in predicting concurrent and future reading ability in poor and developing readers (Compton, 2003; Georgiou, Parrila, Manolitsis, & Kirby, 2011; Neuhaus, Foorman, Francis, & Carlson, 2001).

Despite the consensus that NS and reading are related, it is still unclear how they are related, what specific cognitive processes are involved, or the nature of the difficulties faced by children with dyslexia (Kirby et al., 2010). We use three techniques with three groups of children, one group with dyslexia (ages 9–10) and two control groups—an age-matched (CA) control group and a reading-level (RL) matched control group (ages 6–7)—to address three main research questions regarding the NS–reading relationship. First, we vary the stimulus composition of a letter NS task to emphasize either visual and/or phonological aspects (Compton, 2003) to allow the examination of orthographic and phonological processing. Second, we separate the total NS time into pause and articulation time components. Articulation time is the amount of time needed to name each letter, and represents participants' automaticity of generating a response to name a stimulus once it has been recognized (Georgiou, Parrila, & Kirby, 2006; Hulme, Newton,

[1]Centre for Neuroscience Studies, Botterell Hall, Queen's University, Kingston, ON, Canada
[2]Faculty of Education, Duncan McArthur Hall, Queen's University, Kingston, ON, Canada
[3]Department of Biomedical and Molecular Sciences, Botterell Hall, Queen's University, Kingston, ON, Canada

**Corresponding Author:**
Noor Z. Al Dahhan, Centre for Neuroscience Studies, Queen's University, Botterell Hall, 18 Stuart St., Kingston, ON, K7L 3N6, Canada.
Email: noor.aldahhan@queensu.ca

Cowan, Stuart, & Brown, 1999). Pause time is the time interval between the articulation of two successive letters (Neuhaus et al., 2001) and measures the automaticity of recognizing stimuli, retrieving phonological codes from the lexical store, and shifting attention from one stimulus to the next (Kirby et al., 2010). Third, we use eye movement recording to study the cognitive processes involved in NS; for example, longer fixation durations would implicate weaker orthographic processing as the basis of the relationship, whereas an increased number of saccades could implicate difficulties in eye movement control under speeded conditions.

## *Effect of Stimulus Manipulations*

Our first research question is whether NS performance is affected by increasing visual and/or phonological similarity of the letters in a visual array. This question stems from two main theories that have been proposed to explain the NS–reading relationship (Kirby et al., 2010). The first is that NS is fundamentally a phonological task because it assesses how rapidly participants can access phonological codes from their long-term memory (Torgesen, Wagner, & Rashotte, 1994; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997). The second view is that NS also assesses the automaticity of recognizing symbolic visual stimuli, which contributes to the development of orthographic processing (Bowers & Newby-Clark, 2002; Wolf, Bowers, & Biddle, 2000). If NS is related to reading via phonological processing then increasing the phonological difficulty of a letter NS task should negatively affect naming performance, and may strengthen the relationship between NS and reading. However, if orthographic processing plays a key role in the NS–reading relationship, then increasing the visual difficulty of a NS task should negatively affect naming performance and may strengthen the relationship between NS and reading.

To test the phonological and orthographic hypotheses, Compton (2003) adapted Denckla and Rudel's (1976) letter NS task (original, or OR), which used the letters *a, d, o, p*, and *s*; Compton replaced *o* with *q* in the matrix to make the stimuli more visually similar (VS; because *q* is visually similar to *d* and *p*), replaced *o* with *v* to make them more phonologically similar (PS; because *v* rhymes with *d* and *p*), or replaced *o* with *b* to make them both more visually and phonologically similar (VPS; because *b* is both visually similar and rhymes with *d* and *p*).

Compton (2003) found that for first grade children with and without dyslexia increasing visual similarity decreased both speed and accuracy more so than increasing phonological similarity (PS and VPS). This interpretation was supported by studies using other tasks (e.g., Jones, Obregon, Kelly, & Branigan, 2008). Based on these findings, we hypothesize that naming times will be adversely affected by visual rather than phonological similarity of the letters. We further hypothesize, based on the argument that pause times reflect recognition processes, that pause times rather than articulation times will be increased by visual similarity. Finally, because impaired performance for adults with dyslexia has been shown by increased fixation time and naming latency for target letters (Al Dahhan et al., 2014; Jones et al., 2008), we hypothesize that visual similarity will increase eye movement fixation times.

## *Differences Between Children With and Without Dyslexia*

Our second research question is whether there are differences in behavior and eye movement performance between children with and without dyslexia. Longitudinal and cross-sectional studies have found that both children and adults with dyslexia are slower to name stimuli presented in a visual array than participants without dyslexia, especially when alphanumeric stimuli such as letters are used (Wolf et al., 2000). Thus, we hypothesize that children with dyslexia will be slower and make more errors on the NS tasks compared to control readers. Because differences in performance between average readers and individuals with dyslexia have been found to be due to longer pause times in the latter group (Obregon, 1994), we hypothesize that variability in performance, especially between individuals with dyslexia and CA controls, will be due to the longer pause times in dyslexia.

Previous studies have shown that adults with dyslexia were slower compared to controls on NS tasks that increased either visual or phonological similarity of the letters (Jones et al., 2008), and controls overall had shorter fixation durations, longer saccades, and fewer fixations and saccades compared to adults with dyslexia (Al Dahhan et al., 2014). We hypothesize that children with dyslexia will make longer and more fixations, shorter saccades, and more regressions than CA controls when performing NS tasks.

## *Prediction of Reading Ability*

Our third research question addresses the extent to which the NS components and eye movement parameters are significant predictors of NS efficiency and reading ability. Because pause times have been generally found to be the greater component of NS times and more related to reading than articulation times (Georgiou et al., 2006; Lervåg & Hulme, 2009; Neuhaus et al., 2001; Neuhaus & Swank, 2002), we hypothesize that both NS efficiency and reading ability will be more related to pause time than articulation time (Neuhaus et al., 2001; Neuhaus & Swank, 2002). In terms of the eye movement parameters, we hypothesize that greater reading ability will be associated with shorter fixation duration, greater saccade length, and fewer regressions, all of which are indications of faster information processing (Olitsky & Nelson, 2003).

## Method

### *Participants*

Three groups of 15 participants took part in this study: one group with dyslexia (11 males, ages 8.1–10.9 years, age $M$ = 9.79 years, $SD$ = 0.75) and two control groups—a chronological-age (CA) matched group (6 males, ages 8.1–10.9 years, age $M$ = 9.67 years, $SD$ = 0.68) and a reading-level (RL) matched group (7 males, ages 6.9–7.9 years, age $M$ = 7.34 years, $SD$ = 0.34). Participants were recruited from the greater Kingston, Canada, community, and legal guardians provided informed consent prior to testing.

Participants with dyslexia were initially recruited based on a legal guardian's report that the child had a formal diagnosis of dyslexia from a qualified professional or the legal guardian's opinion that the child had serious reading problems. Status as a participant with dyslexia was confirmed with the *Woodcock Word Identification* test (Woodcock, 1998). Children who scored below 27 were classified as having dyslexia; a score of 27 corresponds to a reading age of 6 years, 11 months; therefore the youngest child in the dyslexia group (age 8 years, 1 month) was at least 14 months behind after 2 years of formal reading instruction. Children in this same age group who scored above 30 were classified as CA controls. Younger children with scores in the same range as those with dyslexia were classified as RL controls. Therefore, the three groups were formed based on raw scores on the *Woodcock Word Identification* test so that the CA group had the same age as the dyslexic group but higher reading ability, and the RL group had the same reading ability as the dyslexic group but younger age (Figure 1A).

### *Reading and Cognitive Measures*

*Letter naming speed.* Four versions (two trials/version) of a letter NS task were administered in counterbalanced order on a computer screen (Figure 1B): the original (OR) task developed by Denckla and Rudel (1976) with the letter matrix composed of *a, d, o, p, s*, and three adaptations to this task developed by Compton (2003)—tasks with (a) increased visual similarity (VS: *o* replaced with *q*), (b) increased phonological similarity (PS: *o* replaced with *v*), or (c) both increased visual and phonological similarity (VPS: *o* replaced with *b*). Each NS task presented 50 letters simultaneously with 10 repetitions of the 5 letters arranged semi-randomly in 5 rows of 10 letters each. Participants were instructed to name all the letters aloud as quickly and accurately as possible from left to right and top to bottom, and their articulations and eye movements were recorded. Prior to the presentation of the tasks, two practice trials were administered. In the first practice trial participants were asked to name the eight letters that were going to be used (i.e., *a, d, b, p, s, q, o, v*) to assess their familiarity with the letter names. In the second practice trial, a NS task consisting of 20 letters in four rows with a random assortment of the eight letters was administered to ensure adequate familiarity with the letters and an understanding with the requirements of the task. Participants' efficiency scores on these tasks were defined as the number of letters named correctly divided by the total naming time. Scores on the two tasks were averaged to create a single score.

*Reading and decoding ability.* Reading ability was assessed with three tasks: Word Identification, Sight Word Efficiency, and WordChains. In Word Identification (Woodcock, 1998) participants were asked to read aloud up to 106 words that increased in difficulty until they either attempted all the words or made six consecutive errors. Participants' scores were the number of words read correctly. In Sight Word Efficiency (Wagner, Torgesen, & Rashotte, 1999) participants were shown a list of 104 words presented in four columns of 26 words each that increased in difficulty and were asked to read the words aloud as quickly as possible. Participants' scores were the number of words read correctly within the 45-s time limit. In WordChains, participants were asked to identify words that were presented as a continuous line of print without interword spaces by inserting a slash between the words (e.g., *boygomeet* → *boy/go/meet*). The test, which is intended to measure silent word reading and orthographic processing, included 17 rows of words increasing in length from two words to seven words. Participants' scores were the number of correctly placed slashes minus the number of errors and slashes omitted (up to the last inserted slash) within the 1-min time limit.

Participants' decoding ability was assessed with two measures: Phonemic Decoding Efficiency and Word Attack. In Phonemic Decoding Efficiency (Wagner et al., 1999) children were asked to read as fast as possible a list of 63 pseudowords that increased in difficulty. Participants' scores were the number of pseudowords read correctly within the 45-s time limit. In Word Attack (Woodcock, 1998) children were asked to read aloud 45 pseudowords that increased in difficulty until they either attempted all the words or made six consecutive errors. Participants' scores were the number of pseudowords read correctly.

*General mental ability.* Nonverbal ability was assessed with the Matrix Reasoning subtest of the *Wechsler Abbreviated Scale of Intelligence* (Wechsler, 1999). A total of 35 incomplete visual patterns each with five possible pieces to complete the patterns were shown to participants one at a time. Participants were asked to point to the piece that would best complete the pattern. Participants were scored either 1 for a

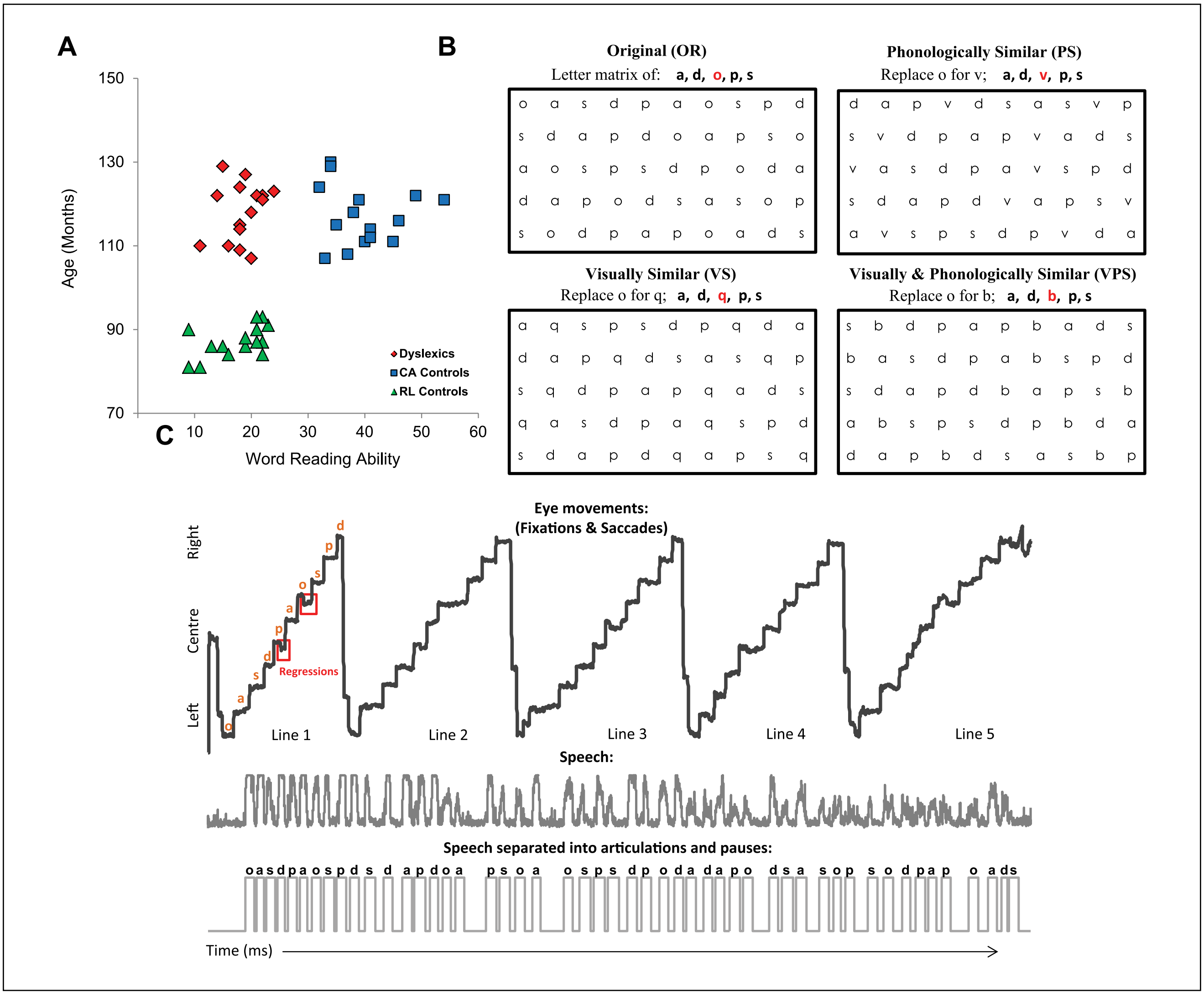


**Figure 1.** (A) Participants' age and word reading ability. Reading ability was based on the *Woodcock Reading Mastery Test–Revised* Form G, Word Identification Subtest. (B) Naming speed task stimuli. The original (OR) NS task was developed by Denckla and Rudel (1976). The phonologically similar (PS), visually similar (VS), and visually and phonologically similar (VPS) tasks were developed by Compton (2003). (C) Example of data recorded during performance of an original letter naming speed task by a CA control participant.

*Note.* NS = naming speed; CA = chronological-age matched controls; RL = reading-level matched controls.

correct answer or 0 for an incorrect answer. Both raw scores and *T* scores were recorded, the latter being age-standardized scores ($M$ = 50, $SD$ = 10) as defined in the test manual.

## *Procedure*

Testing was conducted at an eye tracking center and was divided into two sessions each lasting approximately 30 minutes. In the first session the reading and nonverbal ability tests were administered. In the second session the four NS tasks with two trials/task were administered in counterbalanced order, while eye movements and articulations were recorded. Upon completion of the study, participants' legal guardians received $20 compensation for their time.

## *Eye Tracking and Visual Display*

Eye position was recorded using the Eyelink 1000 head-free eye tracking system (SR Research Ltd, Mississauga, ON, Canada). The 17-inch LCD monitor and mounted infrared camera were placed 60 cm, the optimal camera-eye distance, from the right eye. All recordings and calibrations were done monocularly based on the right eye; viewing of the display was binocular. The position of the right pupil was digitized in both the vertical and the horizontal axes at a sampling rate of 500 Hz. Eye position was first calibrated using nine randomly presented target locations on the screen (eight around the periphery and one central). The targets were flashed sequentially around the screen and the participant fixated on each one. After calibration, the process was repeated one more time to validate that the average error between fixation and target was <2° and that no loss of eye tracking occurred.

For the NS tasks, each trial started with illumination of a central fixation point (FP) for 800 ms. The FP then disappeared and the array of letters were presented in black print (Century Gothic font, size 28) on a white background, with a 3° viewing distance between each letter and 1.9° viewing distance between each row. The horizontal and vertical dimensions of the letter stimulus array were .67° and .85°, respectively. Participants were requested to remain as still as possible while they named the letters on the screen. Vocal responses were recorded by a microphone attached to the infrared camera of the eye tracker. After naming the last letter on the visual array participants were told that the next NS task will be presented. No feedback was given on performance. A break was provided after every two NS trials.

### *Data Manipulation*

Eye movements and articulations were marked and analyzed using custom software developed in MatLab (Version R2011a; MathWorks Inc., Natick, MA, USA). Eye position and articulations were digitized from the start to end of each trial. Fixation duration was defined as the average duration (in milliseconds) of all fixations in the trial. The onset and termination of saccades were determined by using the velocity (30°/sec) and acceleration (8,000°/sec$^2$) threshold criteria. Regressions were defined as leftward saccades that were within 30° of visual angle in the horizontal and were less than 10° in amplitude (so as to omit blinks and eye movements to the next line). Eye tracking data associated with skips or naming errors were removed manually from the data analyses. An example of the eye tracking data from a CA participant is shown in Figure 1C.

The sound files containing the letter naming responses for each participant were analyzed using custom software developed in MatLab (Version R2011a). Data extraction was completed using procedures described previously (Georgiou et al., 2006). Before estimating the means for NS pause and articulation times, four types of errors were removed from the data. First, if there was an incorrect articulation, then the preceding pause time, the incorrect articulation, and the following pause time were removed. Second, if there was a self-correction, then everything between the two correct articulations were removed. Third, if a stimulus was skipped then the pause time between the two correct articulations and the articulation time that followed the skip were removed. Fourth, if off-task behavior (e.g., coughing, self-encouragement) was observed between two articulations, the specific pause time was removed. Therefore, articulation time was the mean of those articulation times that were correctly verbalized and were not preceded by a skipped stimulus. Pause time was the mean of the pause times between two correctly articulated stimuli.

## Results

First we validated group differences on measures of reading and cognitive ability then examined group and task differences in (a) NS efficiency and errors, (b) NS components, and (c) eye movements. We then combined the three groups and collapse measures of components and eye movements across tasks to examine predictors of reading achievement.

### *Performance on Reading and Cognitive Measures*

Means and standard deviations for the reading and nonverbal ability measures are presented in Table 1. To simplify subsequent analyses, an overall reading ability measure was formed by conducting a principal axis factor analysis on the five reading and decoding measures. This analysis yielded one factor, accounting for 80.6% of the variance; each of the measures loaded .80 or higher. Regression factor scores for this factor, identified as overall reading ability, were used in subsequent analyses. One-way ANOVA with Bonferroni post hoc comparisons indicated that the groups differed on overall reading ability, $F(2, 44) = 69.83$, $p < .001$, effect size (ES) = .77, with the CA controls obtaining higher scores than the RL controls and children with dyslexia ($p < .05$). The groups differed on Matrix Reasoning raw scores, $F(2, 44) = 5.59$, $p < .01$, ES = .21, the only significant difference being between the two control groups ($p < .05$), but not on Matrix Reasoning $T$ scores ($p > .05$), indicating that the three groups were of comparable mental ability for their ages.

### *Naming Speed Efficiency and Naming Errors*

Two two-way repeated measures ANOVAs were used to examine the effects of task (the four NS tasks) and group (CA controls, RL controls, and dyslexics) on efficiency and errors. For NS efficiency (Figure 2A), there were significant effects of group, $F(2, 42) = 9.64$, $p < .001$, $d = .32$, and task, $F(3, 126) = 57.90$, $p < .001$, $d = .58$, but no significant interaction, $F(6, 126) = 0.88$, $p = .51$, $d = .04$. The group effect was examined with Bonferroni post hoc tests using the averaged $z$ scores of the four tasks. CA controls were significantly more efficient than the RL controls and dyslexics ($p < .01$), and these latter two groups were not significantly

**Table 1.** Descriptive Statistics of Dyslexic and Control Groups on Reading and Cognitive Measures.

| | CA controls (*n* = 15) | | RL controls (*n* = 15) | | Dyslexics (*n* = 15) | |
|---|---|---|---|---|---|---|
| Variable | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| Word Identification | 39.87 | 6.35 | 17.53 | 4.98 | 18.40 | 3.40 |
| Sight Word Efficiency | 67.93 | 10.44 | 28.47 | 14.74 | 38.73 | 15.55 |
| WordChains | 31.54 | 6.78 | 0.31 | 11.52 | 7.43 | 14.26 |
| Phonemic Decoding Efficiency | 38.00 | 12.78 | 15.80 | 8.42 | 18.07 | 7.41 |
| Word Attack | 25.67 | 2.72 | 8.13 | 3.54 | 15.13 | 6.09 |
| Matrix Reasoning | 40.60 | 7.57 | 28.33 | 4.70 | 33.87 | 6.74 |
| Matrix Reasoning *T* score | 51.93 | 11.31 | 54.13 | 8.52 | 48.33 | 9.01 |

*Note.* CA = chronological-age matched controls; RL = reading-level matched controls.

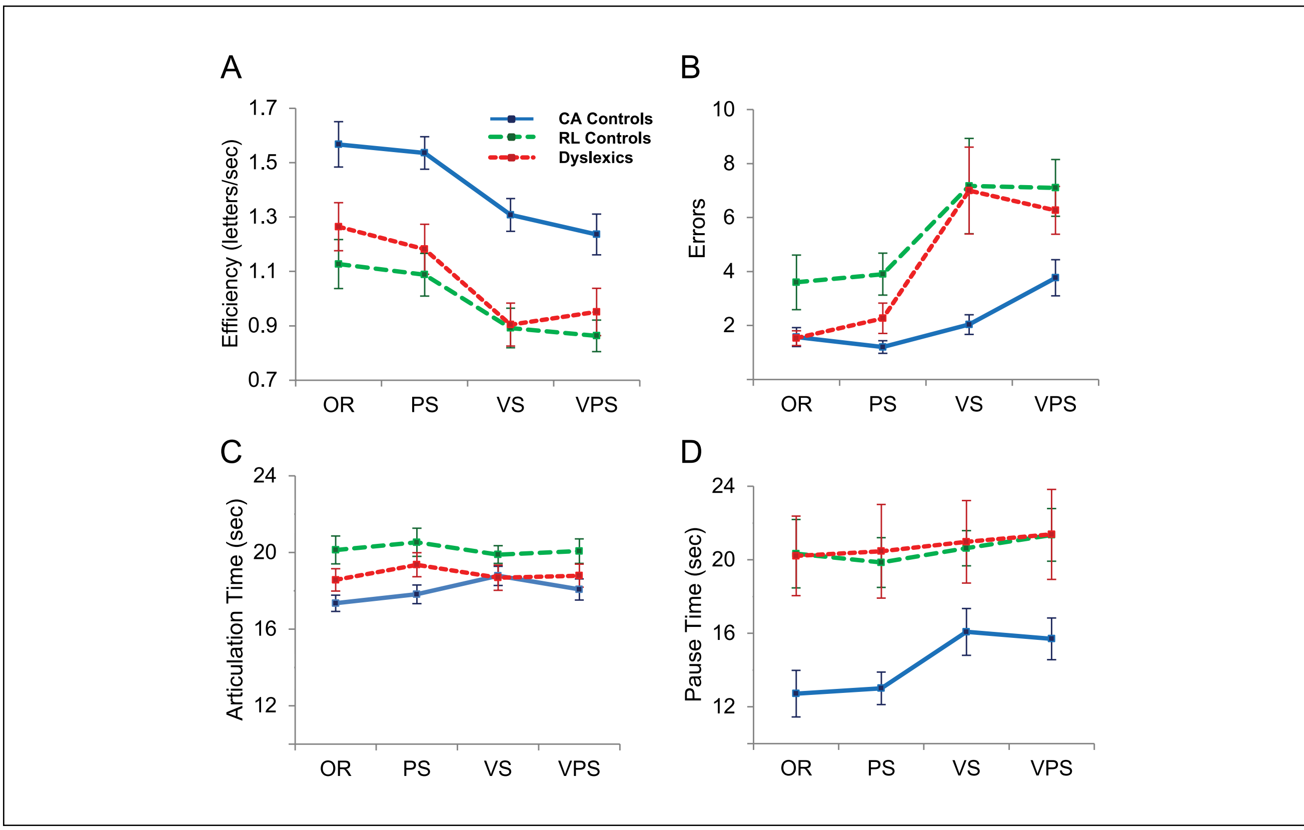


**Figure 2.** Effect of task version on NS performance and NS components in three groups. (A) Efficiency score on the NS tasks. (B) Errors in naming. (C) Average articulation time per trial. (D) Average pause time per trial.
*Note.* CA = chronological-age matched controls; RL = reading-level matched controls; OR = original NS task; PS = phonologically similar NS task; VS = visually similar NS task; VPS = visually and phonologically similar NS task. Standard errors are shown.

different ($p > .05$). To examine the task effect, paired-samples $t$ tests showed that the OR and PS tasks did not differ, $t(44) = 1.92$, $p > .05$, $r = .88$, and neither did the VS and VPS tasks, $t(44) = 0.58$, $p > .05$, $r = .80$. A further paired samples $t$ test showed that the combined OR and PS efficiency scores were higher than the combined VS and VPS efficiency scores, $t(44) = 12.85$, $p < .001$, $r = .92$, indicating that NS efficiency is more a function of the visual similarity of the letters than of their phonological similarity. It should be noted that OR and PS have the same level of visual similarity (low), whereas VS and VPS share high visual similarity (high).

For NS errors (Figure 2B), there were significant effects for group, $F(2, 42) = 5.69$, $p = .01$, $d = .21$, task, $F(3, 126) = 20.90$, $p < .001$, $d = .33$, and the group × task interaction,

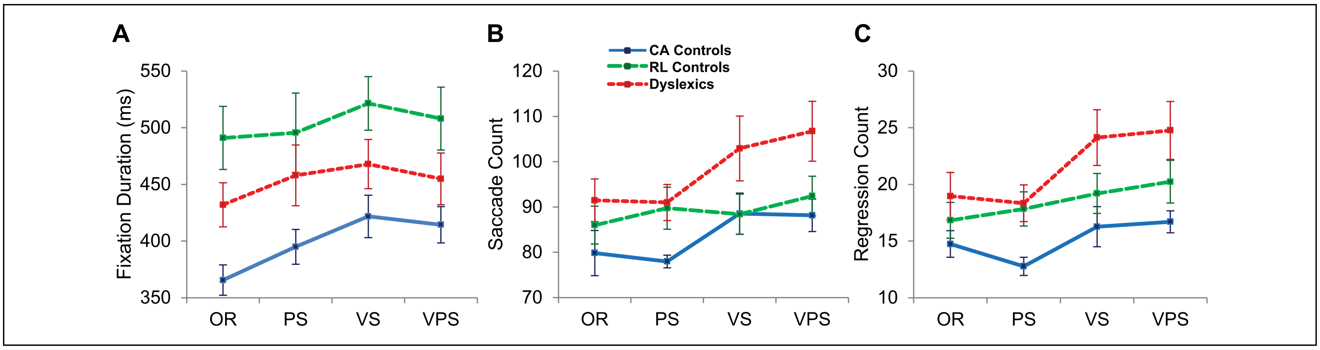


**Figure 3.** Effect of task version on eye movement measures in three groups. (A) Average fixation duration. (B) Saccade count. (C) Regression count.

*Note.* CA = chronological-age matched controls; RL = reading-level matched controls; OR = original NS task; PS = phonologically similar NS task; VS = visually similar NS task; VPS = visually and phonologically similar NS task. Standard errors are shown.

$F(6, 126) = 2.40$, $p = .03$, $d = .10$. Bonferroni $t$ tests on the averaged $z$ scores of the four tasks indicated that the group effect was due to the CA controls making significantly fewer errors than the RL controls ($p < .01$), and there was no significant difference between dyslexics and CA and RL controls ($p > .05$). With respect to the task effect, paired-samples $t$ tests indicated that the OR and PS tasks did not differ, $t(44) = 0.64$, $p > .05$, $r = .57$, and neither did the VS and VPS tasks, $t(44) = 0.45$, $p > .05$, $r = .66$. The combined OR and PS error scores were lower than the combined VS and VPS error scores, $t(44) = 6.76$, $p < .001$, $r = .68$, indicating that the task effect is a function of the visual similarity of the letters and not of their phonological similarity. With respect to the interaction (Figure 2B), dyslexics were similar to the CA controls on the OR-PS score ($p > .05$) but made fewer errors than the RL controls ($p < .05$), whereas they were similar to the RL controls on the VS-VPS score ($p > .05$) but made more errors than the CA controls ($p < .05$). Thus the children with dyslexia performed particularly poorly on the more visually similar tasks.

## Naming Speed Components

Two-way repeated measures ANOVAs were used to examine the effects of task and group on articulation and pause times. For articulation time (Figure 2C) there was a significant main effect for group, $F(2, 42) = 4.27$, $p = .02$, $d = .17$, but no significant task effect, $F(3, 126) = 1.68$, $p = .18$, $d = .04$, or interaction effect, $F(6, 126) = 1.90$, $p = .09$, $d = .08$. Bonferroni comparisons for the group effect using the averaged $z$ scores of the four tasks showed that CA controls had shorter articulation times than the RL controls ($p < .05$), and there was no significant difference between the dyslexics and either control group ($p > .05$).

For pause time (Figure 2D), there were significant effects of group, $F(2, 42) = 5.19$, $p < .01$, $d = .20$, and task, $F(3, 126) = 4.23$, $p = .01$, $d = .09$, but no significant interaction effect, $F(6, 126) = 0.99$, $p = .43$, $d = .05$. Bonferroni comparisons on the averaged $z$ scores of the four tasks indicated that CA controls had shorter pause times than the RL controls and dyslexics ($p < .05$), with no significant difference between dyslexics and RL controls ($p > .05$). With respect to the task effect, paired-samples $t$ tests demonstrated that the OR and PS task pause times did not differ, $t(44) = 0.04$, $p > .05$, $r = .88$, and neither did the VS and VPS pause times, $t(44) = 0.37$, $p > .05$, $r = .78$. The combined OR and PS pause times were shorter than the combined VS and VPS pause times, $t(44) = 3.50$, $p < .001$, $r = .91$, indicating that it is visual similarity and not phonological similarity that increases participants' pause times.

## Eye Movement Measures

Two-way ANOVAs with repeated measures were used to examine the task and group effects on fixation duration, saccade count, and regression count. For fixation duration (Figure 3A), there were significant main effects for group, $F(2, 42) = 6.02$, $p < .01$, $d = .22$, and task, $F(3, 126) = 8.42$, $p < .001$, $d = .17$, but no significant interaction effect, $F(6, 126) = 0.69$, $p = .66$, $d = .03$. Bonferroni post hoc tests comparing the $z$ scores averaged across the four tasks indicated that CA controls had shorter fixation durations than RL controls ($p < .01$), with no significant difference between the dyslexics and either control group ($p > .05$). For the task effect, paired-samples $t$ tests showed that all the tasks were significantly different from one another ($p < .05$) except for the PS-VPS tasks and the VS-VPS tasks ($p > .05$). A further paired-samples $t$ test showed that the combined PS and VPS fixation durations were shorter than the combined VS and VPS fixation durations, $t(44) = 2.24$, $p < .05$, $r = .95$, indicating that it is the visual similarity of the letters that increases fixation duration.

For saccade count (Figure 3B) there were significant effects for group, $F(2, 42) = 3.67$, $p = .03$, $d = .15$, and task, $F(3, 126) = 6.94$, $p < .001$, $d = .14$, but no significant

**Table 2.** Correlations Among Measures.

| Measure | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. Matrix Reasoning | — | | | | | | | | | |
| 2. Reading ability | .53** | — | | | | | | | | |
| 3. NS efficiency | .14 | .41** | — | | | | | | | |
| 4. NS errors | −.27 | −.35* | −.67** | — | | | | | | |
| 5. Articulation time | −.23 | −.31* | −.68** | .33* | — | | | | | |
| 6. Pause time | .04 | −.31* | −.80** | .23 | .57** | — | | | | |
| 7. Fixation duration | −.09 | −.39** | −.71** | .41** | .67** | .67** | — | | | |
| 8. Saccade count | .02 | −.13 | −.49** | .17 | .23 | .50** | −.05 | — | | |
| 9. Regression count | .06 | −.16 | −.62** | .37* | .33* | .54** | .08 | .81** | — | |

*Note.* $N$ = 45. NS = naming speed.
*$p$ < .05. **$p$ < .01.

interaction, $F(6, 126) = 1.17$, $p = .33$, $d = .05$. Bonferroni post hoc tests indicated that CA controls made significantly fewer saccades than dyslexics ($p < .05$), but not fewer than the RL controls ($p > .05$), and dyslexics did not make significantly more saccades than RL controls ($p > .05$). Regarding the task effect, paired samples $t$ tests showed that the OR and PS tasks did not differ, $t(44) = 0.208$, $p > .05$, $r = .60$, and neither did VS and VPS, $t(44) = 0.760$, $p > .05$, $r = .47$. Fewer saccades were made in the combined OR and PS tasks than in the combined VS and VPS tasks, $t(44) = 4.80$, $p < .001$, $r = .76$, indicating that increasing visual similarity of the letters in the matrix increased the number of saccades.

For regression count (Figure 3C) there were significant effects for group, $F(2, 42) = 4.43$, $p = .02$, $d = .17$, and task, $F(3, 126) = 13.77$, $p < .001$, $d = .25$, but no significant interaction, $F(6, 126) = 1.58$, $p = .16$, $d = .07$. Bonferroni comparisons showed that children with dyslexia made more regressions than CA controls ($p < .05$) but not more than RL controls ($p > .05$). Paired samples $t$ tests were conducted to analyze the task effect and indicated that the OR and PS tasks did not differ, $t(44) = 0.76$, $p > .05$, $r = .71$, and neither did VS and VPS, $t(44) = 0.80$, $p > .05$, $r = .74$. Fewer regressions were made in the combined OR and PS tasks than in the combined VS and VPS tasks, $t(44) = 5.82$, $p < .001$, $r = .84$, indicating that it is visual similarity and not phonological similarity that increases number of regressions.

## *Relationships Among Measures and Regression Analyses*

Our final set of exploratory analyses examined which of the NS component and eye movement variables best accounted for variance in NS efficiency and reading ability. We combined the three groups and averaged $z$ scores for each of the predictors across the four NS tasks. Combining groups that were selected to be different has risks, but we thought it worthwhile to explore these cross-group relationships to guide future research; we acknowledge this as a limitation. Before averaging the $z$ scores, we checked that the measures of each construct were highly correlated with each other; all of the following correlations were significant at the $p$ <.01 level (see Note 1). The correlations between NS efficiency scores ranged from .80 to .88, for articulation times from .62 to .88, and for pause times from .77 to .88; those for fixation duration from .80 to .88, for saccade count from .44 to .69, and for regression count from .71 to .75

Table 2 shows the correlations between the main measures. Matrix Reasoning was positively correlated with overall reading ability ($p < .01$), but not with any of the other variables ($p$s > .05). Reading ability was correlated with NS efficiency, both NS components, and fixation duration ($p < .05$). NS efficiency was correlated with articulation time, fixation duration, and regression count ($p < .05$), and with pause time and saccade count ($p < .01$). Hierarchical regression analyses were conducted to investigate how the NS components and eye movement variables predicted NS efficiency and reading; results are shown in Table 3. Because of the relatively small number of participants, as few predictors as possible were employed in each model. Matrix Reasoning was entered in the first step, to control for general ability. In the second step, either NS components (articulation time and pause time; Step 2) or eye movement variables (fixation duration, saccade count, and regression count; Step 2a) were entered together. The third model (Step 2b in the table) used the better component predictor (pause time) and the best eye movement predictor (fixation duration).

General mental ability accounted for only 2% of the variance in NS efficiency. The NS components added a further 71% and the eye movement variables 83%. For the NS components, both articulation time and pause time predicted NS efficiency significantly, but pause times played a larger role ($\beta = .63$) than articulation time ($\beta = .31$). The eye movement variables also predicted NS efficiency significantly, with fixation duration playing the largest role ($\beta = .67$). The third analysis in Table 3 shows that pause time and fixation duration each accounted for a significant proportion of the variance in NS efficiency, with pause time playing the larger role, $\beta = .62$, $p < .001$ versus $\beta = .28$, $p = .02$.

**Table 3.** Summary of Hierarchical Regression Analyses Predicting Naming Speed Efficiency and Overall Reading Ability.

| | NS efficiency | | | | Overall reading ability | | | |
|---|---|---|---|---|---|---|---|---|
| Step, predictor | $\Delta R^2$ | β | *t* | *p* | $\Delta R^2$ | β | *t* | *p* |
| 1. Matrix Reasoning | .02 | .14 | 0.90 | .38 | .28*** | .53 | 4.08 | .001 |
| 2. NS components | .71*** | | | | .11* | | | |
| Articulation time | | −.31** | 2.95 | .01 | | .01 | 0.08 | .94 |
| Pause time | | −.63*** | 6.21 | .001 | | −.34* | 2.21 | .03 |
| 2a. Eye movements | .83*** | | | | .15* | | | |
| Fixation duration | | −.67*** | 10.53 | .001 | | −.34** | 2.79 | .01 |
| Saccade count | | −.18 | 1.70 | .10 | | −.07 | 0.35 | .73 |
| Regression count | | −.43*** | 3.96 | .001 | | −.10 | 0.49 | .63 |
| 2b. | .69*** | | | | .14* | | | |
| Pause time | | −.62*** | 5.40 | .001 | | −.17 | 1.06 | .29 |
| Fixation duration | | −.28* | 2.45 | .02 | | −.23 | 1.42 | .16 |

*Note.* NS = naming speed. β coefficients are from the step at which the predictor entered the model.
*$p < .05$. **$p < .01$. ***$p < .001$.

The second set of regression analyses used the same set of predictors but with reading ability as the outcome. Matrix Reasoning accounted for 28% of the variance in overall reading ability (Table 3). We note that age was not included as a predictor because Matrix Reasoning scores are related to age and we wanted to minimize the number of predictors in the models. NS components and the eye movement variables added a further 11 to 15% of the variance, respectively. Only pause time and fixation duration predicted overall reading ability significantly. Pause time and fixation duration together added 14% of the variance to that accounted for by Matrix Reasoning; neither had a significant unique effect on reading ability, *p*s > .16, indicating that it is the variance shared between pause time and fixation duration that is critical for predicting reading.

## Discussion

The aim of this study was to use stimulus manipulations, NS components, and eye movement methodology to determine (a) whether NS performance, NS components, and eye movements are affected by increasing visual and/or phonological similarity of the letters in a visual array; (b) whether there are differences in behavior and eye movement performance between children with and without dyslexia; and (c) the extent to which the NS components and eye movement parameters are significant predictors of NS efficiency and reading ability. The results indicate that pause time and fixation duration are key features in the NS–reading relationship, and increasing visual similarity of the letter matrix had the greatest effect on performance. The discussion focuses on three questions: (a) What determines NS? (b) What distinguishes children with dyslexia from controls? and (c) What predicts reading ability?

### What Determines NS?

As hypothesized, increasing visual similarity of the letter matrix significantly affected NS performance (Figures 2A, 2B). This indicates that the ability to encode the visual forms of letters influenced NS performance, and supports the argument of Bowers, Golden, Kennedy, and Young (1994) that rapidly accessing the visual forms of letters is the key determiner of NS performance. Furthermore, NS efficiency was associated with pause time and fixation duration; both index the amount of time needed to encode the stimuli (Kirby et al., 2010). Slower encoding would lead to less fluent naming performance, as is shown by the significant negative correlations between both pause time and fixation duration and NS efficiency (Table 2).

Both articulation time and pause time had significant effects in predicting NS efficiency after controlling for general mental ability, but as hypothesized, pause time was substantially stronger (Table 3). Furthermore, the eye movement variables, with fixation duration being the strongest predictor, accounted for 83% of the variance in NS efficiency (Table 3). However, when both pause time and fixation duration were used as predictors of NS efficiency, pause time was a stronger predictor than fixation duration, indicating that pause time plays the largest role in predicting NS performance (Table 3). The effects of visual similarity, pause time, and fixation duration are consistent with the interpretation that NS performance is essentially due to the difficulty of encoding each stimulus (Kirby et al., 2010).

### What Distinguishes Children With Dyslexia From Controls?

Children with dyslexia performed more like RL controls and were less efficient, had longer articulation times, pause times, and fixation durations, and made more errors, saccades, and regressions than CA controls. The longer fixations and pause times found for children with dyslexia indicates that they may have had weaker orthographic processing compared to CA controls, which implies that their recognition of symbolic visual stimuli was not fully automated and so longer fixations and pause times were required to encode and process each stimulus (Bowers & Newby-Clark, 2002; Kirby et al., 2010). We argue that the speeded conditions of this task coupled with the visual similarities between letters made it more difficult for children to accurately access the letter representations from lexical stores.

Shorter fixation durations were associated with increased NS efficiency. Thus, less fluent naming may also be due to a dispersed allocation of visual attention, which leads to a reduced ability to discriminate a fixated letter from its surrounding information (Whitney & Cornelissen, 2005). The perceptual analysis of target letters in dyslexia may be disrupted because less attention is devoted to processing the target letter. This is consistent with evidence that individuals with dyslexia have a more parallel distribution of attention in their visual field compared to controls, leading to a broader and weaker distribution of attention across their visual field (Geiger, Lettvin, & Fahler, 1994; Lorusso et al., 2004).

However, more research needs to be conducted to determine if this parallel distribution of attention is driving the difference in NS performance and performance between children with dyslexia and CA controls. The multiple processes that are required during NS tasks may be more laborious in dyslexia and poor performance may reflect this difficulty to perform processes simultaneously (Nicolson & Fawcett, 1990). Also, if individuals with dyslexia have not automatized the rapid activation and integration of visual stimuli and phonological codes, then NS tasks may tax limited executive processes to a greater extent than controls who have already automatized them (Wolf & Bowers, 1999).

### *What Predicts Reading Ability?*

Pause time and not articulation time made a significant contribution to reading ability (Table 3), consistent with previous research (Georgiou et al., 2006; Lervåg & Hulme, 2009; Neuhaus et al., 2001; Neuhaus & Swank, 2002). This may be due to the speed of processing demands associated with retrieving letter knowledge or orthographic processing (Neuhaus et al., 2001). Fixation duration was the only eye movement variable that was correlated significantly with overall reading ability (Table 2), the only one to predict reading ability after controlling for general mental ability (Table 3), and its covariation with pause time was significantly associated with reading ability (Table 3). The pause time and fixation duration findings suggest that the amount of time needed to acquire or encode stimuli is the most important factor in predicting reading ability and thus in understanding the NS–reading relationship.

## Conclusion

These findings add to a growing number of studies that have examined the underlying cognitive processes involved in the NS–reading relationship. We conclude first that NS is related to reading via pause times and fixation durations, both of which reflect the amount of time needed to encode visual/orthographic information from stimuli. Slower orthographic encoding may be due to a combination of factors: less efficient visual encoding, distributed attention, and poor eye movement control. Poor eye movement control is also implicated in our second conclusion, that children with dyslexia make an increased number of saccades and regressions in the NS task. These findings need to be validated and extended in future studies using larger samples and with additional matching variables.

### Acknowledgments

We gratefully thank members of the Munoz lab for their editorial advice on earlier versions of this article.

### Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

### Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by an operating grant from the Canadian Institute of Health Research: MOP-97741. DPM was supported by the Canada Research Chair Program. The authors declare no competing financial interests.

### Note

1. Full correlation matrices are available from the authors on request.

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