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# Eye movements of university students with and without reading difficulties during naming speed tasks

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**Abstract** Although naming speed (NS) has been shown to predict reading into adulthood and differentiate between adult dyslexics and controls, the question remains why NS is related to reading. To address this question, eye movement methodology was combined with three letter NS tasks (the original letter NS task by Denckla & Rudel, *Cortex* 10:186–202, 1974, and two more developed by Compton, *The Journal of Special Education* 37:81–94, 2003, with increased phonological or visual similarity of the letters). Twenty undergraduate students with reading difficulties (RD) and 27 without (NRD) were tested on letter NS tasks (eye movements were recorded during the NS tasks), phonological processing, and reading fluency. The results indicated first that the RD group was slower than the NRD group on all NS tasks with no differences between the NS tasks. In addition, the NRD group had shorter fixation durations, longer saccades, and fewer saccades and fixations than the RD group. Fixation duration and fixation count were significant predictors of reading fluency even after controlling for phonological processing measures. Taken together, these findings suggest that the NS–reading relationship is due to two factors: less able readers require more time to acquire stimulus information during fixation and they make more saccades.

**Keywords** Adults · Dyslexia · Eye movements · Rapid automatized naming · Reading fluency

Although phonological awareness deficits are known to be the core of reading failure (Bradley & Bryant, 1983; Stanovich, 1992; Vellutino, Fletcher, Snowling, & Scanlon, 2004), some researchers have argued that naming speed (NS) is a second core deficit in dyslexia (Kirby, Georgiou, Martinussen, & Parrila, 2010; Wolf & Bowers, 1999). NS is measured by the rapid automatized naming (RAN) tasks which were initially developed by Denckla and Rudel

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(1974) and ask participants to name as quickly as possible a set of highly familiar visual stimuli such as objects, colors, letters, or digits that are displayed in an array, often of 50 items arranged in five rows of ten.

Extensive developmental behavioral studies have shown that NS is a strong predictor of both concurrent and future reading ability in different languages, surviving the statistical control of other known predictors such as general cognitive ability, letter knowledge, phonological awareness, short-term memory, and orthographic knowledge (Bowey, McGuigan, & Ruschena, 2005; de Jong & van der Leij, 1999; Kirby, Parrila, & Pfeiffer, 2003; Lepola, Poskiparta, Laakkonen, & Niemi, 2005; Lervåg, Bråten, & Hulme, 2009; Manis, Doi, & Bhadha, 2000; Parilla, Kirby, & McQuarrie, 2004). Conversely, NS deficits are a characteristic of reading difficulty from the early stages of reading (Georgiou, Parrila, & Liao, 2008; Kirby et al., 2003; Wolf, Bally, & Morris, 1986) to adulthood (Felton, Naylor, & Wood, 1990; Parilla, Georgiou, & Corkett, 2007). Despite the acknowledged importance of NS in predicting reading, it remains unclear why NS is related to reading or what specific cognitive processes are involved in NS (Arnell, Joanisse, Klein, Busseri, & Tannock, 2009; Kirby et al., 2010; Wile & Borowsky, 2004).

In this study, we combined two methods to examine the nature of the NS–reading relationship. First, we manipulated the composition of the letter naming task by increasing the phonological or visual similarity of the items, to determine whether either component has a greater effect on NS total time and its relation to reading. Second, we used eye-tracking methodology to record online processing during the NS tasks and to determine which parameters (e.g., number and duration of fixations and saccades) are most related to NS performance time and reading ability.

The manipulation of the composition of letter naming is directly related to the prominent explanations of the NS–reading relationship. According to Torgesen, Wagner, and colleagues (e.g., Torgesen, Wagner, & Rashotte, 1994; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997; Wagner & Torgesen, 1987), NS is fundamentally a phonological processing measure and is related to reading because it involves quick access to and retrieval of phonological codes from long-term memory. If this is the case, then increasing the phonological difficulty of the NS task by including phonologically similar items (i.e., b, v) should increase the NS times and strengthen the relationship between NS and reading (Compton, 2003). In turn, Bowers and Wolf (1993) emphasized the extra-phonological features of NS and argued that NS assesses the automaticity of recognizing symbolic stimuli, which, in turn, contributes to the development of orthographic processing. If this is the case, then increasing the visual difficulty of the task by including visually similar items (i.e., p, q) should increase the NS times and strengthen the relationship between NS and reading.

To examine the impact of phonological and visual similarity on the relationship between NS and reading, Compton (2003) adapted Denckla and Rudel's (1974) letter NS task to create versions that were more phonologically similar or more visually similar. The original task used the letters *a*, *d*, *o*, *p*, and *s* repeated ten times each and arranged in five rows of ten. For the phonologically similar task, *v* was substituted for *o*, because it rhymes with *d* and *p*. For the visually similar task, *q* was substituted for *o* because it shares visual features with *d* and *p*. Compton also used a fourth version which was both visually and phonologically similar, substituting *b* for *o* because it is both visually similar and rhymes with *d* and *p*. These four tasks were administered to first grade children at the beginning of the school year (October), and NS performance (accuracy and naming time) was then used to predict word identification skill towards the end of that school year (April). Compton (2003) found that the visually similar version had the greatest effect on NS total time, but it did not account for unique variance in subsequent word identification skill when considered simultaneously with the other three NS versions. In contrast, the two NS tasks that increased phonological processing predicted more unique variance in word reading.

It is possible that Compton's results were affected by the age of the participants, or by the fact that most of the participants were at risk for or had reading difficulties. They made a considerable number of errors on the visually confusing tasks; in other NS tasks, for instance those in the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999), performances with that many errors would have been discarded. Furthermore, grade 1 is a time when phonological processing is the strongest mediator of NS' predictive variance in reading (e.g., Georgiou, Parrila, Kirby, & Stephenson, 2008; Kirby et al., 2003; Poulsen, Juul, & Elbro, 2014), which may help to explain the relationship of the phonologically similar stimuli to reading. In the present study, we examine whether similar results can be found with older participants for whom letter recognition is automatic and orthographic processing more important (e.g., Badian, 2001; Holmes, 2009).

Another approach that could help explain the relationship between NS and reading is to analyze eye movement records collected during NS tasks and examine how they relate to overall NS and reading performance. Eye movements during NS tasks should show many of the same characteristics and group differences as in oral reading tasks, because these two tasks share many similarities (Wolf & Bowers, 1999). For example, subjects are required to move their eyes sequentially across the page in both tasks, encode the stimulus on which they are focusing, access the phonological representation of that stimulus, and then activate the associated motor instructions for naming that stimulus (Kirby et al., 2010). Given that NS total time (as well as reading) is determined by the number and duration of fixations and saccades, identifying which of these parameters are significantly related to overall naming time and reading ability could provide clues regarding the relationship between NS and reading and the differences between participants with and without reading disabilities. For example, longer fixation durations may implicate weaker orthographic processing as the basis of the relationship (Hung, 2012), whereas an increased number of saccades could implicate difficulties in eye movement control under speeded conditions (Yan, Pan, Laubrock, Kliegl, & Shu, 2013).

To our knowledge, only five studies have assessed normal and dyslexic readers' eye movements during NS tasks and they have produced mixed findings (Jones, Ashby, & Branigan, 2013; Jones, Obregón, Kelly, & Branigan, 2008; Jones, Branigan, Hatzidaki, & Obregón, 2010; Kuperman, Van Dyke, & Henry, 2012; Yan et al., 2013). This is due to several factors: first, different studies have used different research paradigms. For example, Jones et al. (2008) used the traditional NS format (4 rows × 10 stimuli; six NS cards) in which only specific pairs of letters within each NS condition (phonologically or visually similar) were scrutinized. Instead, Jones et al. (2013) used the traditional NS format (4 rows × 10 stimuli; 32 NS cards), but controlled with a display-change paradigm when the phonologically or visually similar letters appeared (parafoveally or foveally). For instance, in the visually similar condition, when a participant fixated the target item *q* (in position $n$), the visually similar letter *p* appeared in the parafovea (in position $n+1$). When the eyes shifted across an invisible boundary to the immediate right of the target letter in position $n$, the letter *p* (in position $n+1$) was replaced by a different letter (e.g., *k*). Finally, Yan et al. (2013) used a gaze-contingent paradigm in which the amount of parafoveal information was manipulated (full preview, no preview). Second, there are important differences across studies in the participant characteristics. For example, Jones et al. (2008, 2010, 2013) used English-speaking adult dyslexics and controls, Kuperman et al. (2012) adult normal readers, and Yan et al. (2013) Chinese-speaking children with and without dyslexia. Even among those studies that recruited English-speaking adult dyslexics and controls, there were important differences on the participant characteristics. For example, in Jones et al.'s (2008) study, the dyslexics differed from the controls on spoonerisms (a measure of phonological awareness) and vocabulary, but did not differ on forward and backward digit span. In contrast, in Jones et al.'s (2013) study, the two groups did not differ on spoonerisms or vocabulary, but differed on forward and backward digit span. Given that one of the questions examined in these studies was the effect of phonologically similar items on NS processing times, differences like the ones mentioned above could partly explain the conflicting findings. Finally, different studies have calculated and used different eye movement parameters, thus making it difficult to compare their results. For example, Jones et al. (2008, 2013) used the processing time (sum of all fixation durations on a letter before the eyes move away from it) and the eye–voice span (time from the onset of the first fixation on a letter to the onset of the articulation for that letter). In contrast, Yan et al. (2013) used first fixation time, first fixation duration, gaze duration, first fixation probability, landing position, and saccade amplitude.

Even when the effects of similar variables are compared, the findings vary considerably. For example, given a target letter in position $n$, Jones et al. (2008) examined the effects of presenting a phonologically or visually similar letter in the position that preceded the target letter ($n-1$) versus the position that succeeded the target letter ($n+1$). The results indicated that for normal readers the processing time was influenced by phonologically and visually similar information both preceding and succeeding the target. Dyslexic readers had longer processing times than normal readers, but they were not affected significantly by confusable information. In contrast, Jones et al. (2013) found that phonologically similar parafoveal information did not affect the processing times of either group of readers and visually similar parafoveal information increased the processing times of dyslexics only.

## The present study

The goal of the present study was to investigate how NS is related to reading, through stimulus variation and analysis of eye movements. We compared two groups of university students: a group with no known reading difficulties ($n=27$) and a group with reading difficulties ($n=20$). Three letter NS tasks were administered: the original NS task (see Denckla & Rudel, 1974) and two more that were designed to increase either phonological or visual similarity (see Compton, 2003, for these NS tasks). Based on Compton's results, we expect visual similarity to increase NS total time, but the lack of previous studies with adult participants makes it difficult to draw any firm hypotheses. With respect to eye movements, we expect normal readers to have shorter fixations and larger saccades compared to those with reading difficulties (see Kuperman et al., 2012; Yan et al., 2013, for previous findings), but both groups should have longer fixations and smaller saccades in the visually similar than in the original or phonologically similar NS tasks. In addition, we expect both fixation duration and saccade length to predict individual differences in reading. This is an important contribution of this study as none of the previous NS eye movement studies has examined the relationship of the eye movement parameters with reading.

## Method

### Participants

Two groups of students from a large Canadian university participated in the present study. The group with reading difficulties (RD) consisted of 20 adults (eight males, mean age=24.59, SD

=4.58) with a self-reported history of reading difficulties (indicated by a score higher than 0.45 on the Adult Reading History Questionnaire—Revised (ARHQ-R); Parilla et al., 2007), a reading fluency score at least 1 SD below the mean on two out of three fluency measures (sight word efficiency, phonemic decoding efficiency, and text reading speed, described in the following section), and average nonverbal cognitive ability (indicated by a score higher than 21 on matrix reasoning). The RD participants were recruited through poster advertisements on campus or through the Specialized Support and Disability Services Centre of the university and received $20 for their participation. The group with no reading difficulties (NRD) consisted of 27 adults (nine males, mean age=21.52, SD=2.54) with no self-reported history of reading difficulties (indicated by a score lower than 0.28 on ARHQ-R), high reading fluency scores, and average performance on nonverbal cognitive ability (see Table 1, for descriptive statistics on the screening measures). The NRD participants were recruited from a participant pool program and received credit towards a course for their participation in the study. All participants reported English as their first language and had normal or corrected-to-normal vision. Written consent was obtained prior to testing.

## Measures

*Adult reading history questionnaire—revised* (ARHQ-R; Parilla et al., 2007). The ARHQ-R is based on the Adult Reading History Questionnaire developed by Lefly and Pennington (2000). In the ARHQ-R, respondents are asked about their reading and spelling ability, reading speed, attitudes toward school and reading, additional assistance they received, repeating grades or courses, effort required to succeed, and print exposure separately for elementary school, secondary school, and post-secondary education. Only the questions from the elementary school section were used in this study. Participants responded on a Likert scale from 0 to 4, and their scores were calculated by totaling the points on the eight elementary scale items and then dividing by the maximum possible score (8×4=32). Scores could range from a low of 0 to a high of 1, a low score indicating less difficulty. Cronbach's alpha reliability in our sample was 0.96 (see also Deacon, Cook, & Parrila, 2012, for validity evidence).

*Matrix reasoning* The matrix reasoning task was adopted from Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) to assess nonverbal intelligence. It contains 35 incomplete visual patterns that individuals complete using one of five choices of visual pattern

**Table 1** Descriptive statistics

| | NRD group (*n*=27) | | RD group (*n*=20) | |
|---|---|---|---|---|
| | M | SD | M | SD |
| Sight word efficiency | 98.07 | 6.90 | 85.85 | 7.62 |
| Phonemic decoding efficiency | 59.15 | 3.98 | 41.95 | 9.20 |
| Text reading speed | 2.84 | 0.23 | 2.01 | 0.34 |
| Phoneme elision | 15.44 | 1.40 | 12.60 | 2.62 |
| Phonological choice RT | 1642.08 | 354.12 | 2618.67 | 782.84 |
| Matrix reasoning | 27.15 | 2.96 | 28.45 | 3.19 |

*NRD* no reading difficulties, *RD* reading difficulties, *RT* response time (milliseconds) pieces. Participants were asked to point to or say the number of their choice. Following standardized administration procedures, testing began from item 7 for all participants and ended on the very last item or after four response errors on five consecutive items. Cronbach's alpha reliability in our sample was 0.90.

*Phoneme elision* The phoneme elision task was adopted from CTOPP (Wagner et al., 1999) to assess phonological awareness. Testing began from item 13 for all participants and ended on the very last item (29) or after three consecutive errors. The participants were presented with a word orally through the speakers of a laptop computer, asked to repeat it, and then asked to say the word again after omitting a given sound. Cronbach's alpha reliability coefficient in our sample was 0.81.

*Phonological choice* This task was adopted from Parilla et al. (2007) to measure the speed of access to phonological representations. A pair of pseudowords was presented one at a time juxtaposed on a computer screen. The participants were asked to select one of the pseudowords in each pair that when read out loud would sound like a real word (e.g., fite–fipe). The participants responded to each item as fast as possible by pressing the button of their choice (left or right Alt). The task contained 20 pairs of pseudowords presented in random order. Reaction times on each item were recorded and the mean response time for the correct items was calculated and used as the participants' score. Cronbach's alpha reliability coefficient in our sample was 0.75.

*Letter naming speed* Participants performed three NS tasks—the original letter NS task developed by Denckla and Rudel (1974) with the letters *a*, *d*, *o*, *p*, *s*, and two of Compton's (2003) adaptations of this task, one designed to increase visual similarity (*o* replaced by *q*) and the other to increase phonological similarity (*o* replaced by *v*). Prior to each timed item, participants named the same five letters on a practice trial to ensure familiarity. Each NS task presented 50 letters, ten repetitions of the five letters. Participants were instructed to name all the letters as fast as possible, from left to right starting at the top row, and their response times and errors were recorded. There were very few errors (the mean was less than 1) and so they were ignored. The participants' NS scores were the times taken to name all the letters on each display. Wolf and Denckla (2005) reported test–retest reliability to be 0.92 across ages.

The NS stimuli were presented on a computer screen in Arial 40 point font and head-mounted infrared cameras (Eyelink II, SR Research Ltd.) were used to track vertical and horizontal binocular eye positions with a sampling rate of 500 Hz and average gaze position error of less than 0.5°. Participants sat approximately 60 cm from the screen, wore the head-mount securely on their heads, and were requested to remain as still as possible during testing. The experiment began with the adjustment of the infrared cameras attached to the eye tracker, followed by a brief calibration procedure and drift correction between the NS tasks. The eye movements of each participant were calibrated using nine on screen targets (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 to validate that the average error between fixation and target was <2° and that no loss of eye tracking occurred. Fixation durations, saccade size, and the number of saccades and fixations were recorded.

*Sight word efficiency* Form A from the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999) was used. After an eight-word practice list, participants were shown a list of 104 words, in four columns of 26 words each, and asked to read them as quickly as possible. The score was the number of words read correctly in 45 s. Torgesen et al. (1999) reported test–retest reliability coefficients ranging from 0.82 to 0.87.

*Phonemic decoding efficiency* This test was also adopted from TOWRE (Torgesen et al., 1999). After an eight-pseudoword practice list, participants were shown a list of 63 pseudowords and asked to read them out loud as fast as possible. The participants' score was the number of pseudowords read correctly within 45 s. Torgesen et al. (1999) reported test–retest reliability coefficients ranging from 0.91 to 0.94.

*Text reading speed* Participants were asked to read aloud two passages (nine and 14 from the Gray Oral Reading Test; Wiederholt & Bryant, 2001). The experimenter recorded the time taken to read each passage (in seconds) and deviations from print. For the purpose of our study, the text reading speed score was the number of words read correctly in the two passages divided by the time taken to read the passages. The internal consistency reliability coefficient for reading rate on Form A is 0.96 (Wiederholt & Bryant, 2001).

### Procedure

Tasks were administered in two sessions, each lasting approximately an hour. In session A, the participants completed the ARHQ-R questionnaire and were also assessed on word reading efficiency, phonemic decoding efficiency, text reading speed, phoneme elision, and phonological choice. In session B, they were assessed on the three NS tasks and on matrix reasoning. The testing was conducted in a quiet room at the university by the third author.

### Data analysis

For the eye tracking data the variables of interest were: fixation durations, saccade size, and the numbers of saccades and fixations. To calculate the eye-tracking measures we took into account all eye movements, both forward and regressive. Fixation duration was defined as the average duration (in milliseconds) of all fixations in the trial. Saccade size was defined as the average size (in degrees of visual angle) of all saccades in the trial. The cutoffs for determining both the onset and termination of a saccade were determined by using the saccade parameters of velocity threshold, 30 degrees/s, and acceleration threshold, 8,000 degrees/$s^2$. When the parameters were above these thresholds, the beginning of a saccade was marked, and when they dropped below these thresholds, the end of a saccade was marked.

## Results

### Preliminary analyses

The descriptive statistics for the screening measures as well as for phoneme elision and phonological choice are presented in Table 1 separately for each group. A MANOVA with the reading fluency measures as dependent variables and group as a between-subjects factor revealed a main effect of group, Wilk's $\lambda=0.32$, $F(4,180)=18.33$, $p<0.001$. Subsequent univariate ANOVAs showed that the NRD group performed significantly better than the RD group on each reading fluency measure (sight word efficiency: $F(1,46)=32.98$, $p<0.001$; phonemic decoding efficiency: $F(1,46)=75.69$, $p<0.001$; and text reading speed: $F(1,46)=97.73$, $p<0.001$). Similar results were found for phoneme elision ($F(1,46)=23.05$, $p<0.001$) and phonological choice ($F(1,46)=33.08$, $p<0.001$). Finally, the two groups did not differ on matrix reasoning, $F(1,46)=2.09$, ns.

## NS performance and eye movements

The descriptive statistics for the three NS tasks are shown in Table 2. A 2 (group) × 3 (NS task) mixed analysis of variance indicated that the NRD group was faster in naming time than the RD group, $F(1,46)=26.28$, $p<0.001$, $d=0.37$, but neither the effect of NS task nor its interaction with group was significant (both *p*s>0.15).

Table 2 also shows the descriptive statistics for the eye movement parameters during the NS tasks. A series of group×NS task mixed analyses of variance, one for each eye movement variable, showed significant group effects for fixation duration, $F(1,46)=13.37$, $p<0.001$, $d=0.23$, fixation count, $F(1,46)=14.78$, $p<0.001$, $d=0.25$, saccade size, $F(1,46)=5.18$, $p<0.05$, $d=0.03$, and saccade count, $F(1,46)=14.89$, $p<0.001$, $d=0.25$. The NRD group had shorter fixation durations, larger saccade sizes, and fewer saccades and fixations than the RD group. Although there was no significant NS task effect on fixation duration or saccade size (both *p*s >0.50), there was a significant NS task effect on fixation count, $F(2,90)=3.90$, $p=0.024$, Wilk's $\lambda=0.97$, $d=0.08$, and the effect for saccade count approached significance, $F(2,90)=3.02$, $p=0.054$, Wilk's $\lambda=0.97$, $d=0.06$. Follow-up paired-sample *t* tests indicated that there was a higher number of fixations and saccades in the visually confusing task than in the original task; for fixation count, $t(46)=2.91$, $p=0.006$ and for saccade count, $t(46)=2.51$, $p=0.02$. None of the group × NS task interaction effects was significant (all *p*s>0.30).

## Correlations between NS times, eye movement parameters, and reading outcomes

Table 3 presents the correlations between the NS total times, the eye movement parameters, and the reading outcomes. In both groups, the total times of all three NS tasks correlated significantly with sight word efficiency and text reading speed. The total time in the original NS task also correlated significantly with phonemic decoding efficiency. In terms of the eye movement parameters, fixation duration correlated significantly and negatively with sight word efficiency and text reading speed in both groups of readers. Fixation count and saccade count correlated significantly and negatively with sight word efficiency (irrespective of the NS tasks) and text reading speed (only in the original task), but only in the NRD group. Finally, saccade size in the original and visually confusing tasks correlated significantly and positively with sight word efficiency, but only in the NRD group. When we compared the size of the

**Table 2** Descriptive statistics of naming times and eye movement measures

| | NRD group (*n*=27) | | | | | | RD group (*n*=20) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | OR | | PC | | VC | | OR | | PC | | VC | |
| | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD |
| NS total time | 17.81 | 3.15 | 18.15 | 2.92 | 18.53 | 3.54 | 22.76 | 3.38 | 22.77 | 3.32 | 23.22 | 4.26 |
| Fixation duration | 0.26 | 0.03 | 0.26 | 0.03 | 0.26 | 0.04 | 0.31 | 0.05 | 0.31 | 0.05 | 0.30 | 0.05 |
| Fixation count | 61.00 | 6.55 | 62.37 | 5.42 | 63.00 | 6.46 | 68.15 | 6.51 | 68.00 | 7.14 | 70.05 | 6.90 |
| Saccade size | 2.08 | 0.29 | 2.10 | 0.33 | 2.09 | 0.31 | 1.92 | 0.27 | 1.89 | 0.25 | 1.89 | 0.28 |
| Saccade count | 60.30 | 6.63 | 61.48 | 5.28 | 62.04 | 6.55 | 67.50 | 6.65 | 67.20 | 7.00 | 69.10 | 6.85 |

NS total time and fixation duration are measured in seconds. Saccade size is measured in degrees

*NRD* no reading difficulties, *RD* reading difficulties, *OR* original NS task, *PC* phonologically confusing NS task, *VC* visually confusing NS task

**Table 3** Correlations between the eye movement measures and reading

| | | NRD group ($n$=27) | | | RD group ($n$=20) | | |
|---|---|---|---|---|---|---|---|
| | | Sight word efficiency | Phonemic decoding efficiency | Text reading speed | Sight word efficiency | Phonemic decoding efficiency | Text reading speed |
| OR | Time | −0.73** | −0.41* | −0.58** | −0.64** | −0.48* | −0.62** |
| | FD | −0.72** | −0.35 | −0.43* | −0.47* | −0.44* | −0.52* |
| | FC | −0.40* | −0.27 | −0.45* | −0.19 | −0.03 | −0.10 |
| | SS | 0.46* | −0.13 | −0.10 | 0.09 | −0.53* | 0.23 |
| | SC | −0.41* | −0.25 | −0.44* | −0.19 | −0.03 | −0.09 |
| PC | Time | −0.72** | −0.23 | −0.47* | −0.68** | −0.18 | −0.57** |
| | FD | −0.65** | −0.26 | −0.40* | −0.57** | −0.24 | −0.53* |
| | FC | −0.47* | −0.02 | −0.37 | −0.15 | 0.07 | −0.04 |
| | SS | 0.32 | −0.32 | −0.08 | 0.06 | 0.28 | 0.16 |
| | SC | −0.45* | −0.03 | −0.33 | −0.15 | 0.09 | −0.04 |
| VC | Time | −0.74** | −0.30 | −0.50** | −0.74** | −0.40 | −0.53* |
| | FD | −0.68** | −0.32 | −0.39* | −0.67** | −0.48* | −0.59** |
| | FC | −0.41* | −0.11 | −0.37 | −0.34 | −0.05 | −0.09 |
| | SS | 0.40* | −0.15 | −0.13 | 0.03 | 0.42 | 0.20 |
| | SC | −0.42* | −0.11 | −0.38 | −0.33 | −0.05 | −0.09 |

*NRD* no reading difficulties, *RD* reading difficulties, *OR* original NS task, *PC* phonologically confusing NS task, *VC* visually confusing NS task, *FD* fixation duration, *SS* saccade size, *FC* fixation count, *SC* saccade count

*$p<0.05$; **$p<0.01$

correlations between the eye movement parameters and reading across the three NS tasks separately for each group, we found only one significant difference in the RD group. Specifically, the correlation between saccade size and phonemic decoding efficiency was stronger in the original condition than in the phonologically confusing condition (Steiger's $z$ =2.07, $p<0.05$).

## Prediction of reading ability

To investigate the relationships among the eye movement parameters and reading ability, three series of regression analyses were carried out using the pooled sample, one for each of the reading measures. Each of the regression models included (a) phoneme elision and phonological choice, to ensure that any effects of the NS eye movement parameters were not due to phonological awareness or speed of access to phonological codes, and (b) three eye movement parameters (fixation duration, saccade size, and saccade count). Fixation count was not included because it correlated strongly with saccade count ($r$=0.99). For each of the outcome variables, separate analyses were carried out for each of the three NS tasks. Standardized beta coefficients, level of significance, and total amount of variance explained are presented in Table 4.

The results were largely consistent across the NS tasks, but varied by outcome measure. Considerable variance in sight word efficiency, phoneme decoding efficiency, and text reading speed was predicted, with $R^2$ values ranging from 0.69 to 0.82. Phoneme elision and phonological choice had their greatest effect on phonemic decoding efficiency, a test of pseudoword reading. Of the eye movement parameters, fixation duration predicted

**Table 4** Results of regression analyses

| | Sight word efficiency | | | Phonemic decoding efficiency | | | Text reading speed | | |
|---|---|---|---|---|---|---|---|---|---|
| Predictor variables | OR | PC | VC | OR | PC | VC | OR | PC | VC |
| Phoneme elision | −0.08 | 0.01 | −0.09 | 0.54*** | 0.60*** | 0.58*** | 0.18* | 0.23* | 0.21* |
| Phonological choice | −0.21* | −0.16 | −0.26** | −0.35*** | −0.37*** | −0.39*** | −0.45*** | −0.45*** | −0.52*** |
| Fixation duration | −0.60*** | −0.61*** | −0.58*** | −0.31*** | −0.21* | −0.24** | −0.46*** | −0.39*** | −0.34*** |
| Fixation count | −0.36** | −0.32** | −0.32*** | −0.11 | −0.06 | −0.05 | −0.27** | −0.19 | −0.20* |
| Saccade size | 0.03 | 0.01 | 0.06 | −0.07 | −0.08 | −0.08 | −0.16 | −0.07 | −0.10 |
| Total $R^2$ | 0.70 | 0.68 | 0.74 | 0.82 | 0.78 | 0.80 | 0.80 | 0.75 | 0.75 |

*OR* original NS task, *PC* phonologically confusing NS task, *VC* visually confusing NS task

$N$=47

*$p$<0.05; **$p$<0.01; ***$p$<0.001

significantly all three reading outcomes and saccade count predicted significantly sight word efficiency and text reading speed.

## Discussion

Although NS tasks have been used for several decades to predict reading ability, there is still considerable controversy over what NS measures and why it is related to reading ability (Kirby et al., 2010). Elucidating the processes that underlie efficient NS performance could enhance our understanding of the factors that determine fluent reading and shed light on the nature of dyslexic readers' difficulties. We used two techniques to illuminate the relationship between NS and reading fluency: variation in stimulus composition (based on Compton, 2003) and measurement of eye movements during the NS tasks. The latter is particularly important in light of findings that NS is more strongly related to reading when the stimuli are presented simultaneously than when presented in discrete fashion (Bowers & Swanson, 1991; Georgiou, Parrila, Cui, & Papadopoulos, 2013). This suggests that the key determinant of efficient NS performance and subsequently reading fluency may be the way individuals process foveal and parafoveal information (Jones et al., 2008, 2013; Yan et al., 2013). Our participants were university students, so the students with reading difficulties could be assumed to have developed some coping mechanisms to deal with the increased reading demands of their programs. However, the two groups of students differed on all reading measures. In what follows, we discuss first the effects of stimulus variations and then those of the eye movement parameters.

### NS stimulus variations

The NRD group was faster to name the stimuli in the NS tasks than the RD group. Although both groups were faster on the original task and slower on the visually similar task, as has been found before (Compton, 2003), this difference did not attain significance and neither did the interactions between group and task. The trend suggests that naming times are more a function of the visual similarity of the letters, and not the phonological similarity, however a larger study may be required to find reliable differences. In addition, no differences were found between the three NS tasks when we compared the strength of their correlations with reading (a similar non-significant difference between the correlations can be found in Compton's, 2003, study). This would imply that the underlying mechanism responsible for the NS–reading relationship is independent of the manipulations used in the NS tasks.

### Eye movement parameters

The groups differed on each of the eye movement parameters that we assessed: students without reading difficulties had shorter fixation durations, larger saccade size, and fewer saccades and fixations than those with reading difficulties. These findings are similar to those of previous studies that measured fixation durations (e.g., Jones et al., 2008; Kuperman et al., 2012; Yan et al., 2013) and saccade size (Yan et al., 2013). The lack of significant interactions between group and task for any of the eye movement parameters suggests that the item composition of the NS tasks did not have a differential impact on the processing times of the students with reading difficulties. Thus, we may conclude that it is not the characteristics of the items included in the letter naming task that matter for NS performance, but the process of translating the visual stimuli to their phonological representations (indexed by the prolonged fixation times of the students with reading difficulties). Longer fixation durations suggest that the students with reading difficulties require more time than their normally achieving peers to acquire the same amount of information. On the other hand, shorter and more frequent saccades in the very constrained NS task suggest that the students with reading difficulties have either less efficient processing during the fixations (see Jones et al., 2008, for a similar argument) or less efficient parafoveal processing (see Yan et al., 2013, for a similar argument).

### Eye movement parameters and reading

Despite the significant group differences on all eye movement parameters, only fixation duration predicted each of the reading outcomes. This finding suggests that whereas several factors may contribute to NS performance, fixation duration is most closely associated with individual differences in reading fluency. Given that its effect was independent of phonological processing (operationalized by phoneme elision and phonological choice), access to phonological representations is likely not the critical component underlying the NS–reading relationship (see also Georgiou et al., 2013). The effects of fixation duration in the regression analyses are consistent with the group differences on the same measure (see Table 2) and suggest that the greater time needed to acquire or encode the stimulus information is an important factor in the NS–reading relationship. This finding reinforces the argument put forward by Yan et al. (2013) that the observed advantage of normal readers in parafoveal processing is a result of their more automatic foveal processing (indexed by shorter fixation durations) which allows more attentional resources to be devoted to parafoveal processing. A second, but weaker, effect on two of the outcome measures was for the number of saccades; this too may be due to inefficient parafoveal processing.

### Limitations of the study

Some limitations of the present study are worth mentioning. First, we used phonological choice as an index of the speed of access to phonological representations. Given that performance on this task is mediated by letter–phoneme correspondence ability, it may be an inadequate measure of speed of access to phonological representations. Second, because the three NS tasks differed in only one letter (*q* substituted *o* in the visually confusing condition and *v* substituted *o* in the phonologically confusing condition), this may have reduced our chances to find significant differences across tasks. Finally, our sample size was relatively small and consisted of young adults. Future studies should replicate our findings with a larger sample and with children.

## Conclusion

Our findings add to a growing number of studies examining the underlying mechanism of the relationship between NS and reading (e.g., de Jong, 2011; Georgiou et al., 2013; Jones et al., 2013; Protopapas, Altani, & Georgiou, 2013; Yan et al., 2013; Zoccolotti et al., 2014). Although we did not manipulate the amount or kind of information available to the readers during the NS tasks (see Jones et al., 2013; Yan et al., 2013, for this kind of manipulation), we were able to replicate the findings of previous studies showing that adults with reading difficulties have longer fixation durations and smaller saccade sizes than normal readers (Jones et al., 2008; Kuperman et al., 2012; Yan et al., 2013) and to specify the eye movement parameter (fixation duration) that contributes most to the NS–reading relationship. The composition of NS tasks did not have an impact on the observed differences between the two groups on the eye movement parameters and their relationship with reading, which suggests that the mechanism underlying the NS–reading relationship is not dependent upon the characteristics of the stimuli. We conclude that the relationship between NS and reading is due to two factors: first, the longer fixation durations of less able readers, indicating that they require more time to acquire the same amount of information, and second, the greater number of saccades that less able readers make during the NS task.

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