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To cite this article: Susana Araújo, Falk Huettig & Antje S. Meyer (2021) What Underlies the Deficit in Rapid Automated Naming (RAN) in Adults with Dyslexia? Evidence from Eye Movements, *Scientific Studies of Reading*, 25:6, 534-549, DOI: [10.1080/10888438.2020.1867863](https://doi.org/10.1080/10888438.2020.1867863)

To link to this article: <https://doi.org/10.1080/10888438.2020.1867863>



Published online: 30 Dec 2020.



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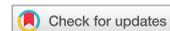
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# What Underlies the Deficit in Rapid Automatized Naming (RAN) in Adults with Dyslexia? Evidence from Eye Movements

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## ABSTRACT

This eye-tracking study explored how phonological encoding and speech production planning for successive words are coordinated in adult readers with dyslexia ( $N = 22$ ) and control readers ( $N = 25$ ) during *rapid automatized naming* (RAN). Using an object-RAN task, we orthogonally manipulated the word-form frequency and phonological neighborhood density of the object names and assessed the effects on speech and eye movements and their temporal coordination. In both groups, there was a significant interaction between word frequency and neighborhood density: shorter fixations for dense than for sparse neighborhoods were observed for low- but not for high-frequency words. This finding does not suggest a specific difficulty in lexical phonological access in dyslexia. However, in readers with dyslexia only, these lexical effects percolated to the late processing stages, indicated by longer offset eye-speech lags. We close by discussing potential reasons for this finding, including suboptimal specification of phonological representations and deficits in attention control or in multi-item coordination.

## Introduction

Developmental dyslexia, which is a persistent reading disorder despite adequate intelligence and no general learning problem (Peterson & Pennington, 2015), is primarily attributed to a phonological processing deficit (Ramus, 2003; Saksida et al., 2016). Some work suggests that the source of phonological problems lies in a poor specification of speech sound representations (Metsala, 1997b; Swan & Goswami, 1997a, 1997b; Vellutino, Fletcher, Snowling, & Scanlon, 2004) or/and in a problem of access to these representations (Boets et al., 2013; Ramus, 2014; Ramus & Szenkovits, 2008). Both possibilities may explain the well-documented difficulties that dyslexic readers experience in tasks of visual naming in addition to their difficulties with reading (for an overview, Araújo & Faísca, 2019). For example, children and adults with dyslexia show impairments in rapid automatized naming (RAN) in which a series of letters, digits, objects, or colors are to be named sequentially as quickly as possible (Denckla & Rudel, 1976). The goal of the present paper was to contribute to a better understanding of the origin of this deficit.

RAN measures the automaticity with which familiar visual stimuli can be retrieved and named and is a powerful predictor of reading ability and dyslexia across developmental stages and languages (Araújo & Faísca, 2019; Araújo, Reis, Petersson, & Faísca, 2015, 2019; Landerl et al., 2013). Reading fluency is often predicted by RAN performance beyond other measures of reading subskills, including phonological awareness and short-term memory, letter knowledge, and vocabulary (e.g., Caravolas, Lervåg, Defior, Málková, & Hulme, 2013; Georgiou, Parrila, & Liao, 2008; Georgiou, Parrila, &

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Papadopoulos, 2008; Parrila, Kirby, & McQuarrie, 2004). A recent meta-analysis confirmed a large impairment in RAN performance in individuals with dyslexia compared to age-matched control readers ( $d = 1.19$ ). The groups differ significantly even with nonalphanumeric stimuli (Araújo & Faisca, 2019). Hence, this impairment is unlikely to be driven merely by decreased automaticity of letter processing. Notably, in adults with dyslexia, the RAN deficit might become even more prominent than residual deficits in other core cognitive skills, such as phonological awareness (e.g., Fernandes, Araújo, Sucena, Reis, & Castro, 2017; Swanson & Hsieh, 2009).

The perceptual and cognitive mechanisms underlying RAN and reading performance are largely shared (from visual object recognition to speech production processes); hence, RAN is interpreted “as a microcosm of the reading system” (Norton & Wolf, 2012, p. 448) that provides a means to index literacy skills. The connection of RAN to phonological processing has received considerable attention, with some researchers suggesting that RAN performance reflects the (in)efficiency in the access to and retrieval of phonological codes from long-term memory (Clarke, Hulme, & Snowling, 2005; Lervåg & Hulme, 2009; Pennington, Cardoso-Martins, Green, & Lefly, 2001; Torgesen, Wagner, & Rashotte, 1994). This view is compatible with the finding that dyslexic readers often display phonological impairment (Ramus, 2003; Saksida et al., 2016).

The results have shown that RAN performance and phonological processing skills are often moderately correlated (e.g., Savage, Pillay, & Melidona, 2007; Schatschneider, Carlson, Francis, Foorman, & Fletcher, 2002). Alternative accounts have been proposed to explain the RAN-reading relationship: it has been hypothesized that RAN is associated with reading via orthographic processing (e.g., Bowers & Newby-Clark, 2002; Bowers & Wolf, 1993) or because both draw upon a domain-general speed-of-processing factor (Kail & Hall, 1994; Kail, Hall, & Caskey, 1999) and rely on the automation or efficiency of translating print to sound (Pan, Yan, Laubrock, Shu, & Kliegl, 2013), among other interpretations and factors (for a discussion see Georgiou & Parrila, 2013).

An interesting finding is that readers with dyslexia perform worse on RAN than one might predict on the basis of their performance on simple confrontation naming with stimuli presented one by one (Araújo & Faisca, 2019; Jones, Branigan, & Kelly, 2009; Zoccolotti et al., 2013). It is not clear why this is the case. Simple confrontation naming and RAN share that items need to be recognized and named. Sequential RAN, furthermore, involves coordinating rapid serial eye movements and speech production planning processes of successive items (Gordon & Hoedemaker, 2016; Henry, Van Dyke, & Kuperman, 2018; Kuperman, Van Dyke, & Henry, 2016; Protopapas, Katopodi, Altani, & Georgiou, 2018). Apparently, the specific requirement of multiple object naming (rather than word naming, as in reading aloud) poses a specific challenge for persons with dyslexia.

In this study, we explored whether and how the coordination of lexical access to the item names on the one hand and speech production planning on the other hand differed for persons with and without dyslexia, and consequently, affected RAN. To do so, we measured dyslexic and control adults' eye movements during RAN with objects. Eye movements provide a sensitive measure of ongoing information uptake and encoding to the level of phonological form (e.g., Griffin, 2004; Griffin & Bock, 2000). How long participants spend looking at a target before moving on to the next item, the *gaze duration*, has been associated with recognition processes up to and including activation of phonological codes (Griffin, 2001, 2004). Performance on oral reading and RAN tasks can also be examined in terms of the efficiency with which the individual coordinates in time the eye movements and vocalization, as measured by *eye-voice span* – *EVS* (see Gordon & Hoedemaker, 2016). The *EVS* refers to the temporal (e.g., Jones, Ashby, & Branigan, 2013; Jones, Branigan, Hatzidaki, & Obregón, 2010) or spatial (e.g., Pan et al., 2013) distance from the onset of viewing a target to the execution of the verbal response. In naming tasks, it is ~250 ms longer than gaze duration, and thus *EVS* is thought to incorporate later processes in addition to identification and lexical access, specifically the programming of to-be-articulated speech (Inhoff, Solomon, Radach, & Seymour, 2011; Jones, Obregón, Kelly, & Branigan, 2008) and working memory processes operating on phonological representations (i.e., output phonological buffer; Laubrock & Kliegl, 2015). Gordon and Hoedemaker (2016) recent work

emphasized that having the eyes sufficiently far ahead of the voice is helpful for fluency because upcoming items in RAN can be encoded for articulation without delays.

To date, there are few studies that have measured dyslexic readers' eye movements during RAN tasks and involved the in-depth analysis of these early and late measures. Jones and colleagues' work (2008), for example, found that readers with dyslexia did not differ from control readers in gaze duration during RAN with letters overall, but readers with dyslexia showed longer time-based EVSs in response to hard items. Specifically, dyslexic readers were significantly slower to initiate articulation when the target letter shared the phonological onset with the preceding or following letter in the array (are "confusable", as in *k* and *q*) compared to nondyslexic readers and their own performance on nonconfusable letters (see also Jones et al., 2013). In another study, lexical competition effects were assessed in a RAN Stroop paradigm using color letters and color unknown symbols (baseline) (Jones, Snowling, & Moll, 2016). Both the control and dyslexic groups showed a classic Stroop effect, with longer gaze durations for color than letter naming. The dyslexic readers were relatively more impaired in EVSs than the control readers, which the authors attributed to their more effortful phonemic computation for output or possibly a deficit in suppressing the phonological response once it is active. However, Pan and colleagues' study (2013) did not support this interpretation. They observed that differences in (spatial) EVS between dyslexic and nondyslexic children were greater for digit RAN than for the rapid naming of dice surfaces, with identical phonological output demands. The former can be assumed to be much more practiced than naming dice. Thus, the authors interpreted the EVS during RAN as a measure of automaticity in print-to-sound conversion, which is affected in dyslexia. Another possibility is that slower RAN is a consequence of automatization of suboptimally developed coordination between the skills required for this conversion routine (see Lachmann, 2018). Moreover, dyslexic readers showed longer EVS even in object categorization (Jones et al., 2010; Experiment 2). This result is at odds with the idea of a selective impairment in output phonology.

The goal of the current study was to obtain additional evidence on how phonological encoding and speech production planning for successive words are coordinated in dyslexic and control adult readers during an object-RAN task. We created easy and difficult items by orthogonally varying *word-form frequency* (high vs. low) and *neighborhood density* (the phonological similarity between words) and examined effects on speech and eye movements and their temporal coordination. These two properties of words are thought to reflect how lexical information is acquired, represented, and accessed (e.g., Metsala & Walley, 1998; Storkel, 2002; Ziegler & Goswami, 2005), and as such, they are acknowledged in most theories of speech perception and production. Surprisingly, very few studies have explored phonological neighborhood effects as a function of reading expertise, and to the best of our knowledge, none has looked at these effects in production. In spoken word recognition, overall group differences between dyslexic and normal readers were not always observed. Using a gating task, Metsala (1997b) found that dyslexic children needed more gates than controls, particularly to identify words in sparse neighborhoods, and Griffiths and Snowling (2001) found no group differences (see also Ziegler & Muneaux, 2007). In turn, dyslexic children have been shown to be particularly poor at naming pictures that have low-frequency names (in confrontation naming: Goswami, Schneider, & Scheurich, 1999; Swan & Goswami, 1997b). In this study, we thus asked whether people with dyslexia show the same or exaggerated effects of these variables on RAN performance. We recognize that the RAN material used here is somewhat atypical but was chosen to suit our purposes. By using an experimental manipulation, we expected to capture (subtle) underlying effects that traditional RAN paradigms may miss.

A second innovative aspect in this experiment was that we measured the lag from the offset of the last look to the object (temporal *offset-EVS*), which is the moment when attention shifts away from it. Viewing offset times is temporally aligned with articulating the object name (e.g., Bock, Irwin, Davidson, & Levelt, 2003; Griffin & Bock, 2000). This is an important contrast with the usual definition of onset-EVS, which refers to the time between the onset of first fixation on an item and the onset of speech (e.g., Jones et al., 2008, 2016). This onset-EVS provides a measure of the efficiency of *all* stages of cognitive processing and articulatory planning required to identify and to produce the stimulus

name. Here, we used offset-EVS because it is a tighter measure of the speaker's temporal coordination of planning and speaking.

It has been shown that gaze durations and naming latencies to individual words and objects are modulated by local processing difficulties, stemming from the printed frequency of words and their phonological similarity to other words in the mental lexicon (e.g., Griffin, 2001; Meyer, Sleiderink, & Levelt, 1998; Yates, Friend, & Ploetz, 2008). Objects with high-frequency names are fixated for less time and are named faster than objects with low-frequency names (Jescheniak & Levelt, 1994; Meyer et al., 1998). The effect of phonological neighborhood density has been more volatile in speech production (Chen & Mirman, 2012; Newman & German, 2005; Perea, 2015; Sadat, Martin, Costa, & Alario, 2014). However, some studies found an advantage of items from *dense* over *sparse* neighborhoods (i.e., with many rather than few phonological neighbors, respectively) in discrete naming times (for a review, see Vitevitch & Luce, 2016).

Our first aim was to replicate these effects of frequency and neighborhood density. This is important in its own right. The hypothesized facilitative effect of high neighborhood density on spoken word production would provide support for Dell's interactive model of lexical access and retrieval (e.g., Dell & Gordon, 2003; Dell, Schwartz, Martin, Saffran, & Gagnon, 1997). According to this model, in production, words with many neighbors may benefit from a boost of activation within the phonological system because for these words many shared phonological representations send feedback that contributes to activating the word to be produced. Hence, the effects of phonological neighborhood should parallel those of word frequency because both affect the speed of word-form retrieval at the lexical level (Andrews, 1989; Jescheniak & Levelt, 1994; Levelt, 2001; Meyer et al., 1998; however, see also Kittredge, Dell, Verkuilen, & Schwartz, 2008; Mousikou & Rastle, 2015).

We thus hypothesized that in the control readers, word frequency and neighborhood density will affect gaze durations but, to a lesser extent, the offset-eye-voice lag. This outcome would indicate that articulatory preparation for the name of object  $n$  is independent of access to the name of object  $n + 1$ . It would also confirm that speakers time the shifts of gaze to occur after phonological encoding of the current object name has been completed (e.g., Meyer et al., 1998; Meyer, Wheeldon, van der Meulen, & Konopka, 2012). Our main second aim was to explore how the variables would affect eye gaze and EVS in participants with dyslexia. If the RAN processes operate in a similar way for typically developing readers and readers with dyslexia, then we should find the same effects in both groups. It is also possible that frequency and neighborhood effects percolate to articulatory preparation to a greater extent in dyslexic readers, signaled by longer offset EVS, especially in words with low frequency and words from sparse neighborhoods. This would suggest that in multiple object naming tasks, dyslexic readers might use different planning strategies and need more time to plan the object's name. This confirmation in turn would contribute to our understanding of why the RAN task is so challenging for this group of participants.

## Materials and methods

### Participants

Twenty-two adults with developmental dyslexia (16 women;  $Mage = 21.7$  yrs,  $SD = 2.6$ ) and 25 control readers (17 women;  $Mage = 21.4$  yrs,  $SD = 2.8$ ) matched on age, years of education, and nonverbal IQ (Matrix Reasoning subtest from the WAIS-IV; Wechsler, 2012) participated in this study. They were all undergraduate students and native speakers of Dutch, who had normal or corrected-to-normal vision and did not report neurological diseases or psychiatric disorders. All participants were recruited through the participant panel of the Max Planck Institute for Psycholinguistics. Participants in the dyslexic group had received a formal dyslexia diagnosis by a specialized therapist during their childhood/adolescence and still presented a reading level  $\leq 10^{\text{th}}$  percentile of the age norms of the GL&SCHR text reading (from the standardized Dutch reading and writing test battery for dyslexia diagnosis in adolescents and adults; De Pessemier & Andries, 2009). In addition, they all had normal-

range nonverbal IQ ( $\geq 7$  standardized score on the Matrix Reasoning of the WAIS-IV), while scoring significantly below the control group on reading fluency for single words (Een Minuut Test: Brus & Voeten, 1973) and nonwords (Klepel test: Van den Bos, Spelberg, Scheepstra, & de Vries, 1994), on phonological working memory (Digit Span: forward and backward repetition of a sequence of digits; WAIS-IV) and on phonological awareness (Word reversal task: requires deciding whether two spoken words are reversals or not, e.g., rac-car; GL&SCHR battery). Participants assigned to the control group had no history of reading and/or spelling problems and exhibited word reading scores in the normal range (GL&SCHR text reading  $\geq 30^{\text{th}}$  percentile). The mean performance of both groups on cognitive and literacy measures can be seen in Table 1.

The study was approved by the Ethics Board of the Social Sciences Faculty of Radboud University in Nijmegen and followed guidelines of the Helsinki declaration. All participants gave written informed consent and were paid for compensation.

### Materials and design

The object-RAN task was based on the original RAN paradigm (Denckla & Rudel, 1976). Line drawings of 20 objects were selected from the picture database developed at the Max Planck Institute for Psycholinguistics in Nijmegen, the Netherlands, according to the 2 Word-form frequency (high vs. low)  $\times$  2 Phonological neighborhood density (dense vs. sparse) of objects' names. Neighborhood density was operationalized as the number of words that differ in one phoneme by addition, deletion, or substitution (for a review, see Vitevitch & Luce, 2016). The four experimental conditions differed in frequency of occurrence (M: 109 vs. 4 per million words for high-frequency vs. low-frequency; SUBTLEX database; Keuleers, Brysbaert, & New, 2010) and neighborhood density (M: 24 vs. 9 neighbors for dense vs. sparse neighborhoods; CLEARPOND database; Marian, Bartolotti, Chabal, Shook, & White, 2012). The conditions were matched ( $t$ -tests, all  $ps > .10$ ) in orthographic and phonological length, orthographic neighborhood density, neighbors' frequency (values taken from the CLEARPOND database), and pictures' visual complexity (Szekely & Bates, 2000). See the Appendix A for the complete list of items and their characteristics.

For each experimental condition, we created two  $6 \times 5$  matrixes of objects. Each matrix used six repetitions of each of the five different objects per condition, with the order pseudorandomized. The same type of design, using "pure" lists, was adopted in prior studies (Araújo, Fernandes, & Huettig, 2019; Wiseheart, Kim, Lombardino, & Altmann, 2019). Each object in the matrix corresponded to a  $75 \times 75$  bit image, which subtended a visual angle of  $2^\circ \times 2^\circ$ . The space between each object on the same row was approximately  $1.7^\circ$  of visual angle, and the space between rows was approximately  $1.5^\circ$ .

Stimulus presentation and data collection were controlled by SR Research Experiment Builder Software. The order of the four sets of matrixes followed a Latin square design. Participants were first given a practice session, and labels other than those expected were corrected. Total naming time was computed as the mean time necessary to name the items of the two matrixes, and the number of items

**Table 1.** Average performance on cognitive and literacy tests of dyslexic and control readers, and group differences ( $t$ -test).

	Dyslexic readers ( $N = 22$ )		Control readers ( $N = 25$ )		$t$ -value
	<b>M</b>	<b>SD</b>	<b>M</b>	<b>SD</b>	
Matrix reasoning	10.9	1.8	10.8	2.0	0.26
Reading	81.1	13.3	99.1	16.1	-4.13***
One-Minute test (máx.116)	64.3	14.2	100.1	8.4	-10.36***
Klepel (máx. 116)	292.3	48.2	231.2	23.3	5.41***
Text reading (total time in sec.)	25.9	13.7	9.8	4.9	5.22***
Text reading (total nº of errors)					
Word reversal task (máx. 20)	15.8	2.8	17.4	1.7	-2.32*
Digit Span	9.0	2.6	11.5	2.9	-2.99**

**Note.** Performance on the Matrix Reasoning and Digit Span tasks expressed in standardized scores (mean = 10, SD = 3). \*\*\*  $p < .001$ ; \*\*  $p < .01$ ; \*  $p < .05$ .

named correctly per second was used as a measure of *naming rate*. Eye movements were recorded with an SR Research Eyelink 1000 eye tracker (1000 Hz sampling rate; remote, head free-to-move system with a target sticker placed on the participants' forehead). Image arrays were presented at a viewing distance of ~60 cm. The system was calibrated using a standard 9-point grid of the right eye at the beginning of the experiment and prior to the 5<sup>th</sup> experimental matrix. The calibration procedure was repeated during the experiment if necessary. At the beginning of each trial, a central fixation dot appeared at the same screen position as the first item to be named (upper left corner), allowing for drift correction. Then, the visual display appeared. Participants were instructed to name the stimuli as quickly and accurately as possible in a left-to-right and down fashion.

### Data analysis

Two time measures were extracted from the RAN task: the *naming rate* (the number of correctly named items per second) and the *articulation time* of each item (corresponding to the mean from onset to offset of the stimulus vocalization for each word). Errors were coded as any response including item-name substitutions and skips and were not analyzed. Self-correction, repetition, or other types of irrelevant speech (e.g., *een glas*) were not coded as errors (less than 2%), but in those cases, articulation durations and associated eye-movement measures were discarded. For eye-movement data, an area of interest (AOI) for each item was defined as a region of 75×75 pixels centered on the object; for each experimental condition, eye-tracking measures related to performance based on 60 AOIs. Fixations were assigned to an AOI, and spaces between items were evenly divided and assigned to adjacent items. Using the Eyelink algorithm, common temporal eye-movement measures were analyzed for the correct speech responses: *i) first-fixation time* (the duration of the first forward fixation on an item irrespective of the number of fixations), *ii) gaze duration* (the total time spent fixating each item before the eye saccaded to the next item), and *iii) the temporal onset-eye-voice span (onset-EVS; the time between the onset of the first fixation on an object to the onset of the articulated name)*. Following Laubrock and Kliegl (2015), we further calculated the temporal EVS from the offset of the last fixation on an object (*offset-EVS*) given that the last fixation on a target is temporally aligned with its articulation (e.g., Bock et al., 2003; Griffin & Bock, 2000). As this measure corresponds to the moment when attention shifts away from the target object, offset-EVS is a better indicator of postlexical processes than onset-EVS (which encompasses the entire processing time per object). To calculate eye-voice spans for each item, speech responses were measured relative to the same zero point (trial onset) as the eye-fixation data; Praat sound editing software was then used to preprocess the sound waves and locate the beginning and the end of the voiced parts.

Approximately 5.6% of the fixation time data<sup>1</sup> were excluded owing to technical faults and participant error. As in most eye movement-based reading research, data from fixations at the first and last items in the grid were not analyzed. Extremely short fixations (< 80 ms) were pooled, as very short fixations are normally associated with false saccade programming and are unlikely to reflect information processing (e.g., Rayner, 1998; approximately 1.7% of the data), and fixation durations with extremely high values were discarded (> 3000 ms; less than 1%). Moreover, a distribution-based criterion was used to reduce the impact of possible spurious outliers, i.e., fixation durations greater than 3 SD beyond the subject and condition means were discarded (less than 2% of the data). For the naming rate measure, to reduce the impact of outliers while maintaining the same number of individuals, the extreme values were winsorized (Wilcox, 2005; 2.5% of the data). We did not exclude items where participants blinked because 1) trial number (i.e., statistical validity) would have been largely reduced, and 2) blinks did not disproportionately affect the different experimental conditions (and no participant exceeded more than 30% of the data points per condition).

Linear mixed effects (LME) models were used to analyze the data (see, e.g., Baayen, Davidson, & Bates, 2008; Quené & van den Bergh, 2008), and the *lmer* function of the *lme4* package in R (Version 3.6.2). LME models are a robust method for data analysis that allow controlling for the variability of items *and* subjects and thus to separate the experimental manipulation under observation from

spurious or “random” effects. They are particularly useful for analyzing data from heterogeneous groups, such as groups with different reading levels. We analyzed group and condition effects (fixed effects) on the various dependent measures, specifying subjects and items as crossed random factors. Since the RAN task is essentially an uninterrupted stream of naming, we moreover assigned the effect of the succeeding item on the target (i.e.,  $n + 1$ ) to the random effect variable “next item.” In this way, we could measure processing times owing to specific item characteristics independently of any additional influence from the item succeeding the target.

Naming times and eye-movement durations were log-transformed to avoid problems with heteroscedasticity. Models were fit using the maximum likelihood criterion. We started with including a maximal random effect structure as justified by the design, and in the case of nonconvergence, we simplified the random effects structure until convergence was reached (Barr, Levy, Scheepers, & Tily, 2013).  $P$  values were estimated using Satterthwaite approximations.

## Results

### Naming rate and articulation duration

As expected, accuracy was close to the ceiling in both groups (>98%) and, accordingly, will not be analyzed further. In the LME model run on the mean naming rate, only the main effect of group was significant ( $\beta = .14$ ,  $SE = 0.05$ ,  $t = 3.11$ ,  $p < .005$ ), indicating that dyslexic participants were slower overall in the RAN task (dyslexic group: Mean = 1.19 items/sec; control group: Mean = 1.45 items/sec). Inspection of means (Table 2) revealed that, relative to control readers, dyslexic readers were more impaired especially for low-frequency words in sparse neighborhoods. We next examined whether articulatory-motor factors, reflected in articulation time for each word, are important in distinguishing between reading groups. The main effects of frequency ( $\beta = .08$ ,  $SE = 0.01$ ,  $t = 8.41$ ,  $p < .001$ ) and

**Table 2.** Means (with 95% confidence intervals, within brackets) for naming rate (correct items/sec) and eye movement measures (ms) as a function of neighborhood density and frequency of the objects' name, separately by group.

	High-frequency names		Low-frequency names	
	Dense PN	Sparse PN	Dense PN	Sparse PN
<i>Dyslexic readers</i>				
Naming rate	1.26 [1.18, 1.34]	1.23 [1.17, 1.28]	1.20 [1.13, 1.26]	1.09 [1.02, 1.16]
Articulation duration	401 [395, 408]	429 [423, 436]	456 [449, 463]	476 [468, 483]
First-fixation time	371 [358, 385]	365 [352, 379]	377 [364, 392]	404 [388, 420]
Gaze duration	580 [562, 598]	573 [555, 591]	578 [560, 597]	614 [594, 635]
Onset-EVS	820 [795, 846]	824 [795, 846]	843 [815, 872]	897 [865, 930]
Offset-EVS	153 [140, 168]	175 [160, 191]	177 [160, 195]	212 [193, 233]
<i>Control readers</i>				
Naming rate	1.46 [1.40, 1.53]	1.51 [1.44, 1.59]	1.43 [1.36, 1.50]	1.40 [1.33, 1.48]
Articulation duration	394 [389, 399]	403 [396, 410]	425 [418, 433]	437 [430, 444]
First-fixation time	365 [355, 376]	370 [360, 381]	379 [367, 391]	408 [396, 420]
Gaze duration	525 [513, 538]	519 [507, 532]	528 [515, 542]	550 [537, 563]
Onset-EVS	706 [688, 725]	698 [681, 715]	710 [689, 732]	720 [701, 740]
Offset-EVS	144 [132, 156]	136 [125, 147]	133 [122, 146]	129 [118, 142]

PN, Phonological neighborhood density.

neighborhood ( $\beta = .03$ ,  $SE = 0.01$ ,  $t = 3.01$ ,  $p < .005$ ) were both significant, as were the interactions with group (frequency x group:  $\beta = .04$ ,  $SE = 0.01$ ,  $t = 3.17$ ,  $p < .005$ ; and neighborhood x group:  $\beta = .03$ ,  $SE = 0.01$ ,  $t = 2.43$ ,  $p = .015$ ). Follow-up separate analyses showed that low-frequency names were articulated slower than high-frequency names by both groups (control:  $\beta = .08$ ,  $SE = 0.01$ ,  $t = 8.05$ ,  $p < .001$ ; dyslexic:  $\beta = .12$ ,  $SE = 0.01$ ,  $t = 12.56$ ,  $p < .001$ ). Moreover, neighborhood density affected the duration of participants' production, with longer articulation durations for words with few phonological neighbors than for words with many phonological neighbors (control group:  $\beta = .03$ ,  $SE = 0.01$ ,  $t = 2.90$ ,  $p < .005$ , dyslexic group:  $\beta = .06$ ,  $SE = 0.01$ ,  $t = 6.32$ ,  $p < .001$ ). The larger difference between groups for the low-frequency words and for words from sparse neighborhoods indicated by the significant interactions suggest that dyslexic readers processed these items less efficiently.

### Eye-movement data

As shown in Table 2, there was a significant main effect of group on gaze duration ( $\beta = .10$ ,  $SE = 0.04$ ,  $t = 2.27$ ,  $p = .027$ ), indicating longer fixation times in dyslexic readers than in control readers. We also observed significant interactions of frequency and neighborhood in first-fixation ( $\beta = .06$ ,  $SE = 0.03$ ,  $t = 2.07$ ,  $p = .038$ ) and gaze duration ( $\beta = .06$ ,  $SE = 0.03$ ,  $t = 2.15$ ,  $p = .032$ ) measures, as the mean viewing time was significantly longer for objects that had low-frequency names *and* few phonological neighbors than for objects that had low-frequency names and many phonological neighbors. All interactions involving group were not significant (all  $ps > .3$ ).

The temporal eye-voice span measure comprised two separate measures. For the onset-EVS, only the main effect of group was again significant ( $\beta = .15$ ,  $SE = 0.05$ ,  $t = 3.16$ ,  $p < .005$ ), as compared with control readers, dyslexic readers had longer EVS. Critically, we observed significant interactions between frequency and group ( $\beta = .23$ ,  $SE = 0.08$ ,  $t = 2.69$ ,  $p = .007$ ) and between neighborhood and group ( $\beta = .19$ ,  $SE = 0.08$ ,  $t = 2.26$ ,  $p = .024$ ) for offset-EVS, i.e., the lag between the offset of gaze to an object and the onset of its spoken name: the group differences were largest for low-frequency words and for words with sparse neighborhoods, in the direction of less efficient processing (i.e., lags were longer) for the dyslexic rather than the control group. We thus proceeded to examine the critical interactions separately for each group. The control group was not affected by frequency ( $t = -1.71$ ,  $p = .09$ ) or neighborhood ( $t = -1.05$ ,  $p > .2$ ; or two-way interaction:  $t = 0.20$ ,  $p > .2$ ) for offset-EVS. In contrast, the dyslexic group was affected, as indicated by significant main effects of frequency ( $\beta = .13$ ,  $SE = 0.06$ ,  $t = 2.11$ ,  $p = .035$ ) and neighborhood ( $\beta = .14$ ,  $SE = 0.06$ ,  $t = 2.19$ ,  $p = .029$ ).

In summary, the critical LME results showed that the time spent fixating on an object was affected by the frequency and phonological neighborhood density of its name, and these effects were observed to the same extent in control and dyslexic readers. Moreover, in participants with dyslexia only, frequency and phonological neighborhood had an influence on late stages of processing (offset-EVS) as well.

### Discussion

The present study explored how phonological encoding and speech production planning for successive words are coordinated in dyslexic and control adult readers during serial rapid naming. For this study, we tracked the effects of word frequency and phonological neighborhood density on the rate of spoken word production, examined with a RAN task and concurrent recordings of participants' naming times and their eye movements. Overall, we provided converging evidence with earlier studies that showed that slow naming speed is a hallmark of dyslexia that persists into adulthood (for a meta-analysis, see Araújo & Faísca, 2019). Slow naming was reflected in total naming time and eye-movement measures. Moreover, the frequency and neighborhood density of the target words were found to affect production times in RAN, and more interestingly, the mean viewing times and the temporal eye-voice span, i.e., the timing of the participants' eye movements relative to the articulation of the object names. Of particular interest is that different patterns of results were seen for control and

dyslexic readers especially for offset-EVS, i.e., the time between the offset of gaze to an object and the onset of naming.

### ***Gaze durations and the lexical access deficit***

In general, our results were in agreement with the idea that high word frequency and high neighborhood density facilitate the activation and retrieval of a lexical word form during speech production (Graves, Grabowski, Mehta, & Gordon, 2007; Jescheniak & Levelt, 1994; Levelt, 2001; Meyer et al., 1998; Wiseheart et al., 2019; Yates et al., 2008). This idea was evidenced by shorter gaze times (first-fixation and gaze duration) for dense as opposed to sparse phonological neighborhoods for low-frequency words, whereas high-frequency words were immune to the phonological similarity relations in both groups. The idea that lexical processing is facilitated for familiar words is well established both in spoken word recognition and in production. The effect of phonological neighborhood density has been equivocal in speech production (for overviews and discussion, see Chen & Mirman, 2012; Perea, 2015; Sadat et al., 2014; Vitevitch & Luce, 2016). Yates et al. (2008) reported the only finding available thus far that sensitivity to phonological neighborhood is mirrored in eye-movement measures in a production task. Using a reading task, the authors observed shorter fixations for words with dense neighborhoods compared to words with sparse neighborhoods. Here, we replicated and extended this finding to an object naming task. This result is interesting as a facilitative effect of high neighborhood density in the lexical retrieval process, demonstrated by means of gaze duration, which fits within an interactive activation framework of lexical access (e.g., Dell & Gordon, 2003; Gordon & Dell, 2001). Dell and Gordon (2003) model this pattern as resulting from interactive feedback from the phoneme level to the word forms: that is, feedback from phonological neighbors boosts target word activation, which is already high, because of the initial jolt of activation from the semantic level. Given that high-frequency words have higher base activation levels, they should be less influenced by the reverberating phoneme-level activation arising from neighboring word units than low-frequency words. This was indeed what we observed.

Importantly, the current study showed that word frequency and neighborhood density exert a facilitative effect on the fast retrieval of words in dyslexic speech production, just as they do in normal readers' speech production. Notably, these effects were already evident in the earliest measures of processing, the first-fixation duration. Hence, people with dyslexia apparently do not have a specific problem in early lexical processing, despite being slower overall and more influenced by both stimulus manipulations adopted. An access problem (Boets et al., 2013; Ramus, 2014; Ramus & Szenkovits, 2008) would predict reduced performance from early on and particularly for difficult lexical items (e.g., Griffin, 2001), which was not observed. Using a Stroop manipulation in a RAN task and eye-tracking, Jones et al. (2016) also found that dyslexic readers were able to activate lexical information in a timeline similar to that of typical readers. Moreover, recent results from adult (il)literacy suggest that the generally slower access to low-frequency items by dyslexic readers is possibly not due to the reading disorder itself but may reflect an effect of reading level. Namely, using a RAN task, Araújo et al. (2019) found a significant advantage in lexical access and retrieval of low-frequency items for adult readers over adults who were illiterate. This result suggests that ample literacy experience per se enhances fast access to lexical-phonological representations during RAN and especially of difficult lexical items.

### ***Findings on eye-speech coordination***

As noted, prior studies pointed to specific differences between control and dyslexic readers at the eye-voice interval and took this to argue for a potential deficit in phonological output processing (Jones et al., 2013, 2008, 2016). However, these studies analyzed temporal-onset EVS, which encompasses the entire fixation time plus preparation of the articulatory response. In contrast, we measured offset-EVS

to advance our understanding of the temporal coordination between eye gaze and speech during RAN. In our study, the mean value of offset-EVS was approximately 140 ms, which is closely aligned with the estimated duration of the articulatory programming stage (Indefrey, 2011).

Prior eye-tracking research on spoken word planning (e.g., Meyer et al., 1998, 2012) suggested that speakers usually shift their gaze and attention from one object to the next after phonological encoding of the current object name has been completed. The results obtained here for control readers fit with this idea, as the effect of lexical factors was significant in gaze duration but not in late EVS. Thus, it seems that in sequential object naming, articulatory planning to name object  $n$  is independent of access to the name of object  $n + 1$ .

However, in dyslexic readers, the lexical effects percolated to the late offset-EVS measure, indicated by a frequency by group interaction and a neighborhood by group interaction. These readers needed more time to initiate the articulatory response of the low-frequency words and of words in sparse phonological neighborhoods, suggesting a larger processing cost than among control readers. It was also for these items that the difference between the two groups was larger and significant. These effects extended to articulation, consistent with other studies reporting lexical effects on articulatory processes (e.g., Goldrick & Blumstein, 2006; Munson & Solomon, 2004).

The locus of this late effect is not clear. Given that the offset-EVS is likely to reflect on phonetic and articulatory encoding, one possibility is that speech production planning takes longer in dyslexic readers, especially for the more difficult items. Alternatively, one could argue that perhaps the offset-EVS captures different stages in control and dyslexic readers. As noted, the sequential constraint of the RAN task means that partial activation of processes related to the  $n + 1$  item may take place during the offset-EVS as well, and it is possible that readers coordinate their eye gaze and speech production planning processes in different ways (Meyer et al., 2012). That is, group differences might arise from a particular planning strategy adopted on different occasions: perhaps dyslexic readers deviate from the default coordination of eye gaze and speech seen for control readers and sometimes move their eyes before and sometimes after completion of phonological encoding. For sets including difficult items, dyslexic readers might, for instance, initiate the shift of gaze to a new object as soon as the current object has been recognized but then need more time to plan and to initiate production of the name. To some extent, this interpretation is in line with the only available evidence on delayed word naming in dyslexia. In a study by Zoccolotti, De Luca, Judica, and Burani (2006), the effect of word length on naming presented by dyslexic readers at 0, 500 and 1000 ms delay conditions was nonsignificant with a sufficiently long cue delay (2000 ms delay). In controls, there was no length effect at any delay. These results suggest that dyslexic readers have no problem in deriving output phonology or, we conjecture, could indicate that with ample time, these readers plan further ahead, i.e., anticipate part of the phonetic and articulatory planning prior to the cued response to ensure the fluency of their utterances.

There is also another possible interpretation stemming from the demands of the RAN task. Readers with dyslexia might have prolonged speech production planning (reflected in longer offset-EVS) and articulation of object  $n$  because they needed more time to process object  $n + 1$ . This interpretation is consistent with the idea that there is a tight coordination between the eyes and the voice during continuous naming/reading for the sake of fluency (e.g., Gordon & Hoedemaker, 2016). It is also in line with prior evidence suggesting that in addition to the core decoding deficit, sequential processing of multiple items presents a specific challenge to readers with dyslexia (Zoccolotti et al., 2013; Zoccolotti, De Luca, & Spinelli, 2015).

Whatever the processing stage executed at the offset-EVS, the larger differences seen for low-frequency words and for words in sparse neighborhoods may tentatively be related to the poor quality of phonological representations. One can assume that in typical adult readers, words varying in frequency and neighborhood density differ in ease of lexical access, but all have detailed segmental representations (Metsala & Walley, 1998; Walley, Metsala, & Garlock, 2003). Hence, any local processing difficulty can be rapidly resolved, and later processing stages are unaffected, as we found.

By contrast, in dyslexic readers, a word's frequency and a word's neighborhood may affect not only the ease of lexical access but also the specification of their representations and the ability to swiftly trigger articulatory commands.

Indeed, these effects of frequency and neighborhood accord with the lexical restructuring account, as low-frequency words and words in sparse neighborhoods are supposedly the last to undergo segmental restructuring during development (Garlock, Walley, & Metsala, 2001; Metsala, 1997a; Metsala & Walley, 1998). Thus, these words should be more susceptible to individual differences in lexical reorganization and representation. By adulthood, perhaps a certain degree of specification/detail in lexical representations in dyslexic readers was sufficient, so that these difficult words did not impose significant costs in early lexical access (first-fixation and gaze duration). It was only late in processing (offset-EVS) that such costs become visible when cognitive resources are less available to the speaker because they are also preprocessing  $n+1$  items. Consistent with a representational deficit, a number of studies have reported that children (Nation, Marshall, & Snowling, 2001; Swan & Goswami, 1997b) and adults (Dietrich & Brady, 2001) with dyslexia are more likely to produce phonological errors when naming. Dyslexic adults also confuse words that sound alike more often than control readers (Elbro, Nielsen, & Petersen, 1994). Less well-specified phonological representations may also explain the lower performance of dyslexic readers than control readers in phoneme awareness tasks (e.g., Elbro & Jensen, 2005) and in speech gating tasks in which they require more speech input to identify words correctly (Boada & Pennington, 2006; Metsala, 1997b).

Another possibility is that differential effects on EVS may reflect strategic adaptation and the possible involvement of controlled attentional processing in the task. Indeed, RAN indexes a complex skill of sequential multi element processing beyond individual word processing (Protopapas et al., 2018). Sustained attention is required to coordinate perceptual encoding and vocal execution to optimize speed while suppressing interference between successive items (Gordon & Hoedemaker, 2016). Importantly, this aspect is known to affect the activation flow that spreads from concepts to word forms (e.g., Roelofs, 2008) and the late processes in naming (Jongman, Meyer, & Roelofs, 2016; Jongman, Roelofs, & Meyer, 2015). Thus, it is possible that group differences in the ability to maintain sustained attention to the production processes, specifically for difficult items, cause the observed late effects.

## Conclusion

In brief, we found that higher word frequency and denser phonological neighborhoods facilitate word selection and phonological encoding, as reflected in shorter naming times and gaze durations, and there was an interaction between these effects: the benefit from dense neighborhoods was only significant for low-frequency words. This phenomenon occurred in dyslexic readers as in control readers and was already evident in fixation measures that are assumed to reflect early lexical processing (i.e., first-fixation duration and gaze duration). Thus, our results do not support a specific difficulty in lexical phonological access in adults with dyslexia. What then makes the RAN task so challenging for persons with dyslexia? We conclude that our results fit best with the notion that the difference in dyslexic readers' RAN performance is due to suboptimal mapping of phonological representations onto articulatory commands and (possibly) to deficits in attention control or in multi-item coordination. Finally, we note that our study is exploratory and the absence of significant interaction effects in the early eye-tracking measures is susceptible to lack of power or sensitivity arguments. We encourage future studies to confirm our results with larger sample sizes.

## Note

1. Regarding the eye-voice span (EVS) and articulation time (AT) measures, the amount of data sample that was entered into the analysis was smaller because of recording problems; yet, the analyses on these measures were still

based on a substantial number of items (In total, 5,460 and 5,447 observations contributed to the EVS and ET analyses, respectively).

## Acknowledgments

The first author and this work were supported by IF 2015 Program of the Portuguese Foundation for Science and Technology, FCT (ref. IF/00533/2015) and by the Research Center for Psychological Science at Universidade de Lisboa (CICPSI). Many thanks are due to anonymous reviewers for their helpful comments on earlier drafts of this article.

## Conflict of Interest

The authors declare no conflict of interest.

## Disclosure statement

The authors declare no conflict of interest.

## Funding

This work was supported by the Portuguese Foundation for Science and Technology [IF/00533/2015].

## Data sharing

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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## Appendix A. List of the objects used in the rapid naming task for each experimental condition, and their characteristics: mean word frequency per million words, and number of phonological neighbors (PN). Standard error of the mean is presented in parenthesis

	High frequency names		Low frequency names	
	Large PN	Small PN	Large PN	Small PN
	bed (bed)	arm (arm)	bijl (ax)	hark (rake)
	mond (mouth)	bank (couch)	vaas (vase)	mais (corn)
	tent (tent)	deur (door)	boon (bean)	dolk (dagger)
	hoed (hat)	glas (glass)	mand (basket)	wieg (cradle)
	paard (horse)	trap (stairs)	pauw (peacock)	slee (sled)
Frequency	113.27 (39.31)	105.62 (36.19)	4.10 (1.48)	3.94 (1.65)
Number of PN	25.40 (3.89)	9.60 (1.12)	22.40 (1.83)	8.00 (1.00)