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Journal of Experimental Psychology: Learning, Memory and Cognition

DOI:
10.1037/xlm0000186

Published: 01/03/2016

Peer reviewed version

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What automaticity deficit? Activation of lexical information by readers with dyslexia in a RAN Stroop-switch task

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Abstract

Reading fluency is often predicted by Rapid Automatized Naming speed (RAN), which as the name implies, measures the automaticity with which familiar stimuli (e.g., letters) can be retrieved and named. Readers with dyslexia are considered to have less 'automatized' access to lexical information, reflected in longer RAN times compared with non-dyslexic readers. We combined the RAN task with a Stroop-switch manipulation to test the automaticity of dyslexic and non-dyslexic readers' lexical access directly within a fluency task. Participants named letters in 10 x 4 arrays whilst eye-movements and speech responses were recorded. Upon fixation, specific letter font colours changed from black to a different colour, whereupon the participant was required to rapidly switch from naming the letter to naming the letter colour. We could therefore measure reading group differences on 'automatic' lexical processing, insofar as it was task-irrelevant. Readers with dyslexia showed obligatory lexical processing and a timeline for recognition that was overall similar to typical readers, but a delay emerged in the output (naming) phase. Further delay was caused by visual-orthographic competition between neighbouring stimuli. Our findings outline the specific processes involved when researchers speak of 'impaired automaticity' in dyslexic readers' fluency, and are discussed in the context of the broader literature in this field.

Keywords: Rapid Automatized Naming, Stroop, Dyslexia, Eye-tracking

What automaticity deficit? Activation of lexical information by readers with dyslexia

A key aim of reading instruction is to ensure the development of fluent reading (Wolf, Miller, & Donnelly, 2000). Definitions of fluency include the need to develop automatic, effortless rates of processing, which free attentional resources for higher-order tasks such as reading comprehension (LaBerge & Samuels, 1974; Logan, 1997; see Wolf & Katzir-Cohen, 2001). A well-known measure of reading subskill - Rapid Automatized Naming (Denckla & Rudel, 1976) - measures naming-speed for highly familiar items (typically letters, digits, objects or colours). RAN tasks typically comprise five items repeatedly presented in random order on a 10 x 5 grid. Items must be named as quickly as possible, moving from left to right and down, in an analogous fashion to text reading. Naming speed is found to strongly predict word and text reading fluency (most commonly, reaction time measures: see Bowers & Swanson, 1991), with slower speeds strongly indicating dyslexia (Bruck, 1998; Denckla & Rudel, 1976; Bowers & Swanson, 1991; Lefly & Pennington, 1991; Shaywitz & Shaywitz, 2003; see Kirby, Georgiou, Martinussen, & Parrila, 2010; Norton & Wolf, 2012; and Wolf & Bowers, 1999 for reviews; see Wile & Borowsky, 2004 for variants of the task). Thus, the ability to 'automatize' low-level lexical processes with repeated exposures is assumed to be one key foundation of reading fluency, which in turn affects reading comprehension (LaBerge & Samuels, 1974; Logan, 1997; see Wolf & Katzir-Cohen, 2001), but it is unclear from current RAN studies what this means in processing terms. Given the widespread use of RAN in research and in clinical practice, it is imperative that an operational definition of impaired automaticity is obtained. In this article, we identify and isolate specific processes

relating to the 'automaticity' construct in order to assess its role in discriminating groups of adult dyslexic and non-dyslexic readers' letter-naming fluency.

Performance on the RAN task is proposed to index the low-level factors involved in reading fluency, including attention to the stimulus, bi-hemispheric visual processing for feature detection, matching of features to patterns conforming to stored orthographic codes, and integration of visual information with phonological codes; ultimately leading to motor activation for articulation (see Wolf & Bowers, 1999). Rapid mapping of the visual code to its phonological counterpart is therefore crucial to effective execution of the task (Jones, Branigan Hatzidaki, & Obregon, 2010; Lervag & Hulme, 2009; Moll, Fussenegger, Willburger, & Landerl, 2009), and evidence suggests that, even at the individual item level, dyslexic readers' naming fluency is impaired (Castel, Pech-Georgel, George, & Ziegler, 2008; Jones, Branigan, & Kelly, 2009). Current theorizing on RAN emphasizes an 'automaticity' deficit in dyslexia, resulting in slower access to phonological codes (Bowey et al., 2005; Clarke, Hulme & Snowling, 2005; Savage, Pillay & Melidona, 2007; Torgesen, Wagner, & Rashotte, 1994, 1999). But the term "automaticity" is opaque, and it is necessary to isolate the separable factors involved.

In relation to reading, automaticity is characterized as the obligatory processing of lexical information, occurring rapidly and without conscious effort (e.g., Kuhn et al., 2010; Moors & de Houwer, 2006; Stanovich, 1990). Word recognition speed can be decoupled from this process; with faster speeds being obtained long after obligatory processing is established (Samuels & Flor, 1997). Findings from the Stroop task (Stroop, 1935; see MacLeod, 1991 for a review) – in which automatic processing of the word (e.g., RED) delays output of the print colour (e.g., "green") - indicate that word recognition is obligatory for dyslexic readers, but it

takes longer compared with typical readers. This is typically manifest in larger Stroop effects (longer RTs): longer activation of the word results in a delay before it can be terminated in order for colour naming to proceed (Everatt et al., 1997; Faccioli et al., 2010; Helland & Asbjornsen, 2000; Kapoula et al., 2010; Protopapas, Archonti, & Skaloumbakas, 2007).

Applying this logic to RAN, it is reasonable to predict that dyslexic naming is characterized by obligatory access to each individual lexical code, but that speed of access to the code is delayed (Note that we use the term 'lexical access' to apply to letter naming in the sense of 'whole item', but in the absence of other linguistic elements involved in access to words, such as decoding, syntax and semantics.) However, there is no current consensus on the locus of the supposed speed deficit. 'Obligatory' processing could take longer to begin, or the various processing stages of lexical access could take longer to complete, perhaps owing to asynchrony between processing levels (e.g., Breznitz, 2005) or degraded representations (e.g., Perfetti, 2007). At the production stage, phonological output could take longer to compute (Shankweiler & Crain, 1986; Hulme & Snowling, 1992; Clarke, Hulme, & Snowling, 2005), or suppressing lexical activation could be impaired (Everatt et al., 1997; Protopapas et al., 2007).

In addition, research has shown that RAN is strongest in its prediction of reading fluency skills when multiple items are presented serially (Bowers, & Swanson, 1991; Walsh, Price, & Gillingham, 1988), as is typically the case in RAN tasks (Denckla & Rudel, 1976). Serial processing is moreover an important discriminator of good and poorer readers' task performance, particularly as skilled readers become more fluent (de Jong, 2011; Georgiou, Parrila, Cui & Papadopoulos, 2013; Jones et al., 2009; Jones, Ashby, & Branigan, 2012; Logan, Schatschneider, &

Wagner, 2011; Protopapas, Altani & Georgiou, 2013). As normally developing readers become more skilled and automatized in naming and reading, executive control schedules and monitors distinct items, thereby enabling relatively smooth parallel processing of multiple items in the array.

Recently, eye-tracking methodology has been used to shed light on the processes underpinning serial naming (e.g., Jones et al., 2008; 2012; Yan, Pan, Laubrock, Kliegl, & Shu, 2013). As with normal reading, naming letters involves processing the fixated item whilst pre-processing the item immediately to its right, and it is perhaps helpful here to draw on findings from eye-tracking research in relation to reading, for which there is a substantial body of literature: When a target word is fixated, lexical selection of the target (*n*) takes place, followed by a shift in visual attention to the upcoming word (*n+1*), viewed at this point in the parafovea (e.g., Pollatsek, Reichle, & Rayner, 2003; Rayner et al., 2005; Reichle et al., 2003). The upcoming word is then fixated for full processing, often simultaneously with naming of the target item (*n*). Fixation times on a single word are typically in the region of 225-250ms (Rayner, 1998)**.**

Thus, reading involves some overlap in processing multiple items, and an analogous process is found to take place during RAN (e.g., Jones et al., 2008). Gaze and naming times to individual letters are slowed by the presence of similar information (letters with similar visual-orthographic or phonological properties) adjacent to the target, but particularly so in dyslexic readers. Dyslexics' prolonged processing times are indicative of a longer period distinguishing the lexical information in *n+1* from the target *n*. (Jones et al., 2008; Jones et al., 2012), which is exacerbated when letters are presented closer together (Moll & Jones, 2013).

Analogous deficits are found in reading, whereby only extra large spacing between words facilitates reading speed for children with dyslexia (Zorzi et al., 2012).

To summarise, the superficially simple RAN task requires precise and fast initiation and conduction of lexical information in order to access individual task items (e.g., letters) automatically, which then need to be rapidly suppressed in order to conduct efficient monitoring and scheduling of multiple items in the array. Here, we test the hypothesis that naming speed deficits in dyslexia involve obligatory processing of lexical information, but with a deficit in one of the following processes: 1) the speed with which obligatory retrieval becomes active, or the speed of lexical access through to recognition of the item; 2) a deficit at the output stage in suppressing the lexical response once it is active. The aim of this study was to pinpoint which of the processes involved in the automaticity construct lead to naming speed deficits in dyslexia.

The current study

We developed a novel RAN Stroop-switch paradigm, for which we collected eye-tracking and synchronous voice-response data from age-matched, adult, high-functioning (University attending) groups of readers with and without dyslexia. This sample was chosen in order to reduce the risk of including participants with comorbid difficulties in the dyslexic group, and to provide a conservative indication of the automaticity deficit characteristic of dyslexia. In the Stroop task, colour words are serially presented in different coloured print (e.g., RED presented in green print), and delay in articulating the print colour signals activation of the word. In our variant of this task, participants were instructed to name letter items as quickly as possible in a continuous RAN task. Upon fixation, specific target letters in the array changed

colour, whereupon participants were required to task switch; producing the colour name, whilst inhibiting the letter name. We therefore primed participants to behave as they usually would in a RAN task, but on target trials, formulation of the letter name required suppression in favor of the color name response. To the extent that automatic lexical activation interfered with colour naming, we could examine sources of divergence in our two reading groups. The Stroop-switch task therefore provided a proxy measure of the automatic processes that occur during a standard rapid naming letter task.

In 'Phonological' letter sets, the pre-target letter item (e.g., g was followed either by a coloured symbol target (e.g., ζ - *no lexical competition* condition), a coloured letter target which was phonologically distinct (e.g., k – *medium* lexical competition condition), or a coloured letter target which was phonologically similar with the name of the preceding letter item (e.g., j – *high* lexical competition condition). In separate 'Visual' letter sets, the pre-target letter item (e.g., p was followed either by the same baseline target (e.g., ζ - *no lexical competition condition*), a coloured lexical target which was visually distinct (e.g., Q – *medium lexical competition condition*), or a coloured letter target which was visually similar with the preceding letter (e.g., q – *high lexical competition*). See Figure 1.

[INSERT FIGURE 1 ABOUT HERE]

Using the Stroop-switch in this naming task, we could measure the extent to which automatic lexical activation competed with the colour naming response. Specifically, the no competition condition indicated baseline performances on the task-switch (colour-naming) response, tapping executive functions associated with task-switching per se (Monsell, 2003). However, of crucial importance was the

comparison of reading group performance across conditions: (1) Group differences in the extent to which automatic lexical access of the target item (medium competition condition) delayed the colour name response *beyond* the task-switch component per se (no competition condition) tested obligatory lexical processing in RAN (akin to a Stroop effect) (2) Group differences in the extent to which inhibition of a competing visual/phonological item immediately prior to the target (high competition condition) delayed the colour naming response beyond a non-competing lexical representation (medium competition condition) tested the influence of inter-item lexical processing on automaticity, i.e., the extent to which inhibition of a competitive lexical representation further delayed the colour naming response. We examined these effects on the length of time readers spent looking at the target, before moving on to the next item (gaze duration), and the time from first viewing the target to execution of the verbal response (eye-voice span). (See Results section for more detail on these dependent measures.)

For *typical readers (controls)*, we predicted that the three conditions outlined above would result in an increase in processing times as a function of lexical competition. Specifically, we predicted that looks to the target and production of its verbal colour name response (e.g., "blue") would be slower in the medium lexical competition condition, owing to competition from obligatory lexical access of the target item, compared with the no competition condition. In the high lexical competition condition, it was hypothesized that participants' target processing would be delayed further by competition elicited by visual or phonological features of the letter in the *n-1* position, compared with the medium condition. We also predicted that these findings would be present in the measure of gaze duration measure (fixation time), but were less likely to occur in the eye-voice span measure (fixation time plus

preparation of the articulatory response): Previous work has shown that typical readers can rapidly assimilate sources of confusion in RAN, leaving the eye-voice span unaffected (Jones et al., 2008).

For *readers with dyslexia*, we predicted that lexical competition would elicit larger effects for the medium vs. no competition comparison compared with typical readers, in line with the literature reviewed (Everatt et al., 1997; Faccioli et al., 2010; Helland & Asbjornsen, 2000; Kapoula et al., 2010; Protopapas et al., 2007). If dyslexic readers' automaticity deficits in RAN implicate slower initiation of lexical access, or longer completion times of the stages leading to recognition, a larger lexical competition effect in the gaze duration measure was expected. However, if the deficit occurred during phonological encoding for articulation, larger effects for dyslexics would only manifest in the eye-voice span measure (cf. Jones et al., 2008). At the inter-item level (medium vs. high competition comparison), we predicted that failure to adequately inhibit lexical information across successive stimuli would lead to greater competition from lexical information in dyslexic compared with typical readers.

Method

Participants

Two groups of 18 native British-English speaking students were recruited. Participants in the 'dyslexic' group (age: $M = 20.6$, $SD = 2.4$; gender: 6 males, 12 females) had been formally assessed by an Educational Psychologist during primary or secondary education, and diagnosis was confirmed during their University degree. Participants in the control group (age: $M = 20.1$, $SD = 2.5$; gender: 5 males, 13 females) reported no history of literacy difficulties. All participants had normal or

corrected vision and reported no other problems (e.g., hearing loss, specific language impairment, ADHD etc.).

Materials and Design

Literacy skills and general cognitive ability.

Word and nonword reading fluency was assessed using the *Test of Word Reading Efficiency (TOWRE*; Torgesen, Wagner, & Rashotte, 1999). This test requires reading aloud a list of high-frequency words or nonwords as accurately and quickly as possible within 45 seconds. Standard scores were calculated for each subtest. Total naming times per trial on another on-screen version of RAN (comprising a separate experiment) were collected and indicated global naming time measures averaged across four 10 x 4 arrays consisting of the letters *k*, *b*, *g*, *z*, *t* (selected for minimum inter-item visual and phonological similarity) in 18 point font, presented at 2.5 visual angle between the centre point of successive letters.

Verbal and nonverbal IQ was estimated using two subtests from the *Wechsler Abbreviated Scale of Intelligence* (*WASI*; Wechsler, 1999). In the verbal subtest 'Vocabulary' the participant is asked to define as precisely as possible orally presented words; the nonverbal subtest 'Matrix Reasoning' requires the participant to select the correct response from five possible choices in order to complete a grid pattern. The Symbol search subtest of the *Wechsler Adult Intelligence Scale* (*WAIS-III*; Wechsler, 1998) was administered in order to assess nonverbal processing speed. The task requires deciding whether one of two varying target symbols appears within a row of distracters.

Experimental Design & Procedure.

The RAN-letters task (Denckla & Rudel, 1976) was adapted in order to include a Stroop-switch component. In each trial, 40 letters were presented in Courier New font in a 10 x 4 grid with each letter subtending a visual angle of 1°. Four rows of letters were presented (rather than the traditional five lines in RAN) in order that the gaze-contingent change manipulations – described below – were likely to be triggered accurately. Each grid contained 8 target items, which were defined as regions of interest. Upon fixation, when the eye saccaded across an invisible boundary placed at the exact midpoint between the target letter and the letter placed immediately before it (see Figure 1), the font colour of each target item changed from black to another colour (pink, blue, red or green). As in all RAN tasks, participants were asked to name the letters in the grid line-by-line as quickly as possible, working from the top left hand corner to the bottom right hand corner. However, in this experiment, when the letter changed colour, they were required to name the letter colour (which required suppression of the letter name).

Experimental conditions were constructed with respect to the target item and the preceding letter in the array. The factor Lexical Competition comprised three levels: No, medium and high lexical competition. No lexical competition trials (baseline) included target items comprising symbols for which the name is not commonly known[1] (Ξ, δ, φ, or ζ) and therefore no suppression of a letter name is required. Lexical target items were manipulated with respect to their confusability with adjacent items in the array: Medium lexical competition trials (non-confusable) included target items that were non-confusable with the preceding item in the array. High lexical competition trials (confusable) included target items that were

[1] Before testing commenced, participants were asked whether they could name any of the Greek symbols used in the experiment. Not a single symbol was named correctly, validating the no competition condition as a non-lexical baseline condition for this sample of participants.

phonologically or visually confusable with the preceding item in the array (see Table 1). Phonological items had similar onsets, whilst visually similar items included those that were mirror images on the vertical axis, and pose a difficulty for dyslexic readers. Crucially, in visual conditions, phonological output was controlled (identical) across medium and high similarity conditions by presenting upper and lower case letters, respectively. To avoid conspicuity of upper case letters in the experiment, half of all RAN arrays in the 'Phonological' letter sets were also presented in upper case. Thus, our letter similarity manipulation was similar to that used in Jones et al. (2008, 2012). In a given trial (10 x 4 grid), targets were derived from just one condition: no, medium or high lexical competition conditions). In both 'Phonological' and 'Visual' letter sets, a given letter in the pre-target position (*n-1*) would be followed either by a symbol, a non-confusable letter, or a confusable letter in target position (*n*).

[INSERT TABLE 1 HERE]

Both 'Phonological' and 'Visual' sets comprised twelve trials each (four no competition trials, four medium competition trials and four high competition trials), resulting in twenty-four trials in total, and 192 target letters (x 8 per trial). The order of trials was randomized and the position of letters within each trial was pseudo-randomized, such that letters counterbalanced across both *n-1* and *n* positions. In the 10 x 4 item grid, critical pairs occurred in grid positions 2-3, 7-8, 12-13, 17-18, 23-24, 28-29, 33-34, 38-39 or 3-4, 8-9, 13-14, 18-19, 22-23, 27-28, 34-35, 37-38. Thus, neither item was presented at the beginning or end of a line and the grid position was not predictable. Eye-movements were monitored by an SR Research Eyelink 1000 eye-tracker controlled by SR Research Experiment Builder software. Viewing was binocular, but only the dominant eye was tracked. Image arrays were presented on a

21 in. CRT monitor at a viewing distance of 70 cm with a refresh rate of 60 Hz. Following calibration (9 screen locations), trials began with a drift correction (small circle) in the same screen position as the first letter to be named (top left hand corner). On fixation of the circle, the experimenter initiated the trial. Spoken output for each item was recorded on the PC via an ASIO sound card. The session took 45 minutes, cognitive and literacy tests inclusive.

Results

Background measures for both groups are summarized in Table 2. Consistent with the diagnosis, the group with dyslexia read significantly fewer words and nonwords than controls, and obtained slower naming times in RAN, but performed similarly on IQ measures and in nonverbal processing speed. In line with previous studies, the total naming time over all 24 grids used in the main experiment was significantly slower in the group with dyslexia ($t = 3.28$, $p < .01$).

[INSERT TABLE 2 ABOUT HERE]

The spatial fixation coordinates from the eye-tracking output for the 192 target letters were defined as regions of interest. A region of interest comprised 70 x 180 pixels (2.29° visual angle) surrounding the midpoint of each target letter. Using this region we could determine when, with reference to a zero point representing the beginning of the trial, the participant's gaze entered each region and how long the participant stayed in each region before saccading to the next region. Extremely short fixations (below 80ms) and short fixations succeeding a longer fixation but lying within 0.5° of visual angle were pooled. Very short fixations are normally associated with false

saccade programming and are unlikely to reflect information processing (e.g., Rayner & Pollatsek, 1989).

Our first measure comprised *gaze duration*: how long participants gazed at the target region before saccading to the next region, also sometimes referred to as 'first pass' in the eye-tracking literature (Rayner, 1998). Our second measure comprised the *eye-voice span*, which measured the point at which participants fixated a letter to the point at which they initiated the articulatory response (see also Jones et al, 2008; 2010). In naming tasks, gaze duration has been associated with recognition processes up to and including activation of phonological codes (Griffin, 2001, 2004). The eye-voice span is defined by the time from when the target is first fixated to the onset of the articulatory response (cf. Buswell, 1920 and Fairbanks for 1937 for pioneering work in this domain; Inhoff, Solomon, Radach, & Seymour, 2011; Jones et al., 2008; Laubrock & Bohn, 2008 for its modern application using eye-tracking and digitized speech methods), and therefore includes full phonological planning up to the point of articulation. In RAN tasks, it is found to be approximately 250ms longer than gaze duration (Jones et al., 2010; 2012).

Both gaze duration and eye-voice span measures were positively skewed and were log transformed for analysis (Tabachnick and Fidell, 2006). For both our dependent measures, only correct verbal responses were included in the analysis. In total, 9.4% of the data were excluded, across both groups. Of this figure, 1.4% comprised verbal errors on the target (colour response) letter, 5.2% comprised errors in letter naming, and the remainder comprised technical faults. Total counts of verbal errors in each session did not differ as a function of group in letter naming (control: $M = 49.22$, $SD = 20.86$; dyslexic: $M = 51.06$, $SD = 15.28$, $t = 0.638$, $p = .765$) or colour naming (control: $M = 12.33$, $SD = 8.58$; dyslexic: $M = 14.50$, $SD = 10.79$; $t = 0.667$

(34), $p = .510$).

Linear Mixed Effects models were used to analyse the data (see Baayen, 2008; Baayen, Davidson, & Bates, 2008), implemented with `lme4` (Bates, Maechler, & Dai, 2008), and the languageR package (Baayen, 2008) in R Development Core Team (2008). LME models assess the amount of variance contributed to a measure by experimental manipulation(s), whilst separating the variance contributed by 'random' effects. This is a useful method for analyzing data from heterogeneous groups (such as those with dyslexia) performing complex tasks such as RAN, particularly in eye-tracking research, in which there is often missing data (see Jones et al., 2008).

Separate analyses were conducted for Phonological and Visual letter sets, in order to see whether or not automaticity effects would be similar for both types of lexical information. Each analysis comprised two fixed effects (Group and Lexical Competition), with 2 (dyslexia vs. control) and 3 (no, medium, high) levels. Note that, the Group effect compared dyslexic and control readers on the baseline no-competition condition. The fixed effect of Lexical Competition was determined on the basis of the control group only, reflecting automaticity of lexical activation in controls. An absence of an interaction effect would imply that dyslexic readers performed similarly to the controls. An interaction effect would imply that readers with dyslexia behave differently compared with controls. In accordance with our hypotheses, planned comparisons on the Lexical Competition factor and ensuing interactions with Group were made for no competition vs. medium competition conditions, and medium competition vs. high competition conditions. In all analyses, participant and item variances were entered as random effects variables, for which intercepts and slopes on the within-subjects factor Lexical Competition were modeled (Barr, Levy, Scheepers & Tily, 2013). Since target items were not free to vary from

the item in position *n-1*, item variance was characterized by the matched item set (i.e., the constant item in position *n-1* – e.g., 'q' – paired with items in position *n* from no, medium and high conditions). An example of the formal specification of our model in `lme4` would be: `log(eye-voice) ~ group*comp + (1+comp|ppt) + (1+comp*group|item)`. For each analysis (for gaze duration and eye-voice span measures), we report *t*- and *p*-values for each coefficient. Coefficients (*b*) represent log coefficient values. P values are derived from the normal approximation method (Barr et al., 2013).

Figure 2 (left side) shows the *gaze duration* measures for each group in no, medium and high lexical competition conditions. Analyses showed no Group differences on the baseline condition (Phonological: $b = .07$, $t = 1.00$, $p = .319$; Visual: $b = .08$, $t = 1.41$, $p = .158$), though a trend indicated longer time to task switch in the dyslexia group. Main effects on the Lexical Competition factor revealed that control readers' gaze duration increased as a function of increased lexical competition: differences were found between no-medium competition levels (Phonological: $b = .08$, $t = 2.36$, $p = .018$; Visual: $b = .07$, $t = 2.21$, $p = .033$), and medium - high competition levels, for the Phonological letter set ($b = .05$, $t = 2.11$, $p = .035$), but not for the Visual letter set ($b = .01$, $t = .47$, $p = .639$). For the no – medium competition comparison, no significant interactions emerged (*ps* > .05). For the medium – high competition comparison, an interaction emerged by Group, such that visual confusability delayed colour naming ($b = .10$, $t = 2.99$, $p = .001$). No comparable interaction emerged for phonological items ($b = .03$, $t = 1.11$, $p = .27$).

Figure 2 (right side) also shows the *Eye-Voice span* measures for each group in no, medium and high lexical competition conditions. Analyses showed no Group differences on the baseline condition (Phonological: $b = .09$, $t = 1.41$, $p = .167$;

Visual: $b = .09$, $t = 1.78$, $p = .11$, though the trend suggested slower task switching for dyslexic readers. No main effects emerged on the Lexical Competition factor, showing that for controls, the eye-voice span did not significantly increase as a function of increase in lexical competition (*ps* > .05). However, Group x Lexical competition interactions in the no-medium comparisons showed that readers with dyslexia yielded significantly longer eye-voice spans compared with controls (Phonological: $b = .10$, $t = 2.05$, $p = .040$; Visual: $b = .08$, $t = 2.10$, $p = .036$). Moreover, in the Visual letter sets, readers with dyslexia yielded longer eye-voice spans still (compared with controls) in the medium-high comparison ($b = .10$, $t = 2.06$, $p = .039$), but an analogous effect was not found in Phonological letter sets ($b = .01$, $t = .24$, $p = .810$).

[INSERT FIGURE 2 ABOUT HERE]

Discussion

In this experiment we investigated the nature of dyslexic and non-dyslexic readers' 'automatic' lexical processing in a rapid naming task. A primary aim was to assess which impairments in dyslexia constitute a deficit in 'automaticity' of naming. To this end, groups of adult dyslexic and control readers performed a version of the Rapid Automatized Naming task, which included a "Stroop-switch" component: target symbols/letters changed font colour upon fixation, requiring participants to name the colour of the font rather than the letter name and therefore to suppress activation of the competing lexical code.

Our results showed that for *typical readers*, lexical competition affected processing times in ways that were broadly consistent with our hypothesis: Control readers yielded longer gaze durations in response to medium lexical competition

items, in both Phonological and Visual letter sets, compared with no competition items. In other words, activation of the lexical code (e.g., 'k') in the medium condition resulted in a processing delay. Moreover, in Phonological letter sets, high lexical competition items resulted in longer gaze durations than medium competition items: When a letter with similar lexical phonology preceded the target letter (e.g., 'g' preceding the target item 'j'), lexical competition increased. These findings suggest that, for typical readers, lexical processing is obligatory in the context of the rapid naming task, consistent with an automaticity account of rapid naming (cf. Denckla & Rudel, 1976; Wolf & Bowers, 1999; Norton & Wolf, 2012). Further, the speed with which obligatory processing is executed is to some extent dependent on the lexical information activated by previously processed items in the array. However, these findings emerged only in the gaze duration measure; a measure that is sensitive to lexical access (Griffin, 2001, 2004). A similar pattern of results did not emerge in the eye-voice span measure, which includes full phonological encoding and initiation of articulators in addition to lexical access processes (Inhoff et al., 2011; Jones et al., 2008). The current findings suggest that, typical readers automatically activated the task-inappropriate lexical information, but were able to suppress it at the output stage, before the later stages of phonological encoding and articulation of the colour name response (cf. Jones at al., 2008; Protopapas et al., 2007).

For *readers with dyslexia*, gaze durations patterned similarly with typical readers (there was an absence of interaction effects), suggesting that for both types of readers, the initial stages of lexical activation are automatic. The one exception was in high visual confusability conditions, in which successive items with similar visual characteristics delayed gaze durations to the target. However, the eye-voice span measure yielded a number of group discrepancies: A significant interaction emerged

in the no-medium comparison in both Phonological and Visual letter sets: Dyslexic readers continued to be affected by the activation of lexical information for output, even though this activation had been resolved in the control group. This finding is consistent with current theorizing on Stroop effects, in which (typical) readers are able to block the lexical response at the output stage, allowing colour naming to commence (Roelofs, 2003). For dyslexic readers, lexical information cascaded into phonological encoding, which interfered with production of the colour name. Dyslexic readers also showed longer eye-voice spans compared with controls on high vs. medium competition conditions, in Visual letter sets. Thus, inter-item competition at the visual-orthographic level between the target letter and the letter in position *n-1* elicited a further delay in the colour-naming response (see also Jones et al., 2012).

Since the first demonstration of naming deficits in dyslexia, the concept of impaired automaticity in dyslexia has been enshrined in slower performance on Rapid Automatized Naming tasks (Denckla & Rudel,1976). The traditional, serial format of this task has eluded a full explanation of its processing requirements, yet it is routinely used in a clinical setting as a measure of reading fluency. Recent work has made large strides in providing plausible hypotheses for dyslexics' difficulties in serial naming (e.g., Kirby, Georgiou, Martinussen, & Parrila, 2010; Protopapas et al., 2013; Moll & Jones, 2013; Jones et al., 2008, 2009, 2010, 2012; Yan et al., 2013). In relation to dyslexic performance on RAN, it is usual to refer to 'slower access' of lexical codes (e.g., Cutting & Denckla, 2001; Hawelka & Wimmer, 2008; Hawelka, Gagl & Wimmer, 2010; Powell et al., 2007). Our findings refine this assumption, showing that the initiation and time course of lexical recognition in dyslexia appears relatively normal. However, readers with dyslexia show impairment at the output stage, involving phonological encoding leading to articulation (Hulme & Snowling,

1992; Ramus & Szenkovits, 2008). Specifically, we suggest that typical readers encode the lexical verbal output response, which is rapidly suppressed. In contrast, dyslexic readers show difficulty either in the speed with which phonemic output can be computed (before it can be suppressed), or in the cognitive control mechanisms enabling suppression of the phonological response; hypotheses that are not mutually exclusive. At the inter-item level, there is evidence of inadequate suppression of preceding representations in the array, particularly in relation to visual-orthographic codes (see Jones, 2012).

Taken together, our findings suggest that when dyslexic readers perform rapid serial letter naming, early lexical processes appear to be 'automatic', whereas delay occurs at the output stage. Delay at the output stage may be caused by slower activation of phonemic encoding for output (Shankweiler & Crain, 1986; Hulme & Snowling, 1992; Clarke, Hulme, & Snowling, 2005), and/or in the ability to inhibit the output response once it is activated (Everatt et al., 1997; Protopapas et al., 2007; Neuhaus et al., 2001). At the inter-item level (medium vs. high competition condition), presenting two successive items with similar visual-orthographic features led to a longer delay in colour naming, beyond the delay observed for unrelated items. Thus, dyslexic readers demonstrated impaired inhibition of visual-orthographic information relating to the pre-target (*n-1*) item, which then compounded lexical processing difficulty on the target *n*. In other words, the speed of processing / inhibition problem outlined above (in relation to the no-medium comparison) became exaggerated. We note that a parsimonious explanation of the findings would favour an inhibition account: Dyslexic readers experience difficulty in terminating a lexical response once it is activated, which impacts on efficient sequencing of subsequent letters in the array.

Finally, dyslexic readers' difficulty in sequencing more than one item crucially implicated a deficit in visual-orthographic processing (see also Jones et al., 2012). Visual-orthographic information is the direct source of input in reading, from which phonology and meaning are extracted. Adams (1990) characterizes efficient visual-orthographic processing – the ability to quickly recognize letters, whole words and spelling patterns - as the corner stone of fluent reading (cf. Badian, 1994). Formation of fine-grained orthographic codes is determined by feedback from the corresponding phonological code (Badian, 2001; Ehri, 2005a, 2005; Ehri & Saltmarch, 1995; Share, 1995). Thus, compromised neural links enabling adequate feedback can lead to a relatively under-specified orthographic lexicon. In relation to rapid naming, momentary indecision concerning the identity of the orthographic code (particularly in the presence of competitors) would delay naming, impairing fluency.

In summary, we investigated the nature of impaired automaticity for dyslexic readers in rapid naming - a task that has become an almost ubiquitous test in most assessment batteries due to its strong association with reading fluency. We showed that for these adult, high functioning dyslexic readers, lexical processing is obligatory and recognition proceeds along a similar timeline to controls. However, prolonged processing times occurred at the phonological output stage, owing either to a deficit in speed of processing, or in inhibiting the output response. Processing times were prolonged further when visual-orthographic information was difficult to distinguish from the previous stimulus in the array. Researchers who work in the domains of reading and dyslexia commonly refer to dyslexic readers' 'impaired automaticity' in rapid naming and fluency tasks. Our findings identify the processes alluded to in this assumption, and pave the way for further research in this area.

Acknowledgements

This research was funded by the European Commission FP7 grant to the ELDEL (Enhancing literacy development in European Languages) Initial Training Network (ITN). The first author is sponsored by the Coleg Cymraeg Cenedlaethol (www.colegcymraeg.ac.uk). We thank Barbara Haley and Niclaire Parker for assistance.

References

Adams, M. J. (1990). *Beginning to Read: Thinking and Learning about Print*. Cambridge, MA: MIT Press.

Baayen, H. (2008). *Analyzing linguistic data. A practical introduction to statistics*. Cambridge, UK: Cambridge University Press.

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modelling with crossed random effects for subjects and items. *Journal of Memory and Language*, *59*, 390 – 412.

Badian, N. A. (1994). Preschool prediction: Orthographic and phonological skills, and reading. *Annals of Dyslexia*, *44*(1), 1-25.

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, *68*, 255-278.

Bates, D. M., Maechler, M., & Dai, B. (2008). *Lme4: Linear mixed-effects models using S4 classes*. R package version 0.999375–24.

Bowers, P. G., & Swanson, L. B. (1991). Naming speed deficits in reading disability: Multiple measures of a singular process. *Journal of Experimental Child Psychology, 51*,195–219.

Bowey, J. A., & Muller, D. (2005). Phonological recoding and rapid orthographic learning in third-graders' silent reading: A critical test of the self-teaching hypothesis. *Journal of experimental child psychology*, *92*, 203-219.

Breznitz, Z. (2005). Brain activity during performance of naming tasks: Comparison between dyslexic and regular readers. *Scientific Studies of Reading*, *9*, 17-42.

Bruck, M. (1998). Outcomes of adults with childhood histories of dyslexia. *Reading and spelling: Development and disorders*, *179*, 200.

Buswell, G. T. (1920). An experimental study of the eye-voice span in reading. Supplementary Educational Monogram, 17.

Castel, C., Pech-Georgel, C., George, F., & Ziegler, J. C. (2008). Lien entre deÅLnomination rapide et lecture chez les enfants dyslexiques. *L'Année Psychologique*, *108*, 395-422

Clarke P. J., Hulme, C., Snowling, M. J. (2005). Individual differences in RAN and reading: A response timing analysis. *Journal of Research in Reading, 28*, 73-86.

Cutting, L. E., & Denckla, M. B. (2001). The relationship of rapid serial naming and word reading in normally developing readers: An exploratory model. *Reading and Writing*, *14*, 673-705.

de Jong, P. F. (2011). What discrete and serial rapid automatized naming can reveal about reading. *Scientific Studies of Reading*, *15*(4), 314-337.

Denckla, M., & Rudel, R. G. (1976). Rapid “automatized” naming (RAN): Dyslexia differentiated from other learning disabilities. *Neuropsychologia, 14*, 471–479.

Ehri, L. C. (2005a). Development of sight word reading: Phases and findings. In M. J. Snowling & C. Hulme (Eds.), *The science of reading: A handbook* (pp. 135-154). Malden, MA: Blackwell.

Ehri, L. C. (2005b). Learning to read words: Theory, findings, and issues. *Scientific Studies of Reading*, *9*, 167-188.

Ehri, L. C. & Saltmarsh, J. (1995). Beginning readers outperform older disabled readers in learning to read words by sight. *Reading and Writing*, *7*, 295-326.

Everatt, J., Warner, J., Miles, T. R., & Thomson, M. E. (1997). The incidence of Stroop interference in dyslexia. *Dyslexia*, *3*(4), 222-228.

Faccioli, C., Peru, A., Rubini, E., & Tassinari, G. (2008). Poor readers but compelled to read: Stroop effects in developmental dyslexia. *Child Neuropsychology*, *14*(3), 277-283.

Fairbanks, G. (1937). The relation between eye-movements and voice in the oral reading of good and poor silent readers. *Psychological Monographs*, *48*, 78.

Georgiou, G. K., Parrila, R., Cui, Y., & Papadopoulos, T. C. (2013). Why is rapid automatized naming related to reading?. *Journal of experimental child psychology*.

Griffin, Z. M. (2001). Gaze durations during speech reflect word selection and phonological encoding. Cognition, 82, B1–B14.

Griffin, Z. M. (2004). Why look? Reasons for eye movements related to language production. In J. Henderson, & F. Ferreira, (Eds.), *The interface of language, vision, and action* (pp. 213–247). New York, NY: Taylor and Francis

Hawelka, S. & Wimmer, H. (2008). Visual target detection is not impaired in dyslexic readers. *Vision Research*, *48*, 850-852.

Hawelka, S., Gagl, B., & Wimmer, H. (2010). A dual-route perspective on eye movements of dyslexic readers. *Cognition*, *115*, 367-379.

Helland, T., & Asbjørnsen, A. (2000). Executive functions in dyslexia. *Child Neuropsychology*, *6*, 37-48.

Hulme, C., & Snowling, M. (1992). Deficits in output phonology: an explanation of reading failure?. *Cognitive Neuropsychology*, *9*, 47-72.

Inhoff, A. W., Solomon, M., Radach, R., & Seymour, B. A. (2011). Temporal dynamics of the eye–voice span and eye movement control during oral reading. *Journal of Cognitive Psychology*, *23*(5), 543-558.

Jones, M. W., Ashby, J., & Branigan, H. P. (2012). Dyslexia and fluency: Parafoveal and foveal influences on Rapid Automatized Naming. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 554-67.

Jones, M. W., Branigan, H. P., Hatzidaki, A., & Obregón, M. (2010). Is the 'naming'deficit in dyslexia a misnomer? *Cognition*, *116*, 56-70.

Jones, M. W., Branigan, H. P., & Kelly, M. L. (2009). Dyslexic and nondyslexic reading fluency: rapid automatized naming and the importance of continuous lists. *Psychonomic Bulletin and Review,* 16, 567-572.

Jones, M. W., Obregon, M., Kelly, M. L. Branigan, H. P. (2008). Elucidating the component processes involves in dyslexic and nondyslexic reading fluency: an eye-tracking study. *Cognition*, *109*, 389-407.

Kapoula, Z., Lê, T. T., Bonnet, A., Bourtoire, P., Demule, E., Fauvel, C., ... & Yang, Q. (2010). Poor Stroop performances in 15-year-old dyslexic teenagers. *Experimental brain research*, *203*(2), 419-425.

Kirby J. R., Georgiou G. K., Martinussen, R., Parrila, R. (2010). Naming speed and reading: from prediction to instruction. *Reading Research Quaterly, 45*, 341–62.

Kuhn, M. R., Schwanenflugel, P. J., & Meisinger, E. B. (2010). Aligning theory and assessment of reading fluency: Automaticity, prosody, and definitions of fluency. *Reading Research Quarterly*, *45*(2), 230-251.

LaBerge, D., & Samuels, J. (1974). Towards a theory of automatic information processing in reading. *Cognitive Psychology, 6,* 293-323.

Laubrock, J., & Bohn, C. (2008, June). Broadening the scope of eye-movement research in reading: Oral reading and proof reading. In *International Journal of Psychology* (Vol. 43, No. 3-4, pp. 190-190). 27 CHURCH RD, HOVE BN3 2FA, EAST SUSSEX, ENGLAND: PSYCHOLOGY PRESS.

Lefly, D., Pennington, B. (1991). Spelling errors and reading fluency in dyslexics. *Annals of Dyslexia. 41*,143–162.

Lervåg, A., & Hulme, C. (2009). Rapid automatized naming (RAN) taps a mechanism that places constraints on the development of early reading fluency. *Psychological Science*, *20*, 1040–1048.

Logan, G. D. (1997). Automaticity and reading: Perspectives from the instance theory of automatization. *Reading & Writing Quarterly: Overcoming Learning Difficulties*, *13*(2), 123-146.

Logan, J. A., Schatschneider, C., & Wagner, R. K. (2011). Rapid serial naming and reading ability: The role of lexical access. *Reading and Writing*, *24*, 1-25.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: an integrative review. *Psychological bulletin*, *109*, 163.

Moll, K., Fussenegger, B., Willburger, E., & Landerl, K. (2009). RAN is not a measure of orthographic processing. Evidence from the asymmetric German orthography. *Scientific Studies of Reading*, *13*, 1-25.

Moll, K., & Jones, M. (2013). Naming fluency in dyslexic and non-dyslexic readers: Differential effects of visual crowding in foveal, parafoveal and peripheral vision. *The Quarterly Journal of Experimental Psychology, 66*, 2085-91.

Monsell, S. (2003). Task switching. *Trends in cognitive sciences*, *7*(3), 134-140.

Moors, A., & De Houwer, J. (2006). Automaticity: a theoretical and conceptual analysis. *Psychological bulletin*, *132*(2), 297.

Norton, E. S., & Wolf, M. (2012). Rapid automatized naming (RAN) and reading fluency: Implications for understanding and treatment of reading disabilities. *Annual review of psychology*, *63*, 427-452.

Perea, M., Panadero, V., Moret-Tatay, C., & Gómez, P. (2012). The effects of inter-letter spacing in visual-word recognition: Evidence with young normal readers and developmental dyslexics. *Learning and Instruction*, *22*, 420-430.

Perfetti, C. (2007). Reading ability: Lexical quality to comprehension. *Scientific Studies of Reading, 11,* 357–383.

Powell, D., Stuart, M., Garwood, H., Quinlan, P., & Stainthorp, R. (2007). An experimental comparison between rival theories of Rapid Automatized Naming (RAN) performance and its relationship to reading. *Journal of Experimental Child Psychology, 98*, 46-68.

Protopapas, A., Archonti, A., & Skaloumbakas, C. (2007). Reading ability is negatively related to Stroop interference. *Cognitive Psychology*, *54*(3), 251-282.

Protopapas, A., Altani, A., & Georgiou, G. K. (2013). Development of serial processing in reading and rapid naming. *Journal of Experimental Child Psychology*, *116*, 914-929.

Ramus, F., & Szenkovits, G. (2008). What phonological deficit?. *The Quarterly Journal of Experimental Psychology*, *61*, 129-141.

Pollatsek, A., Reichle, E., & Rayner, K. (2003). Modeling eye movements in reading. In J. Hyona, R. Radach, & H. Deubel (Eds.), *The mind's eyes: Cognitive and applied aspects of eye movement research* (pp. 361–390). Amsterdam: Elsevier.

Pollatsek, A., Reichle, E. D., & Rayner, K. (2006). Tests of the EZ Reader model: Exploring the interface between cognition and eye-movement control. *Cognitive Psychology*, *52*, 1-56.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*, 372.

Rayner, K., & Pollatsek, A. (1989). The psychology of reading. Englewood Cliffs, NJ, US: Prentice-Hall.

Rayner, K., Reichle, E. D., & Pollatsek, A. (2005). Eye movement control in reading and the E-Z Reader model. In G. Underwood (Ed.), *Cognitive processes in eye guidance*. Oxford: Oxford University Press.

Reichle, E. D., Rayner, K., & Pollatsek, A. (2003). The E-Z Reader model of eye movement control in reading: Comparison to other models. *Brain and Behavioral Sciences*, *26*, 445–476.

Roelofs, A. (2003). Goal-referenced selection of verbal action: modeling attentional control in the Stroop task. *Psychological Review, 110*, 88–125.

Samuels, S. J., & Flor, R. F. (1997). The importance of automaticity for developing expertise in reading. *Reading & Writing Quarterly: Overcoming Learning Difficulties*, *13*, 107-121.

Savage, R., Pillay, V., & Melidona, S. (2007). Deconstructing rapid automatized naming: Component processes and the prediction of reading difficulties. *Learning and Individual Differences*, *17*, 129-146.

Shankweiler, D., & Crain, S. (1986). Language mechanisms and reading disorder: A modular approach. *Cognition*, *24*, 139-168.

Share, D. L. (1995). Phonological recoding and self-teaching: Sine qua non of reading acquisition. *Cognition*, *55*, 151-218.

Shaywitz, S. E., & Shaywitz, B. A. (2003). Dyslexia (specific reading disability). *Pediatrics in Review*, *24*, 147-153.

Stanovich, K. E. (1990). Concepts in developmental theories of reading skill: Cognitive resources, automaticity, and modularity. *Developmental review*, *10*(1), 72-100.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of experimental psychology*, *18*(6), 643.

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1994). Longitudinal studies of phonological processing and reading. *Journal of learning disabilities*.

Torgesen, J.K., Wagner, R.K., & Rashotte, C. A. (1999). *Test of Word Reading Efficiency (TOWRE)*. Austin, Texas: Pro-Ed.

Walsh, D. J., Price, G. G., & Gillingham, M. G. (1988). The critical but transitory importance of letter naming. *Reading Research Quarterly*.

Wechsler, D. (1998). *Wechsler Adult Intelligence Scale – Third Edition (WAIS-III)*. San Antonio, TX: Harcourt Assessment.

Wechsler, D. (1999). *Wechsler Abbreviated Scale of Intelligence (WASI)*. San Antonio, TX: Harcourt Assessment.

Wile, T. L., & Borowsky, R. (2004). What does rapid automatized naming measure? A new RAN task compared to naming and lexical decision. *Brain and language*, *90*, 47-62.

Wolf, M., & Bowers, P. G. (1999). The double-deficit hypothesis for the developmental dyslexias. *Journal of Educational Psychology, 91*, 415–438.

Wolf, M., & Katzir-Cohen, T. (2001). Reading fluency and its intervention. *Scientific studies of reading*, *5*(3), 211-239.

Yan, M., Pan, J., Laubrock, J., Kliegl, R., & Shu, H. (2013). Parafoveal processing efficiency in rapid automatized naming: A comparison between Chinese normal and dyslexic children. *Journal of experimental child psychology*, *115*(3), 579-589.

Zorzi, M., Barbiero, C., Facoetti, A., Lonciari, I., Carrozzi, M., Montico, M., ... & Ziegler, J. C. (2012). Extra-large letter spacing improves reading in dyslexia. *Proceedings of the National Academy of Sciences*, *109*, 11455-11459.

Table 1

Items per condition in Phonological and Visual letter sets

Phonological					Visual			
n-1	*n* no	*n* medium	*n* high		*n-1*	*n* no	*n* medium	*n* high
g (G)	δ / ζ	k (K)	j (J)		p (P)	δ / ζ	Q	q
j (J)	ж / ф	q (Q)	g (G)		q (Q)	ж / ф	P	p
q (Q)	δ / ζ	j (J)	k (K)		b (B)	δ / ζ	D	d
k (K)	ж / ф	g (G)	q (Q)		d (D)	ж / ф	B	b

Table 2

Group scores on background measures

	Mean (SD)		*T*	*Cohen's d*
	18 Dyslexic	18 Non-Dyslexic		
Age	20.56 (2.41)	20.06 (2.48)	0.61	0.20
Gender (male : female)	6 : 12	5 : 13	0.35	0.11
Word reading[1]	90.72 (9.13)	97.89 (9.30)	2.33*	-0.78
Nonword reading[1]	85.61 (9.06)	102.89 (10.95)	5.16***	-1.72
Verbal-IQ[2]	59.56 (8.41)	58.33 (6.54)	0.49	0.16
Nonverbal-IQ[2]	57.22 (7.46)	56.44 (5.80)	0.35	0.12
Processing speed[3]	11.83 (2.85)	12.22 (2.46)	0.44	-0.15

[1]standard-scores; [2]T-scores; [3]scaled-scores; ***p< .001; **p< .01; *p< .05

Figure captions

Figure 1: Example stimuli of no, medium and high lexical competition conditions from Visual and Phonological letter sets. *Note*. Medium/high lexical competition for Visual letter sets necessitated use of upper /lower case letters, with the result that upper/lower counterbalancing was conducted across all other conditions.

Figure 2: Gaze duration and eye-voice span measures for Phonological and Visual *Note*. * $p<.05$, ** $p<.01$. Estimated log coefficients and 95% confidence intervals are presented as exponential values (gaze durations and eye-voice spans in ms). Grey brackets denote a main effect in the non-dyslexics; black brackets denote an interaction effect.

Figure 1

Visual letter sets				Phonological letter sets				
z	p	ζ	z	z	g	ζ	z	- **No** lexical competition
Z	P	Q	Z	z	g	k	z	- **Medium** lexical competition
z	p	q	z	z	g	j	z	- **High** lexical competition

Figure 2