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Activation time-course of phonological code in silent word recognition in adult readers with and without dyslexia

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Abstract

In skilled adult readers, reading words is generally assumed to rapidly and automatically activate the phonological code. In adults with dyslexia, despite the main consensus on their phonological processing deficits, little is known about the activation time-course of this code. The present study investigated this issue in both populations. Participants' accuracy and eye-movements were recorded while they performed a visual lexical decision task in which phonological consistency of written words was manipulated. Readers with dyslexia were affected by phonological consistency during second fixation duration of visual word recognition suggesting a late activation of the

phonological code. Regarding skilled readers, no influence of phonological consistency was found when the participants were considered as a homogeneous population. However, a different pattern emerged when they were divided into two subgroups according to their phonological and semantic abilities: Those who showed better decoding than semantic skills were affected by phonological consistency at the earliest stage of visual word recognition while those who showed better semantic than decoding skills were not affected by this factor at any processing stage. Overall, the findings suggest that the presence of phonological deficits in readers with dyslexia is associated with a delayed activation of phonological representations during reading. In skilled readers, the contribution of phonology varies with their reading profile, i.e., being phonologically or semantically oriented.

Keywords: Developmental dyslexia, Phonological consistency, Inter-individual differences, Eye-movements, Reading profile, Adults with dyslexia

Introduction

According to the triangle model, visual word recognition results from fast and automatic activation of orthographic, phonological, and semantic codes (Harm and Seidenberg 2004). Numerous studies reported evidence with skilled adult readers. For example, Zeguers et al. (2014) demonstrated that during word reading, skilled readers first extract the orthographic code (i.e., within the first 33 ms), and rapidly translate it into phonological code within 50 ms after word exposure (see Ferrand and Grainger 1992, 1993, 1994 for similar results in French).

In adult readers with dyslexia, visual word recognition is impaired mainly because of deficits in phonological processing (Cavalli et al. 2016; Ramus and Szenkovits 2008). These readers experience difficulties in tasks assessing phonological awareness such as phoneme deletion (Cavalli et al., 2016; Martin et al., 2010), verbal short-term memory (Paulesu et al. 2001; Vasic et al. 2008), and speech sound discrimination (Berent et al. 2013). The specific nature of their phonological deficits is still under debate (Ramus 2014; Szenkovits et al. 2016): whether caused by underspecified phonological representations or by a difficult and/or delayed access to and retrieval of phonological code (Boets et al. 2013; Ramus and Szenkovits 2008). Whatever the nature of the phonological deficit be, one consequence is impaired phonological-orthographic mapping, inducing less efficient visual word processing in this population. This interpretation is confirmed by several studies suggesting that grapheme-phoneme decoding is not as automatic in individuals with dyslexia compared to skilled readers, even in adulthood (Boets et al. 2013; Suárez-Coalla and Cuetos 2015).

Despite the main consensus on phonological deficits in readers with dyslexia, little is known about the activation time-course of phonological code during silent reading, especially in adults. The aim of the present study is to address this issue by comparing the activation time-course of phonological code in adult readers with and without dyslexia when they performed a visual lexical decision task on monosyllabic French words. This question was examined through the manipulation of phonological consistency of written words (Malins et al. 2016), which refers to the number of pronunciations of a given letter string. Letter strings associated with only one pronunciation (e.g., –

uck in *duck* or *luck*) are categorized as consistent. Letter strings associated with more than one pronunciation (e.g., *–ough* in *tough* and *plough*) are categorized as inconsistent.

In skilled readers, behavioral studies showed a phonological consistency effect: reading phonological inconsistent words induce slower latencies than reading consistent ones in visual lexical decision, naming, and silent reading tasks (Graves et al. 2010; Lacruz and Folk 2004; Malins et al. 2016). This effect has been interpreted as reflecting an activation of competing pronunciations making the recognition of inconsistent words more difficult (Graves et al. 2010; Malins et al. 2016). Moreover, using naming tasks, several studies showed increased activation in several brain regions during the processing of inconsistent words, thus suggesting that more resources are needed to process phonological inconsistency (Graves et al. 2010; Malins et al. 2016). Such pattern of activations has also been found with briefly presented targets (Peng et al. 2004), suggesting an automatic reliance on phonological information during visual word recognition in skilled adult readers. However, the robustness of this effect remains debatable, especially in silent reading tasks – such as lexical decision – that do not explicitly require an activation of phonological code (Lacruz and Folk 2004; Taft and van Graan 1998; Ziegler et al. 2008).

In individuals with dyslexia, very few studies examined the influence of phonological consistency during silent word recognition (Bosman et al. 2006; Davies and Weekes 2005) and, to our knowledge, only one investigated this question in adults (Kunert and Scheepers 2014). Kunert and Scheepers (2014) manipulated words' phonological consistency and recorded eye-movements while participants performed an adapted version of the lexical decision task involving a forced choice between two alternatives. In this study, a word and a pseudoword were simultaneously displayed on the screen for 3 seconds. Participants were required to fixate the real word as soon as they recognized it. This experimental design was employed to avoid the speed-accuracy trade off induced by the classical lexical decision paradigm. Overall, readers with dyslexia were slower than skilled readers. Although both groups were slower to recognize inconsistent compared to consistent targets, only the accuracy scores of readers with dyslexia were further affected by the target's phonological consistency. Based on these findings, the authors concluded that adults with dyslexia demonstrated

deficits in both general processing speed and phonological processing. However, the authors did not investigate the influence of phonological consistency on more fine-grained markers like first and second fixations. Therefore, no information on the precise time-course of phonological code activation could be inferred.

The present study

The present study specifically focused on the contribution of phonological codes to reading in university students with dyslexia. We argued that, despite their good level of vocabulary and academic success (Cavalli et al. 2016), this high-functioning dyslexic population might still show subtle phonological deficits even in a relatively elementary reading task. To this aim, participants performed a lexical decision task while we manipulated the phonological consistency of written words and recorded participants' eye-movements. By using eye-tracking measures, we could compare the eye gaze patterns of readers with and without dyslexia and investigate the activation time-course of phonological code during written word recognition at a more fine-grained level than allowed by traditional behavioral measures (i.e., reaction times and accuracy). Previous studies showed that participants often make multiple fixations even during isolated word recognition, which make the examination of eye gaze pattern feasible (Miwa and Dijkstra 2017). In addition, to further ensure that participants' eyes would not remain static, participants were required to respond by eyes rather than by hand as in the classical design of word recognition tasks (the specificities of the experimental design are further developed in the method section). In order to cover a wide range of processing stages, several eye movement measures were considered. Gaze duration (i.e., the sum of all fixations falling on a word before leaving it for the first time) and single fixation duration (i.e., the duration of the first fixation on a word when only one was made during the first reading pass) are both considered as relatively coarse measures reflecting cumulative processing efforts (Leinenger 2014; Rahmanian and Kuperman 2018; Rayner et al. 1998) and will therefore be taken as global measures indexing late processing stages of single word recognition. First fixation duration (i.e., the duration of the first fixation on a word when more than one was made on it during the first pass) and second fixation duration (i.e., the duration of the second fixation falling on a word during the first pass) are taken as

more fined-grained measures reflecting initial (Mousikou and Schroeder 2019; Sereno et al. 2018) and subsequent (Colé et al. 2003; Rahmanian and Kuperman 2018; Reichle et al. 2003) processing stages, respectively. Finally, refixation probability (i.e., the probability that a word will be fixated more than once) can be taken as an indication of the proportion of words read by the direct (orth-sem) and phonologically-mediated (orth-phon-sem) pathways (Hawelka et al. 2010): Words fixated only once are assumed to be recognized via the direct pathway while words fixated more than once would be recognized via the phonologically-mediated one.

Based on previous studies, we expected readers with dyslexia to exhibit longer fixations than skilled readers on every measure (i.e., gaze duration, single, first and second fixations) and to make more refixations (Hawelka et al. 2010). Regarding the influence of the phonological code, as words fixated more than once are assumed to be recognized via phonologically-mediated pathway, their recognition would be more sensitive to the manipulation of phonological consistency of the rime. For these words, if phonological code is readily activated during early processing stages of visual word recognition, as it could be expected in skilled readers, consistency effect should affect the early measures of visual inspection (e.g., first fixation duration, see Sparrow and Miellet 2002). However, the presence of phonological deficits in readers with dyslexia may interfere with this process. In this population, one could expect the influence of phonological code to be delayed (e.g., to occur only during second fixation duration) or absent. Given that words fixated only once are assumed to be processed by means of the direct pathway, phonological consistency of word's rime should not affect single fixation durations. Finally, as gaze duration is a more global and coarse measure encompassing both direct and phonologically-mediated pathways, the influence of phonological consistency on this measure may be unstable, as previously reported for behavioral measures (Lacruz and Folk 2004; Ziegler et al. 2008).

Method

Participants

The experiment was conducted in accordance to the Declaration of Helinski and with the understanding and written consent of each participant. The project was approved by the local ethics

committee (Aix-Marseille University, Marseille, France). We recruited thirty university students with dyslexia (15 women) and 30 gender-matched skilled readers. All were French native speakers from Aix-Marseille University, right-handers, had a normal or corrected to normal vision, and had non-verbal IQ (Raven's Matrices: Raven et al. 1998) within the normal range (above the 75th percentile). None of them reported neither neurological nor psychiatric disorder. All participants with dyslexia reported major difficulties in learning to read during childhood and had received a formal diagnosis of dyslexia.

As reported in Table 1, the two groups were also matched on chronological age (mean: 21.45 years old), educational level (mean: 1.85 years of higher education), vocabulary knowledge (the EVIP scale, Dunn et al. 1993), and non verbal IQ. They were also matched on field of study (humanities and social science, psychology, biology, neuroscience, and mathematics).

Reading efficiency was assessed with a French reading test standardized for adults (*l'Alouette*, Cavalli et al. 2018), taking both accuracy and speed into account. Efficiency of the direct and phonologically-mediated reading pathways (Pritchard et al. 2012) were assessed with irregular words and pseudoword reading tasks from EVALEC (Sprenger-Charolles et al. 2005). Phonological skills involved in reading were assessed through EVALEC's initial phoneme deletion and verbal short-term memory tasks. The two groups differed significantly in reading and phonological skills (Table 1).

Table 1: Cognitive profile of readers with and without dyslexia. Standard deviations are reported in parentheses. Efficiency scores were obtained by dividing accuracy scores with the averaged speed (in ms) for each participant. T-values were obtained from paired student t-tests comparing the two groups of participants (***: $p < .001$; ns: $p > .10$).

	Readers with dyslexia	**Skilled readers**	**t values**	
Chronological age	21.6 (2.3)	21.3 (2.3)	0.356	ns
Years of higher education	1.8 (1.5)	1.9 (1.4)	-0.108	ns
Raven's matrices (max = 58)	45.1 (6.1)	47.1 (5.5)	-1.041	ns

Pretests				
Vocabulary score (*EVIP*, max = 51)	39.8 (4)	40.4 (4.1)	-0.415	ns
Reading efficiency score (*Alouette*)	332.6 (65.6)	483.6 (55.1)	-7.924	***
Irregular word reading *(efficiency)*	1.2 (0.2)	1.4 (0.2)	-4.877	***
Pseudoword reading *(efficiency)*	0.8 (0.2)	1.2 (0.2)	-6.335	***
Phonemic awareness *(efficiency)*	0.4 (0.1)	0.7 (0.1)	-9.721	***
Verbal STM *(span)*	4.6 (0.8)	5.6 (0.6)	-4.523	***

Stimuli

Twenty pairs of phonologically consistent (e.g., *cloche* where –*oche* can only be pronounced /ɔʃ/ in French) and inconsistent (e.g., *clef* where –*ef* can be pronounced /e/ or /ɜf/) monosyllabic words were constructed (Ziegler et al. 1996). Within each pair, words were matched on gender, first letter and first phoneme. As can be seen in Table 2, they were also matched on token and type bigram log frequency, spoken and written log frequency, and orthographic neighborhood (*lexique.org*, New et al. 2001). However, due to material constraints, the words' pairs could not be matched on number of phonemes and letters, and on orthographic and phonological uniqueness points. This will be considered when analyzing the results. A list of the words used in the present study is available in the appendix A.

For the purpose of the lexical decision task, forty pseudowords were created by replacing initial letters of the critical words.

Table 2: Psycholinguistic characteristics of consistent and inconsistent words. Standard deviations are reported in parentheses. T-values were obtained from paired student t-tests comparing the two words' categories on each variable (*: p <.05; **: p <.01; ns: p > .10).

	Consistent words	**Inconsistent words**	**t values**	
Token bigram frequency (log)	3.72 (0.17)	3.72 (0.24)	0.067	ns
Type bigram frequency (log)	4.22 (0.23)	4.21 (0.32)	0.128	ns

Spoken frequency (log)	1.37 (0.54)	1.37 (0.88)	0.01	ns
Written frequency (log)	1.54 (0.47)	1.42 (0.83)	0.539	ns
Number of letters	5.4 (0.8)	4.3 (1.1)	3.488	**
Number of phonemes	3.7 (0.5)	3.2 (0.6)	2.939	*
Orthographic uniqueness point	5.4 (0.8)	4.3 (1.1)	3.317	**
Phonological uniqueness point	3.7 (0.5)	3.2 (0.6)	2.939	*

Procedure

Participants were tested individually in a dimly lit room. They were sitting at 60 cm from the screen, with a chinrest and a forehead rest. Subjects' gaze location was recorded at 1000 Hz with an EyeLink 1000 eye tracker (Eyelink 1000 Tower Mount distributed by SR Research Ltd., Mississauga, Ontario, Canada). Before each session, nine-point gaze calibration and validation were performed and repeated until the validation error was smaller than 1° on average and than 1.5° for the worst point. Ocular data were used online and recorded with the Data Viewer software (SR Research Ltd.). Only the position of the dominant eye was recorded. As several previous studies showed that there is no clear relationship between eye-dominance and reading abilities (Fagard et al. 2008; Newman et al. 1985), this variable was not taken into account in the subsequent analyses.

Stimuli were displayed at the center of a 21-inch CRT monitor (ViewSonic P227f, refresh rate = 85Hz, resolution = 1600*1200 pixels), in black (luminance: 0.3 cd/m²) on a light grey background (luminance: 60 cd/m²) in a *Courier New* font (*x*-height = 0.25°). Participants were asked to avoid any movement during the experiment. They were instructed to decide as fast and accurately as possible if the stimuli were real words. Half of the participants had to provide a 'yes' response by looking at the point in the top right of the screen and a 'no' response by looking at the point in the bottom right (● in Figure 1). The other half of participants received the reversed instructions.

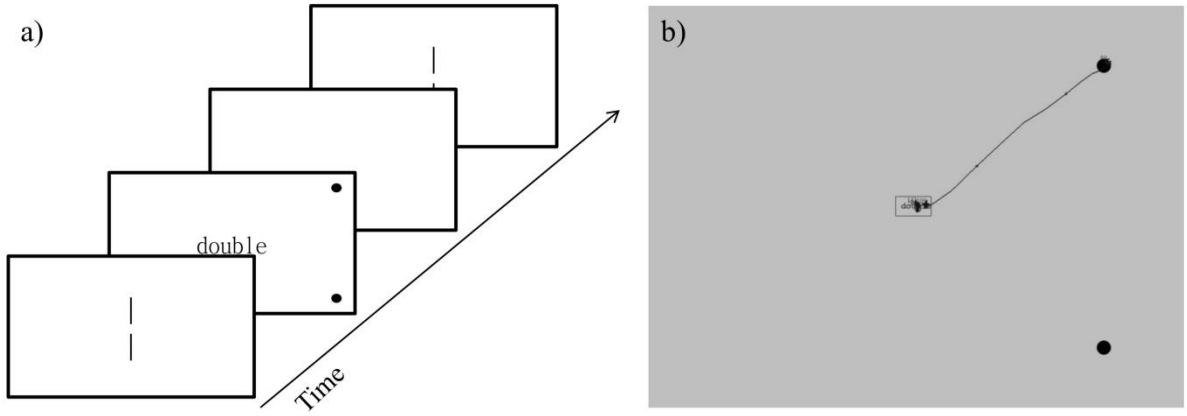

Figure 1: The panel a) shows an illustration of the timed-sequence of a trial. The panel b) shows a screenshot of a trial presentation. The area within the grey box (invisible to the participants) corresponds to the interest area. The grey line illustrates the fixations and a trajectory of a participant's eyes when reading the stimulus and giving a response.

Each trial started with a fixation screen containing two vertical bars at the center (Figure 1, panel a). Participants were required to fixate the area between these bars (fixation area, an invisible 1° window). Once ready, they pressed a button on the response box while keeping the eyes on the fixation area. A stimulus was immediately displayed at the center of the screen and remained visible until participants provided a response. Participants were instructed to blink between trials.

Stimuli were divided into 2 blocks of 40 items (20 words, 20 pseudowords). A new pseudo-randomized list of stimuli was generated for each pair of readers with and without dyslexia. The session started with a practice session containing 26 additional stimuli (13 words, 13 pseudowords).

Data analysis

Data of two individuals with dyslexia (and therefore of their paired skilled readers) were excluded from the analysis due to long fixation duration (deviating more than 2.5 std of the mean of the group) and atypical ocular patterns. Two inconsistent words (and their associated consistent words) were further discarded due to unusually high error rates (≥ 66%, corresponding to $p < .05$ according to a binomial test).

To compare the performances and the activation time-course of phonological code in readers with and without dyslexia, six dependent variables were considered: response accuracy, gaze duration, refixation probability, single, first and second fixation durations. The first four variables provided information on global processes of word recognition (Rahmanian and Kuperman 2018). The two latter provided fine-grained measures of the activation time-course of phonological code (Colé et al. 2003; Sparrow and Miellet 2002).

Incorrect responses, fixations falling outside the target's interest area (see Figure 1), trials with blinks or with fixation durations longer or shorter than the mean ±2.5 std computed on each subject and in each condition were excluded (see Townsend 2018 for a similar procedure). Statistical analyses were performed using *R* (Version 3.5.0) and the *lme4* package (Bates et al. 2015). Fixation durations were analyzed through linear mixed-effects models (LME, Baayen 2008), while accuracy scores and refixation probability (i.e., binary data) were analyzed through generalized linear mixed-effects models (gLME). To select the model that best explains the data and to control for the unmatched psycholinguistic characteristics, we added these unmatched factors as covariates (i.e., number of letters, of phonemes, orthographic uniqueness point, and phonological uniqueness point). Then, we compared each of the combinations we could make with these factors as covariate to the simplest model through the *anova* function from *lme4* package in order to select the best adapted model as indicated by the lowest Akaike information criterion (Matuschek et al. 2017). As the analysis relies on a factorial design, contrasts were assessed with the method of "estimated marginal means" (Searle et al. 1980) using *emmeans* (Lenth 2016) and *multcomp* (Hothorn et al. 2006) packages. This method estimates the marginal means predicted by a given model and proceeds with estimation of various types of contrasts (with Tukey adjustments).

Results

Eye gaze pattern during word reading

For four out of the six dependant variables (i.e., refixation probability, single, first, and second fixations' durations), adding random slopes for subjects and items and the number of letters as

covariate significantly improved the model to a greater extent than any other covariate or combination of covariates. To keep coherence between the analyses, we created the same LME/gLME model for all dependent variables. The model contains two fixed-effects ('group': readers with vs. without dyslexia; 'consistency': consistent vs. inconsistent words), their interaction, the covariate 'number of letters', and random intercepts with random slopes for subjects and items. For the two variables with which adding random slopes for subjects and items as well as the number of letters as covariate did not improve the model (i.e., accuracy and gaze duration), we ensured that it did not significantly decrease the model fit. We first investigated the eye gaze pattern of readers with and without dyslexia, independently of the manipulation of phonological consistency. The mean values of each of the six dependent variables as well as the F ratios of the main effects of group are reported in Table 3. Unsurprisingly, readers with dyslexia made longer fixations than skilled readers on all fixation duration measures (i.e., gaze duration, single, first, and second fixation duration). Although they also tended to be more accurate than skilled readers, the difference did not reach significance. Interestingly, skilled readers mostly made only one fixation on the target word (for 82.1% of trials) while readers with dyslexia fixated only once less often (64.3% of trials).

Table 3: Mean performance obtained in readers with and without dyslexia for the six dependent variables. Standard deviations are reported in parentheses. F ratios and p-values correspond to the main effect of group and were obtained from LME/gLME models (*: p <.05; ***: p <.001; ns: p >.10).

Measure	**Skilled readers**	**Readers with dyslexia**	**Main effect of group**	
Gaze duration (ms)	428 (109)	593 (186)	F(1,62)=53.87	***
Accuracy (%)	87.7 (32.9)	92.0 (27.1)	F(1,Inf)=3.28	ns
Single fixation duration (ms)	432 (112)	557 (190)	F(1,60)=26.92	***
First fixation duration (ms)	180 (96)	234 (153)	F(1,39)=6.63	*
Second fixation duration (ms)	229 (109)	326 (173)	F(1,42)=18.54	***
Refixation probability (%)	17.9 (38.4)	35.7 (47.9)	F(1,Inf)=13.78	***

Phonological code activation

Mean accuracy scores and refixation probabilities for each group and condition are reported in Figure 2. Analysis on accuracy scores showed no main effect of consistency [F <1]. The interaction between group and consistency was significant [F(1,inf) =4.32, p <.04]. Post-hoc comparisons revealed that simple effects of consistency were not significant in either group (readers with dyslexia: estimates =0.65, standard deviation =0.43, z ratio =1.535, p =.13; skilled readers: estimates =-0.20, standard deviation =0.40, z ratio =-0.512, p =.61), although the advantage of consistent over inconsistent words seems somewhat larger in the dyslexic group. Analysis on refixation probability revealed neither main effect of consistency nor interaction between group and consistency [both Fs <1].

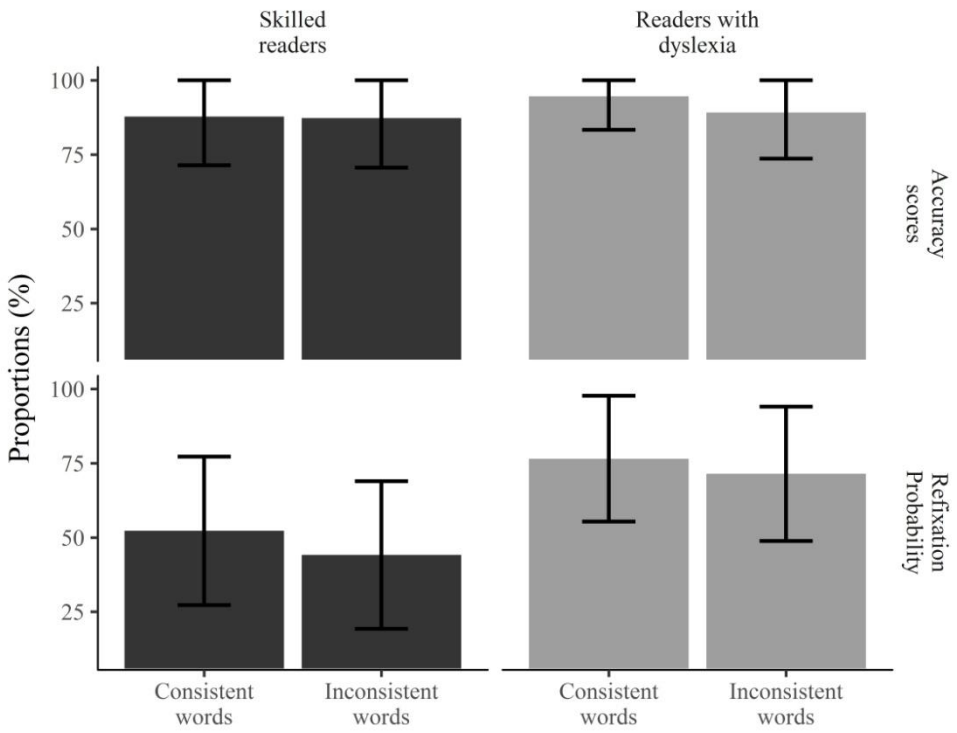

Figure 2: Mean proportions of correct responses (top panel) and refixation probability (bottom panel) on consistent and inconsistent words in readers with (light grey) and without (dark grey) dyslexia. Error bars represent standard deviations.

Mean fixation durations for each group and condition are reported in Figure 3. The analysis on gaze duration and single fixation duration showed neither main effect of consistency nor interaction between group and consistency for any of these measures [all Fs <1].

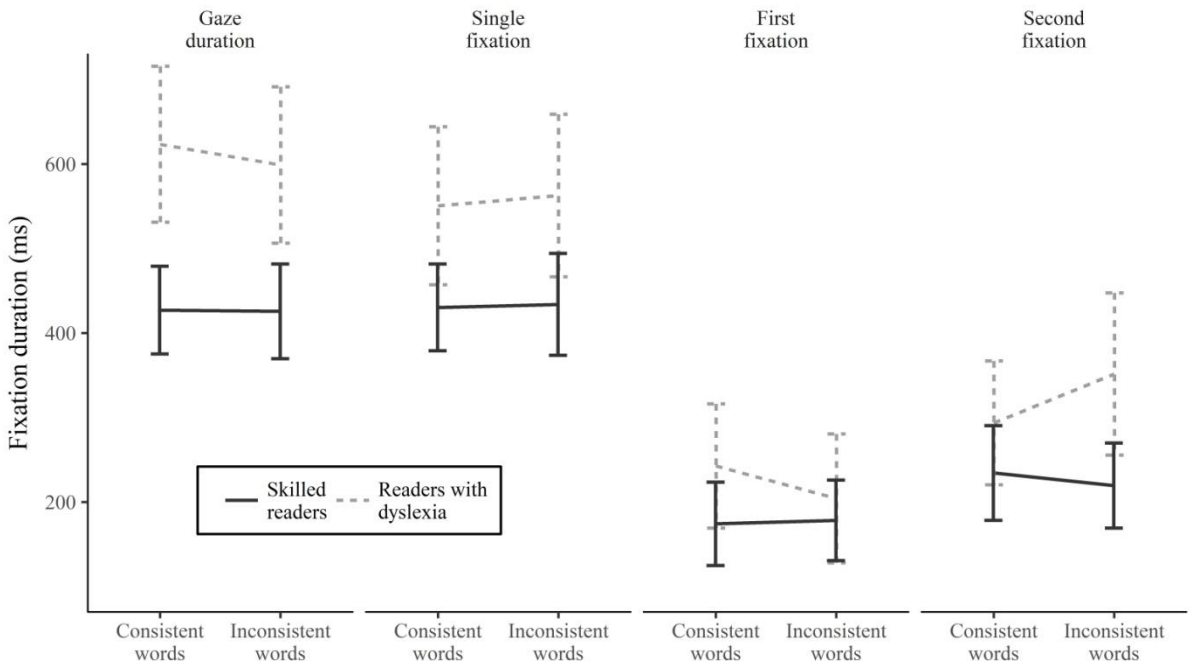

Figure 3: Mean durations of fixations on consistent and inconsistent words in readers with (dashed light grey lines) and without (dark lines) dyslexia for gaze duration, single, first, and second fixations. Error bars represent standard deviations.

The analysis performed on first fixation duration revealed no significant main effect of consistency [F<1]. The interaction between group and consistency failed to reach significance [F(1,27) =2.99, p =.10]. Finally, the analysis of second fixation duration showed no main effect of consistency [F<1] but a significant interaction between group and consistency [F(1,20) =5.50, p <.03]. Post-hoc comparisons showed that readers with dyslexia made longer fixations on inconsistent than on consistent words (estimates = -44.16, standard deviation =20.47, t ratio =-2.157, p =.04), while skilled readers showed no difference between the two conditions (estimates =27.56, standard deviation =25.45, t ratio =1.083, p =.29).

Several interpretations can be put forward to explain the absence of the phonological consistency effect in skilled readers. One comes from the fact that the words used in the experiment

were very short and frequent (see Table 2) and were mostly recognized in only one fixation (82.1% of trials). Since they were most likely recognized via the direct pathway (Difalcis et al. 2018), the impact of the manipulation of phonological consistency on a sublexical unit might have been reduced. Previous behavioral studies indeed showed that this kind of manipulation had stronger effect for low-frequency words than for high-frequency words (Seidenberg et al. 1984).

Another interpretation, more related to the characteristics of participants, comes from recent studies manipulating the phonological consistency of written words in naming tasks. These studies suggest that the influence of phonological consistency in skilled readers may depend on individuals' reading profile, that is, whether they rely more on their phonological or semantic skills when they recognize written words (Hoffman et al. 2015; Woollams et al. 2016). Using a naming task, Woollams et al. (2016) investigated this question by manipulating semantic (i.e., imageability) and phonological (i.e., consistency) properties of written words that they presented to skilled readers with different reading profiles. The authors showed that readers with high semantic reliance exhibited a larger imageability effect than readers with low semantic reliance when they processed inconsistent words, but not when they processed consistent words. Furthermore, when using low imageability words, readers with high semantic reliance were more affected by phonological consistency than readers with low semantic reliance. They interpreted these results as suggesting that skilled readers with relatively higher semantic but lower phonological skills compared to their peers (henceforth, "semantic readers") seemed to rely more on the connections between the orthographic and semantic codes when recognizing words, and had less well developed phonological representations. Although the causal link remains to be investigated, they speculated that this mild disadvantage in phonological skills might have increased their reliance on semantic activation to cope with the processing load induced by phonological inconsistency (Woollams and Patterson 2012). However, those who showed the opposite profile (henceforth, "phonological readers") seemed to rely more on the connections between orthography and phonology regardless of the imageability degree of the stimuli (see also Hoffman et al. 2015).

As mentioned above, the literature on skilled readers suggests a negative correlation between semantic and phonological abilities (Hoffman et al. 2015; Woollams et al. 2016; Woollams and Patterson 2012). In the present sample of skilled readers, we indeed found such correlation between the raw scores of vocabulary knowledge (which highly contributes to proficient semantic reading skills, according to Nalom et al. 2015) and the efficiency scores of pseudoword reading (r = -0.390, p =.04; see Figure 4, right panel). The same correlation was not significant in readers with dyslexia (r = -0.004, p =.98; see Figure 4, left panel).

Thus, we decided to conduct post-hoc analyses taking into account the inter-individual differences among skilled readers and examined whether the activation time-course of the phonological code depended on their reading profile. We expected "phonological readers" to exhibit a stronger and probably earlier influence of phonological consistency than "semantic readers" who are more likely to bypass the phonological code activation during silent reading.

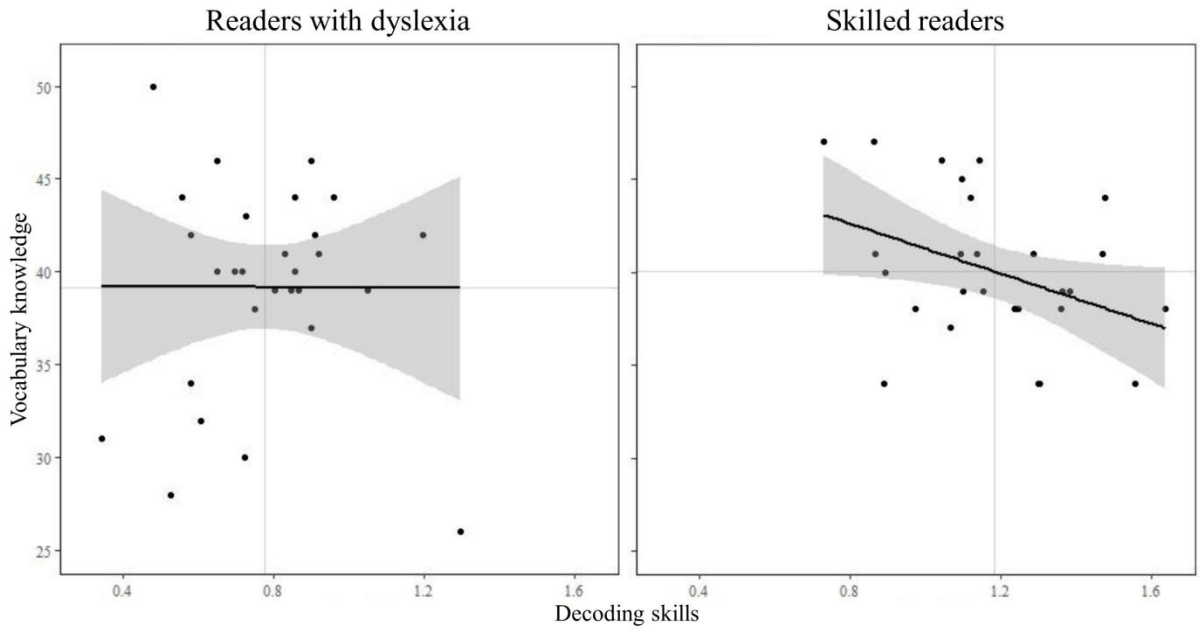

Figure 4: Performances of individual subjects on vocabulary knowledge (y axis, raw scores) and phonological decoding skills (x axis, efficiency scores of pseudoword reading) for readers with dyslexia (left panel) and skilled readers (right panel). The black lines represent the correlations between the two variables and the grey areas represent standard deviations. The light grey lines represent the mean performance of each group on each variable.

Moreover, despite the absence of a significant correlation between vocabulary knowledge and phonological decoding skills in individuals with dyslexia, we also conducted post-hoc analyses examining the inter-individual differences in this group of participants. These additional analyses were motivated by two arguments. First, the emerging literature on protective and compensatory mechanisms in readers with dyslexia (Cavalli et al. 2017; Farris et al. 2016; Haft et al. 2016; Moojen et al. 2020). In particular, several studies reported that some individuals with dyslexia show a relatively good comprehension level despite poor decoding skills, which highlights a discrepancy these two types of skills in readers with dyslexia (Aboud et al. 2016; Cutting et al. 2016; Patael et al. 2018; Welcome et al. 2010). Second, the fact that linear correlations are not always the best way to investigate relations between different skills, especially when there is a strong heterogeneity among individuals. Similarly to the skilled readers group, we hypothesized that readers with dyslexia who showed better semantic skills (hereafter, sem+ dyslexics) could be less influenced by phonological consistency than those who showed better phonological skills (hereafter, sem- dyslexics). However, in the latter group, the phonological consistency effect was expected to occur only on the second fixation (which reflects a late processing stage) given the lack of strong and efficient connections between the phonological and orthographic codes in this population.

Post-hoc analyses: Exploring inter-individual differences in the contribution of phonology to reading among skilled readers

Based on Woollams et al. (2016)'s assumptions and on the negative correlation we observed, we classified our skilled readers as phonological or semantic readers according to their performance on pseudoword naming and vocabulary tasks. For each of these two variables, we calculated the median of the group and subtracted it from the subjects' scores. Following previous studies (Hoffman et al. 2015; Woollams et al. 2016), we ranked each skilled reader from 1 to 28 (from the highest to the lowest value). To take into account both variables, we subtracted the rank position obtained in the pseudoword naming task from the one obtained in the vocabulary task. Phonological readers obtained positive scores (i.e., higher decoding skills than vocabulary knowledge), while semantic readers obtained negative scores (i.e., higher vocabulary knowledge than decoding skills). As described in

Table 4, the comparison of the cognitive profiles of the two subgroups indeed showed that the semantic and phonological readers performed differently in tasks involving vocabulary, phonological decoding, and phonological STM while showing similar reading performance on the *Alouette* Test which confirmed that, despite their different reading profile, the two subgroups were matched on overall reading efficiency.

Table 4: Cognitive profile of ’phonological’ and ’semantic’ skilled readers. Standard deviations are reported in parentheses. Efficiency scores were obtained by dividing accuracy scores by the averaged speed (in ms) for each participant. T-values were obtained from paired student t-tests comparing the two subgroups of participants (***: $p < .001$; *: $p \leq .05$; ns: $p > .10$).

	Phonological readers	**Semantic readers**	**t values**	
Raven’s matrices (max = 58)	49.6 (4.5)	49.7 (5.4)	-0.044	ns
Reading efficiency score (*Alouette*)	496.2 (30.5)	474.2 (55.8)	0.192	ns
Pseudoword reading *(efficiency)*	1.3 (0.2)	1.0 (0.2)	4.983	***
Vocabulary score (*EVIP*, max = 51)	37.6 (2.9)	42.5 (3.2)	-4.916	***
Irregular word reading *(efficiency)*	1.5 (0.2)	1.3 (0.2)	4.490	***
Phonemic awareness *(efficiency)*	0.8 (0.1)	0.7 (0.2)	1.501	ns
Verbal STM *(span)*	5.8 (0.4)	5.4 (0.7)	2.482	*

The role of phonology in reading was examined through LME/gLME models. We applied the same selection procedure as in the first analyses to select the model that best fits the data. For three out of the six dependent variables (i.e., gaze duration, accuracy, and single fixation duration), adding random slopes for subjects and items and the covariate ‘orthographic uniqueness point’ significantly improved the model. Therefore, we created the same LME/gLME model for the six dependent variables. The model included two fixed-effects (‘subgroup’: phonological vs. semantic readers; ‘consistency’: consistent vs. inconsistent words), their interaction, the covariate ‘orthographic uniqueness point’, and random intercepts with random slopes for subjects and items. Again, adding

random slopes for subjects and items as well as the orthographic uniqueness point as covariate did not systematically improve the model (i.e., refixation probability and first and second fixation durations). In those specific cases, we ensured that it did not significantly decrease the model fit. To ensure comparability with the comparison between readers with and without dyslexia, we also conducted the analyses using the same model as in the initial analyses, i.e., using 'number of letters' instead of 'orthographic uniqueness point' as covariate. The results are available in the appendix B and were similar to those obtained with the model including 'orthographic uniqueness point' as covariate.

Mean accuracy scores and refixation probabilities for each subgroup and each condition are reported in Figure 5. Analysis on accuracy scores showed no main effect of consistency and no interaction between subgroup and consistency [both Fs <1]. Analyses on refixation probability did not reveal either main effect of consistency or interaction between subgroup and consistency [both Fs <1].

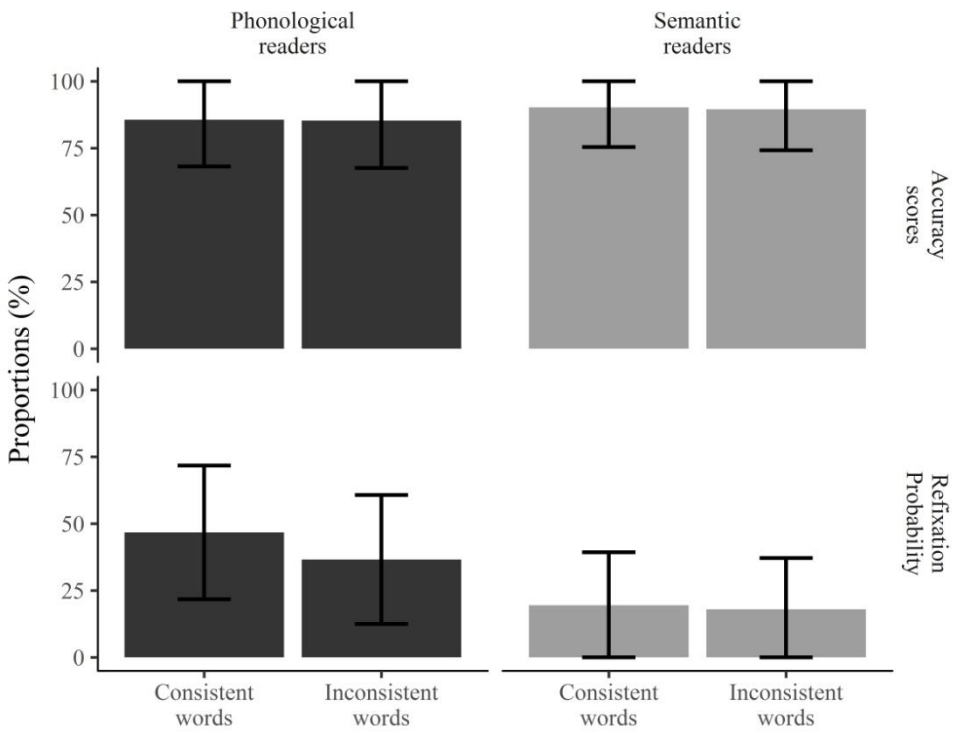

Figure 5: Mean proportions of correct responses (top panel) and refixation probability (bottom panel) on consistent and inconsistent words in phonological (dark grey) and semantic readers (light grey). Error bars represent standard deviations.

Mean fixation durations for each subgroup and condition are reported in Figure 6. Analysis on gaze duration revealed neither main effect of consistency [F(1,27) =1.37, p =.25], nor interaction between subgroup and consistency [F(1,23) =1.18, p =.29]. The same pattern of results was observed when analyzing single fixation duration: no main effect of consistency [F <1], and no interaction between subgroup and consistency [F(1,20) =1.71, p =.21].

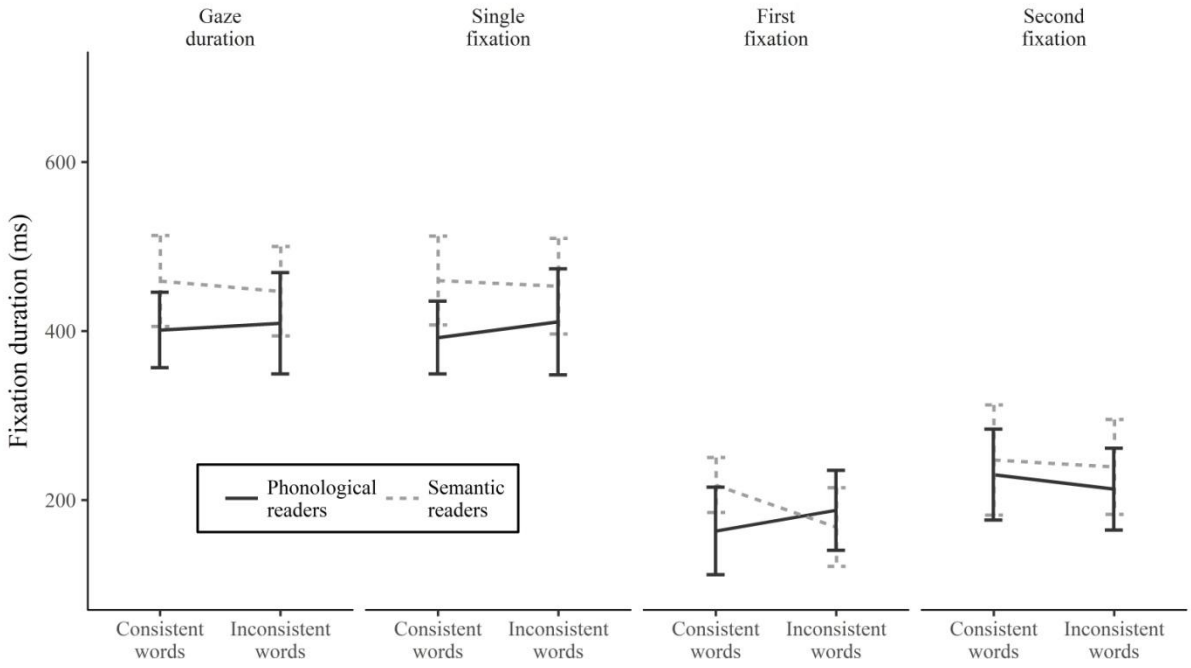

Figure 6: Mean fixation durations on consistent and inconsistent words in phonological (dark lines) and semantic readers (dashed light grey lines) for gaze duration, single, first, and second fixations. Error bars represent standard deviations.

We then examined the first and second fixation durations. However, since words that were fixated more than once represent only 17.9% of the correctly recognized words on average (25.9% in phonological readers, 10.1% in semantic readers), these results must be taken with caution. The analysis of first fixation duration showed no main effect of consistency [F <1]. However, the interaction between subgroup and consistency was significant [F(1,9) =6.09, p <.04]. Interestingly, post-hoc comparisons indicated that phonological readers were affected by phonological consistency: they tended to make longer fixations on inconsistent than on consistent words (estimates =-42.29, standard deviation =21.03, t ratio =-2.011, p =.06) while semantic readers were not influenced by this

factor (estimates =41.49, standard deviation =29.22, t ratio =1.420, p =.18). For second fixation duration, the analyses did not reveal either main effect of consistency or interaction between subgroup and consistency [both Fs <1].

Post-hoc analyses: Exploring inter-individual differences in the contribution of phonology to reading among readers with dyslexia

The emerging literature on protective and compensatory mechanisms in readers with dyslexia suggests that strong morphological awareness (Cavalli et al. 2017; Haft et al. 2016; Law et al. 2015) and/or strong vocabulary skills (Cavalli et al. 2016; Haft et al. 2016; Rose and Rouhani 2012) have protective effects against poor reading outcomes. Moreover, it has been reported that some readers with dyslexia exhibited a discrepancy between decoding and comprehension skills (Aboud et al. 2016; Cutting et al. 2016; Patael et al. 2018; Welcome et al. 2010). Therefore, despite the absence of linear correlation between vocabulary knowledge and phonological skills in our sample of readers with dyslexia (r = -0.004, p =.98; Figure 4, left panel), it was still worth examining whether the contribution of phonology to reading was modulated by inter-individual differences regarding these two abilities. Readers with dyslexia were divided into sem+ and sem- dyslexics following the same procedure applied on skilled readers. As shown in Table 5, the comparison of the cognitive profile of the two subgroups showed that they only differed on pseudoword reading efficiency and vocabulary scores, which are the two variables that we used to separate them. This observation suggests that the two subgroups were matched on overall reading efficiency and phonological skills.

Table 5: Cognitive profile of ’sem-’ and ’sem+’ dyslexics. Standard deviations are reported in parentheses. Efficiency scores were obtained by dividing accuracy scores by the averaged speed (in ms) for each participant. T-values were obtained from paired student t-tests comparing the two subgroups of participants (*: p ≤ .05; ns: p >.08).

	Sem- dyslexics	**Sem+ dyslexics**	**t values**	
Raven’s matrices (max = 58)	48.71 (48.7)	48.07 (48.1)	0.372	ns
Reading efficiency score (*Alouette*)	365.91 (365.9)	338.97 (339)	1.136	ns

Pseudoword reading *(efficiency)*	0.88 (0.9)	0.68 (0.7)	2.728	*
Vocabulary score (*EVIP*, max = 51)	36.57 (36.6)	41.79 (41.8)	-2.714	*
Irregular word reading *(efficiency)*	1.23 (1.2)	1.1 (1.1)	1.803	ns
Phonemic awareness *(efficiency)*	0.43 (0.4)	0.42 (0.4)	0.187	ns
Verbal STM *(span)*	4.5 (4.5)	4.79 (4.8)	-0.968	ns

Again, the role of phonology in reading was examined through LME/gLME models and we applied the same selection procedure as described above. For four out of the six dependent variables (i.e., durations of single fixation, first and second fixations, and accuracy scores) adding random slopes for subjects and items as well as the covariate 'number of letters' significantly improved the model. For the two other variables (i.e., gaze duration and second fixation duration), this did not significantly decrease the model fit. We therefore created the same LME/gLME model for the six dependent variables. The model included two fixed-effects ('subgroup': sem- vs. sem+ dyslexics; 'consistency': consistent vs. inconsistent words), their interaction, the covariate 'number of letters', and random intercepts with random slopes for subjects and items. To ensure comparability with the model applied on the data on skilled readers, we also conducted the analyses using 'orthographic uniqueness point' instead of 'number of letters' as covariate. The results are available in the appendix C and were similar to those obtained with the model including 'number of letters' as covariate.

Mean accuracy scores and refixation probabilities for each subgroup and each condition are reported in Figure 7. Analysis on accuracy scores showed no main effect of consistency and no interaction between subgroup and consistency [Fs <1]. Analyses on refixation probability did not reveal either main effect of consistency [F(1,inf) =1.84, p =.18] or interaction between subgroup and consistency [F <1].

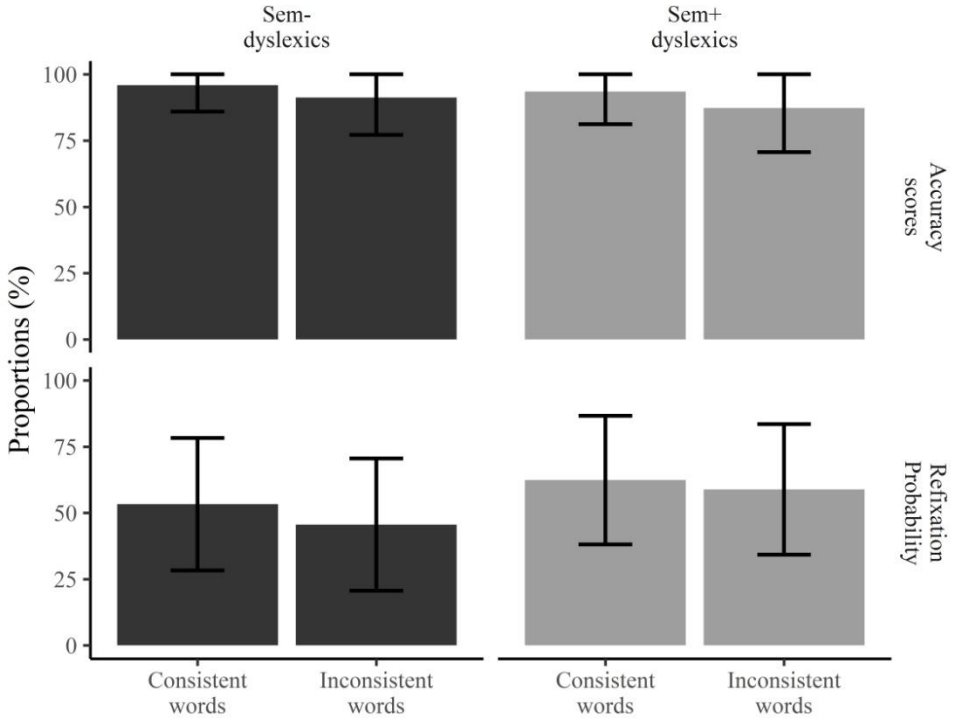

Figure 7: Mean proportions of correct responses (top panel) and refixation probability (bottom panel) on consistent and inconsistent words in sem- (dark grey) and sem+ dyslexics (light grey). Error bars represent standard deviations.

Mean fixation durations for each subgroup and condition are reported in Figure 8. Analysis on gaze duration revealed neither main effect of consistency, nor interaction between subgroup and consistency [both Fs <1]. The same pattern of results was observed when analyzing single fixation duration: no main effect of consistency [F <1], and no interaction between subgroup and consistency [F(1,19) =1.13, p =.30].

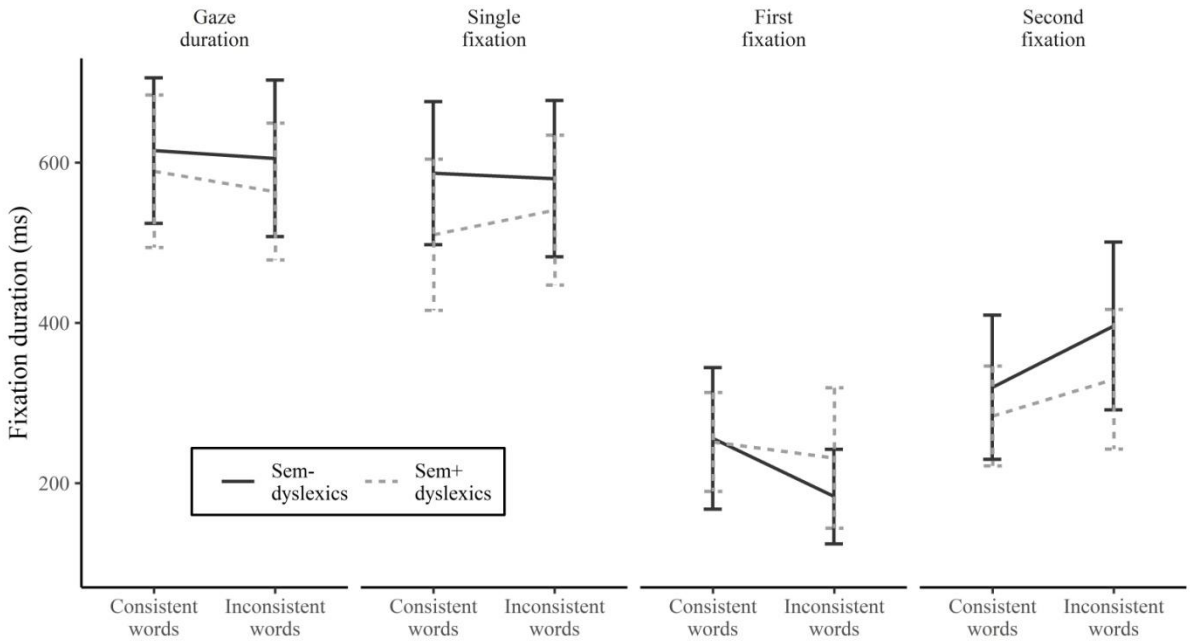

Figure 8: Mean fixation durations on consistent and inconsistent words in sem- (dark lines) and semantic dyslexics (dashed light grey lines) for gaze duration, single, first, and second fixations. Error bars represent standard deviations.

We then examined the first and second fixation durations. Since words that were fixated more than once represent only 33.9% of the correctly recognized words on average (29.2% in sem- dyslexics, 38.7% in sem+ dyslexics), these results must be taken with caution. The analysis of first fixation duration showed no main effect of consistency [$F(1,23) = 1.27$, $p = .27$] and no interaction between subgroup and consistency [$F(1,16) = 1.90$, $p = .19$]. For second fixation duration, the analyses revealed a marginally significant main effect of consistency [$F(1,18) = 3.40$, $p = .08$] but no interaction between subgroup and consistency [$F(1, 15) = 1.72$, $p = .21$].

Discussion

The present study investigated task performance and eye gaze patterns of adults with and without dyslexia when they recognized visual words, as well as the contribution and the activation time-course of phonological code in this process. To this aim, we recorded the accuracy score and several coarse-grained and fine-grained parameters related to eye-movements during a lexical decision task in which the phonological consistency of written words was manipulated.

Phonological skills in adults with dyslexia

Before performing the lexical decision task, all participants completed a battery of pre-tests that evaluated different aspects of phonological processing. The results showed that adults with dyslexia had poorer performance than skilled readers in all tasks, indicating their persistent phonological deficits in phonemic awareness (Cavalli et al., 2016; Martin et al., 2010), verbal short-term memory (Paulesu et al. 2001; Vasic et al. 2008) and pseudoword reading (Suárez-Coalla and Cuetos 2015). The first two phonological skills, namely the ability to explicitly manipulate speech sounds and the ability to store phonological structure of words during a very short period of time are central abilities linked to reading success and are determinant for pseudoword reading. Phonemic awareness is necessary to understand the alphabetic principle and allows the learning of letters-sounds correspondences to decode written words. During the reading process, the sounds generated from the perceived letters are stored in memory, which allows a subsequent activation of the associated semantic codes. In addition, many studies suggest that during reading acquisition, the automation of this decoding procedure or phonologically-mediated pathway (orth-phon-sem) allows children to develop the direct pathway (orth-sem; Windfuhr and Snowling 2001; Ziegler et al. 2013). Thus, the presence of deficits at the decoding stage may explain why readers with dyslexia show persistent reading deficits in adulthood.

In addition to the poor performance observed in the diagnostic tasks, eye gaze patterns recorded during the lexical decision task further contributes to a better specification of the underlying deficits in adults with dyslexia. First, we found that even in this relatively elementary task performed on familiar, high-frequency words, readers with dyslexia made more refixations and longer fixation duration than skilled readers on both global (i.e., gaze duration and single fixation duration) and fine-grained measures (i.e., first and second fixations' duration). This pattern of results obtained in French replicates those previously reported in both more and less transparent orthographic systems, such as Italian (De Luca et al. 2002) and English (Rayner 2009; Vagge et al. 2015; Yagle et al. 2017). It reflects a profound and general deficit which is independent of the transparency of the orthographic system (Rayner 2009; Vagge et al. 2015).

Second, by combining the eye movement technique with the manipulation of word's phonological consistency, we were able to identify another aspect of the reading process that may contribute to reading difficulties, namely, the activation of phonological code. The coarsest measures (i.e., accuracy scores, gaze duration, and single fixation duration) did not show any influence of phonology during written word recognition, in either populations, which is consistent with previous studies (see also Balota et al. 2004; Pexman et al. 2002; Ziegler et al. 2008 for similar observations). However, the finer-grained measures (i.e., first and second fixations' durations) revealed different time courses of phonological code activation in these two populations. Given the existence of phonological deficits in readers with dyslexia as revealed by the pretests, one could expect that the activation of the phonological code would be delayed or absent in this population compared to skilled readers whose activation of the code has been reported to be fast and automatic (Pattamadilok et al. 2017; Zeguers et al. 2014).

Indeed, the analyses of eye gaze patterns in readers with dyslexia showed that only the duration of second fixation, which reflects a late processing stage, was affected by phonological consistency. This delayed activation of the phonological code may contribute to slow written word recognition in readers with dyslexia (Boets et al. 2013; Cavalli et al. 2018). If in skilled readers, words could be recognized in parallel by both direct and phonologically-mediated pathways (Castles et al. 2006, 2009), the delayed activation of the phonological code in readers with dyslexia would inevitably render the phonologically-mediated pathway less efficient and therefore reduce the overall speed of word recognition.

The delayed activation of the phonological code in adults with dyslexia reported here may reflect a general weakness of the reading system, which itself, was caused by inadequately developed phonological representations during oral language acquisition. As previously argued in the literature (Torppa et al. 2010), a poorly developed oral language would entail poorly developed orthographic code, diminished synchronization between the phonological and orthographic codes (Breznitz and Misra 2003), as well as less efficient connections with the semantic code (Gentaz et al. 2015).

Nonetheless, it is worth noting that more and more studies highlight the heterogeneity of the cognitive profiles in readers with dyslexia. More precisely, it has been shown that well developed morphological (Cavalli et al. 2017; Law et al. 2015) and vocabulary (Cavalli et al. 2016; Rose and Rouhani 2012) skills are protective factors against poor reading outcomes and can enhance both reading comprehension and reading fluency in this population (Haft et al. 2016). Some studies also point out a discrepancy between decoding and comprehensions skills in this population (Aboud et al. 2016; Cutting et al. 2016; Patael et al. 2018; Welcome et al. 2010). However, the analyses comparing the influence of phonological consistency in readers with dyslexia who exhibited better vocabulary knowledge while being poor decoders (i.e., sem+ dyslexics) and those who showed the opposite profile (sem- dyslexics, who remained poor decoders when compared to skilled readers) did not show a significant interaction between consistency and dyslexics' subgroups on any measure. A marginally significant main effect of consistency was found on second fixation duration, which confirmed the result observed in the entire group of participants.

Two reasons of this absence of a significant interaction can be put forward. First, this could be due to a lack of power, as each subgroup contained only 15 individuals, which might not be enough to reveal interactions between dyslexics' subgroups and consistency, especially in this very heterogeneous population. Second, it is also possible that the task used in the present study was not the most appropriate to highlight the difference between the two subgroups since participants were presented with isolated words. Indeed, protective factors based on semantic skills may be more efficient in the presence of contextual information (Bruck 1990; Corkett and Parrila 2008). As mentioned in the introduction, due to their persistent and pervasive difficulties in decoding abilities, readers with dyslexia have difficulties to synchronize the phonological and orthographic codes (Breznitz and Misra 2003), leading to less efficient connections with the semantic code (Gentaz et al. 2015) and, therefore, a less automated direct pathway. As a result, even those who developed protective factors based on strong semantic skills may experience difficulties and continue to rely on inefficient connections between the orthographic and phonological codes when recognizing isolated

words. In addition, all the words used in the experiment were mono-morphemic, which might not allow readers with dyslexia to take an advantage of semantic information conveyed by morphemes.

Visual word recognition in skilled readers

Taken as a group with homogeneous reading skills, our skilled reader participants did not show a phonological consistency effect neither on first nor on second fixation duration. This observation is surprising as many studies claimed that in this population, phonological code is rapidly and automatically activated during visual word recognition (Pattamadilok et al. 2017; Zeguers et al. 2014).

In an attempt to explain this unexpected finding and based on the proposal from recent studies on skilled readers that looked at the effect of phonological consistency on written word naming, we performed additional post-hoc analyses. Several studies argued that the influence of phonology during reading might also depend on the balance between participants' phonological and semantic skills (Hoffman et al. 2015; Woollams et al. 2016). According to these studies, skilled readers with higher phonological than semantic skills (i.e., phonological readers) seem to rely more systematically on the connections between orthographic and phonological codes when recognizing words. Reversely, readers showing higher semantic than phonological skills (i.e., semantic readers) seem to rely more systematically on the connections between orthographic and semantic codes (Woollams et al. 2016; Woollams and Patterson 2012). Based on the claim that skilled readers may not represent a homogeneous population with identical reading profile, we decided to conduct exploratory analyses of inter-individual differences in our sample of skilled readers and test the hypothesis that participants' reading profile might have affected the contribution of phonology during reading.

In other words, the literature suggests a negative correlation between semantic and phonological abilities in skilled readers. In line with this observation, we indeed found a correlation between vocabulary knowledge and phonological decoding skills which was significant in skilled readers only. This observation further justified the separation of these participants into two subgroups according to their cognitive profile.

Based on the classification proposed by Woollams et al. (2016), skilled readers were separated into two subgroups according to their decoding skills and vocabulary knowledge. According to these authors, we expected phonological readers to be influenced by the phonological code from the earliest processing stages of visual word recognition. However, the semantic readers, who have developed strong connections between orthographic and semantic codes, would be more likely to bypass phonological code during silent reading, especially when high-frequency words are used, and thus may not show a phonological consistency effect at any processing stage.

The analyses on the global measures (i.e., gaze duration, single fixation duration, and accuracy) did not reveal any influence of the phonological consistency on written word recognition. Interestingly, the analyses of first and second fixation durations providing more fine-grained measures of the different processing stages showed that phonological readers were influenced by phonological consistency during first fixation while semantic readers did not show any phonological consistency effect. Although this exploratory finding should be considered with caution, this pattern of results suggests that the rapid activation of phonological code during reading may not be a general characteristic of skilled readers as typically assumed but may be restricted to individuals who have developed high decoding skills and consequently for whom phonological code activation is a key process when reading words.

The above observation nicely fits into the framework of the triangle reading model which assumes that the strength of the connections between orthographic, phonological and semantic codes depends on individual's decoding and semantic skills (Harm and Seidenberg 2004; Hoffman et al. 2015; Woollams et al. 2016). Skilled readers with high decoding skills may rely more strongly on the phonological or phonologically-mediated pathway (connections between orthographic and phonological codes) when reading words while skilled readers with high semantic skills may rely more strongly on the semantic or direct pathway (connections between orthographic and semantic codes). Although this model was initially created to explain the reading performance in a relatively opaque language like English where the differences between the mechanisms involved in regular and

irregular word reading is discernible, our findings suggest that the same dissociation also applies to readers of a more transparent orthographic system like French.

As an initial step, the present study only focused on monosyllabic word recognition. While multisyllabic words tend to differ from monosyllabic ones in different ways (Yap and Balota 2009), previous studies found that psycholinguistic variables like word frequency, orthographic neighborhood size, age of acquisition, imageability, or phonological consistency could similarly predict performance on both monosyllabic and multisyllabic words recognition in skilled readers (Cortese and Schock 2013; Yap and Balota 2009). Based on these researches, we expect that our conclusion could be generalized to multisyllabic words.

Conclusion

Using fine-grained measures provided by the eye-tracking technique, we showed that university students with dyslexia still show a delayed activation of phonological representations despite their relatively good level of vocabulary. Studying the same population, Cavalli et al. (2017) reported a spatio-temporal cortical reorganization of the reading network which reflects an earlier activation of morphological codes of words than in skilled readers. Although the present study does not allow us to draw a conclusion on a direct link between these two observations, one could speculate that high-functioning dyslexic population might have developed a reading strategy based on morphological information to compensate for their persistent phonological deficits reported here. Thus, our findings highlight the need for further research investigating the impact of phonological deficits on the different processing stages of visual word recognition and how these deficits induce a more general reorganization of the cognitive system in individuals with dyslexia.

Our results also suggest that skilled readers may not be considered as a homogenous group, which may partly explain some contradictory results on consistency effects reported in the literature. The different reading profiles that we highlighted may reflect the differences in the strength of connections between the three essential codes involved in visual word recognition. Further research

on the interplay between the different components of language is needed to obtain a complete picture of how language is processed in both dyslexic and heterogeneous skilled reader populations.

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Appendix A

List of the consistent and inconsistent words used in the present study and their corresponding measure of phonological consistency (Ziegler et al. 1996).

Stimulus	Words type	Phonological consistency
Carte	Consistent	1
Chien	Consistent	1
Chiffre	Consistent	1
Cloche	Consistent	1
Culte	Consistent	1
Double	Consistent	1
Foule	Consistent	1
Fourche	Consistent	1
Gorge	Consistent	1
Groupe	Consistent	1
Guide	Consistent	1
Juge	Consistent	1
Masque	Consistent	1
Ordre	Consistent	1
Prince	Consistent	1
Sable	Consistent	1
Singe	Consistent	1
Stage	Consistent	1
Vague	Consistent	1
Forme	Consistent	1
Quille	Inconsistent	0.494
Chef	Inconsistent	0.826
Short	Inconsistent	0.017*

Clef	Inconsistent	0.174
Cap	Inconsistent	0.165
Drap	Inconsistent	0.835
Femme	Inconsistent	0.997
Fille	Inconsistent	0.494
Flemme	Inconsistent	0.003
Grille	Inconsistent	0.494
Gaz	Inconsistent	0.948
Gang	Inconsistent	0.003
Jus	Inconsistent	0.002
Mail	Inconsistent	0.106*
Os	Inconsistent	0.033
Prix	Inconsistent	0.255
Sens	Inconsistent	0.391
Stand	Inconsistent	0.001
Stop	Inconsistent	0.006
Ville	Inconsistent	0.507

* The degree of phonological consistency was computed from the Lexique.org database (New et al. 2001) following the same criterion and methodology as described by Ziegler et al. (1996).

Appendix B

*Regression coefficients of the main effects of subgroup, consistency, and their interaction (for each dependant variable separately) calculated through LME/gLME models when analyzing the inter-individual differences in skilled readers (**: p <.01; *: p <.05; ns: p >.10.). Models: dependant variable ~ SR subgroup * Consistency + Number of letters + (1+Consistency | Subject) + (1+SR subgroup | Item).*

Dependent variable		**Degrees of freedom**	**F ratio**	**P values**
Accuracy scores	Subgroup	1, inf	2.53	ns
	Consistency	1, inf	0.21	ns
	Subgroups * Consistency	1, inf	0.12	ns
Gaze duration	Subgroup	1, 26	4.39	*
	Consistency	1, 27	0.95	ns
	Subgroups * Consistency	1, 21	1.21	ns
Single fixation duration	Subgroup	1, 26	5.14	*
	Consistency	1, 26	0.26	ns
	Subgroups * Consistency	1, 21	1.68	ns
First fixation duration	Subgroup	1, 21	0.16	ns
	Consistency	1, 19	0.003	ns
	Subgroups * Consistency	1, 9	6.13	*
Second fixation duration	Subgroup	1, 21	1.40	ns
	Consistency	1, 17	0.38	ns
	Subgroups * Consistency	1, 11	0.25	ns
Refixation probability	Subgroup	1, inf	10.17	**
	Consistency	1, inf	0.00	ns
	Subgroups * Consistency	1, inf	0.80	ns

Appendix C

*Regression coefficients of the main effects of subgroup, consistency, and their interaction (for each dependant variable separately) calculated through LME/gLME models when analyzing the inter-individual differences in readers with dyslexia (--: p <.075; ns: p >.10.). Models: dependant variable ~ DYS subgroup * Consistency + Orthographic uniqueness point + (1+Consistency | Subject) + (1+DYS subgroup | Item).*

Dependent variable		**Degrees of freedom**	**F ratio**	**P values**
Accuracy scores	Subgroup	1, inf	0.70	ns
	Consistency	1, inf	1.13	ns
	Subgroups * Consistency	1, inf	0.03	ns
Gaze duration	Subgroup	1, 31	0.69	ns
	Consistency	1, 43	0.38	ns
	Subgroups * Consistency	1, 36	0.02	ns
Single fixation duration	Subgroup	1, 29	2.69	ns
	Consistency	1, 29	0.51	ns
	Subgroups * Consistency	1, 20	1.11	ns
First fixation duration	Subgroup	1, 20	0.79	ns
	Consistency	1, 23	1.60	ns
	Subgroups * Consistency	1, 16	1.81	ns
Second fixation duration	Subgroup	1, 24	1.74	ns
	Consistency	1, 17	3.61	--
	Subgroups * Consistency	1, 15	1.70	ns
Refixation probability	Subgroup	1, inf	2.36	ns
	Consistency	1, inf	1.13	ns
	Subgroups * Consistency	1, inf	0.60	ns