Visual-attentional and phonological deficits explored in French dyslexic students: eye movements recorded during a phonological lexical decision task

Aikaterini Premeti (kpremeti@gmail.com)
MoDyCo, CNRS-Paris Nanterre University
Frédéric Isel
MoDyCo, CNRS-Paris Nanterre University
Maria Pia Bucci
MoDyCo, CNRS-Paris Nanterre University

Article

Keywords:

Posted Date: April 27th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2842576/v1

Additional Declarations: No competing interests reported.

Abstract

Whether dyslexia is a phonological or a visual attention problem remains a widely debated issue. This study aimed to compare the eye movements of 32 French university students with and without dyslexia while performing a phonological lexical decision task on 300 visually presented stimuli. Stimuli involved either a lexical (i.e., words) or a non-lexical route relying on a grapheme-phoneme correspondence (pseudohomophones and pseudowords), while others involved only a visual search (consonant and symbol sequences). We recorded the number and the duration of single and double fixations and the number and amplitude of the first saccade made on the stimuli. Compared to controls, dyslexics made fewer single than double fixations during reading regardless of the type of stimulus (lexical and non-lexical), while the number and the amplitude of the first saccade was similar in the two groups of participants. Taken together, these results suggest that both visual and phonological impairments may be observed in dyslexia and support the hypothesis that dyslexia is a multifactorial deficit.

Introduction

The main cause of dyslexia is considered to be the phonological deficit, i.e., a difficulty in the use of grapheme-to-phoneme conversion rules[1–3]. However, many researchers query whether a phonological deficit is the only cause of dyslexia [4–6]. Other theories such as auditory deficits [7], working memory impairment [8], attentional abnormalities [9] and magnocellular abnormalities [10] have been proposed as alternative explanations. Among them, the visuo-attentional deficit hypothesis [9] postulates that dyslexics have a reduced visuo-attentional span (i.e., the number of letters treated simultaneously within a single fixation), which could explain the abnormal eye movement pattern reported in dyslexic subjects during reading. Irrespective of the language, it has been observed that dyslexic individuals make a large number of saccades of smaller amplitude [11–18], several retro-saccades in order to re-fixate the word [16, 19–21], and longer fixation durations (for a recent review, see [22]). Interestingly, this abnormal oculomotor pattern has been observed when reading a text (in German), but also when reading a list of pseudowords [23], or isolated words of different lengths (in Italian [24]; in German [25]) and lexical frequency (in German [25]).

Several studies reported that this abnormal oculomotor pattern in dyslexics is only found during reading tasks (reading short passages vs a fixation task [13]; reading a text and reading lists of words and of non-words vs a visual search task [26]; reading pseudowords vs processing consonant strings [27]; sentence reading vs dot scanning [28]; text reading vs pictogram naming [29]), suggesting that it may be related to a deficit of processing linguistic information. Other studies, however, found an abnormal eye movement pattern during both reading and non-reading tasks (reading isolated words vs visually guided saccades to target- LEDs [30]; text reading vs visual search [31]; text reading vs free exploration of a painting [32]) in line with the idea of an immaturity of cortical structures responsible for visual processing. According to Prado et al. [33], impaired visual attentional processes may contribute to the abnormal eye movements observed in dyslexic readers.

In order to answer this question, Hutzler et al. [27] sought to understand whether abnormal eye movements in dyslexic German children were associated to a magnocellular deficit or to a phonological deficit at the stage of grapheme-to-phoneme conversion. For this purpose, they compared eye movements in dyslexic and non-dyslexic children depending on whether they were performing an experimental task involving phonological processing (i.e., reading pseudowords) or not (i.e., reading consonant strings of different lengths, which is a purely perceptive activity). The authors found more frequent and longer first fixation durations and gaze durations (i.e., the total time spent on each item during first pass reading) but only when dyslexics read pseudowords. This result suggests that the abnormal oculomotor pattern may be mainly related to a deficit in phonological processing involving grapheme-to-phoneme correspondence (GPC). This finding lends support to the hypothesis that the difficulties reported in dyslexic readers could be due to linguistic disturbances rather than to perceptual ones. Similarly, Hatzidaki et al. [26] reported abnormal eye movements (more numerous fixations, longer fixation durations, more numerous pro- and retro-saccades) during text reading but not during visual search in Greek dyslexic children as compared to control children. These converging data strengthen the conclusion that dyslexics' difficulties could be mainly related to linguistic information processing and not just to purely visual information processing. All these findings suggest that the abnormal eye movement patterns could be the consequence, rather than the cause, of the phonological deficit.

A recent study by Denis-Noël et al. [34] recorded eye movements in French dyslexic and non-dyslexic university students while reading pairs of phonologically consistent (e.g., cloche where –oche can only be pronounced /   / in French) and inconsistent (e.g., clef where –ef can be pronounced /e/ or / f/) monosyllabic words [35]. The authors found that when reading inconsistent words, where phonological processes are increased in comparison to consistent words, dyslexic students made several fixations and the duration of the second fixation was longer than the duration of the first fixation. One possible explanation is that the conflicting pronunciations may slow down the recognition process of inconsistent words. The authors claimed that the longer fixation duration could reflect delayed activation of phonological information during reading, which is in line with the phonological deficit hypothesis.

To sum up it remains an open question whether abnormal eye movements in dyslexia are associated to a visuo-attentional deficit or whether they are the consequence of the phonological deficit. This study provides new behavioral evidence for disentangling the respective role of the visuo-attentional and phonological factors using a continuum of stimuli ranging from French words to symbol strings to pseudowords and pseudohomophones.

Present study

In this study, we compared the eye movements of dyslexic and non-dyslexic French university students while processing different types of visual stimuli involving either a grapheme-to-phoneme conversion of varying depth (words < pseudohomophones < pseudowords) or a purely visual processing (such as consonant and symbol strings). Participants performed a phonological lexical decision task which consisted in deciding whether each visual sequence presented sounded like a French word. The strength of the experimental design we used was to allow us to test the two major hypotheses discussed in the literature on the causes of dyslexia, namely, the visuo-attentional deficit hypothesis and the phonological one using a continuum of stimuli ranging from French words to symbol strings to pseudowords and pseudohomophones. Our driving hypothesis is that if dyslexics have a deficit in phonological processing only, abnormal eye movements (longer fixation durations, more numerous fixations and saccades, and larger saccade amplitude) in dyslexics should only be found when reading words, pseudohomophones and pseudowords. On the other hand, if abnormal eye movements are observed in dyslexics also when processing consonant and symbol sequences, we can assume that dyslexics' reading difficulties may be associated to poor visual perception and impaired visual attentional processes.

Results

Single fixation duration

The duration of the single fixation was similar in the two groups of participants. ANOVA failed to report a significant main effect of Condition ([$F(4,120) = 1.698$, $MSE = 97.78$, $p = 0.18$]) or of Group: [$F < 1$]. The Condition by Group interaction did not reach the significance level [$F < 1$] either (see Fig. 1).

Double fixation duration (first and second fixation)

ANOVA showed a significant main effect of the duration of fixations [$F(1,30) = 7.16$, $MSE = 34685.18$, $p = 0.01$, $\eta^2_p = 0.193$]: the mean duration of the first fixations was significantly longer than that of the second ones (370 ± 75, ms *vs* 314 ± 74, ms, respectively). No other main effect or interaction was found for the first and second fixations (main effect of Condition: [$F < 1$; main effect of Group: [$F(1,30) = 1.415$, $MSE = 330.87$, $p = 0.24$]; Condition by Group interaction: [$F(4,120) = 1.33$, $MSE = 927.36$, $p = 0.260$]; interaction Order of fixation by Group: [$F(1,30) = 2.04$, $MSE = 34685.18$, $p = 0.163$]; interaction Condition by Order of fixation: [$F(4,120) = 1.54$, $MSE = 7618.97$, $p = 0.209$]; interaction Condition by Order of fixation by Group [$F(4,120) = 2.52$, $MSE = 7618.97$, $p = 0.064$], (see Fig. 2A and 2B).

Occurrence of fixations

Figure 3 shows the number of fixations measured in the two groups of participants for single (A) and double (B) fixations. ANOVA showed a main effect of number of fixations per item [$F(1,30) = 11.85$, $MSE = 535.67$, $p = 0.002$, $\eta^2_p = 0.283$], indicating that single fixations occurred significantly more frequently than double fixations (mean difference = 8.98).

ANOVA also indicated a significant Group × Number of fixations interaction per item [$F(1,30) = 6.87$, $MSE = 535.67$, $p = 0.014$, $\eta^2_p = 0.186$]. Further post-hoc analyses revealed that controls made more single fixations than dyslexics ($p_{holm} = 0.006$; mean difference = 10.73), and controls made more single fixations than double fixations ($p_{holm} < 0.001$; mean difference = 15.81).

Furthermore, ANOVA also revealed a significant interaction between Condition and Group [$F(4,120) = 4.14$, $MSE = 14.72$, $p = 0.010$, $\eta^2_p = 0.121$]. Post-hoc analyses indicated that dyslexics made more fixations in the consonant strings condition than in the pseudowords one ($p_{\text{holm}} = .027$; mean difference = 3.04).

In addition, ANOVA showed a significant Condition by Number of fixations interaction per trial [$F(4,120) = 4.859$, $MSE = 33.87$, $p = 0.01$, $\eta^2_p = 0.139$]. Post-hoc analyses revealed that there were more single fixations in the word than in the pseudohomophone ($p_{holm} = 0.016$; mean difference = 3.80) and in the symbol condition ($p_{holm} = 0.007$; mean difference = 4.06).

Finally, ANOVA also indicated that in both word and pseudoword conditions, there were more single than double fixations (words: $p_{holm} = 0.004$; mean difference = 12.30; pseudowords: pholm = 0.029; mean difference = 10.27; consonant: $p_{holm} = 0.038$; mean difference = 9.94).

Occurrence and amplitude of saccades

With respect to the occurrence of single saccades, ANOVA showed a main effect of Condition [$F(4,120) = 3.22$, $MSE = 18.93$, $p = 0.026$, $\eta^2_p = 0.097$]. Post-hoc analyses revealed that there were more saccades in the symbol condition compared to the word ($p_{holm} = 0.038$) and the pseudoword condition ($p_{holm} = 0.025$), independently of the group (see Fig. 4A).

ANOVA failed to report any significant difference for the amplitude of saccades (main effect of Condition: [$F(4,120) = 2.30$, $MSE = 0.004$, $p = 0.070$]; main effect of Group: [$F < 1$]; interaction Condition by Group: [$F(4,120) = 2.30$, $MSE = 0.004$, $p = 0.701$], (see Fig. 4B).

Discussion

To the best of our knowledge, this is the first study comparing oculomotor patterns in dyslexic and non-dyslexic students during a phonological lexical decision task. The most important findings are: 1) dyslexics made fewer single fixations than controls, while controls made more single than double fixations; 2) dyslexics made more fixations in the consonant strings condition than in the pseudowords condition than controls; 3) both groups presented similar durations of single as well as double fixations. Lastly, with respect to the type of stimulus, the oculomotor pattern was similar in the two groups of participants as we reported: 4) more single fixations in the word than in the pseudohomophone and symbol conditions; 5) more frequent single than double fixations in the word and the pseudoword conditions; 6) more single saccades in the symbol condition compared to the word and pseudoword conditions.

These findings are discussed below.

The main difference between dyslexic and control participants found in this study was that dyslexics made fewer frequent single than double fixations when compared to the controls. These findings are in accordance with the visuo-attentional deficit in dyslexics suggested by Bosse et al. [9]; the lower number of letters processed in parallel and the shorter visual attentional span (as shown in Table 1) could lead to the abnormal oculomotor pattern reported in dyslexics during reading, in line also with the findings reported in dyslexic children during a reading task as well as during a visual search task [18]. In addition, the absence of Condition by Group interaction highlights difficulties in all stimuli independently of their linguistic information. What strengthens the interpretation in favor of a visuo-attentional deficit in dyslexics is the occurrence of several single and double fixations, which was significantly larger in consonant strings as compared to pseudowords. This result could be explained by the fact that dyslexics may have difficulties at an early level of visual processing including perceptual processing.

Table 1
Assessment of reading and other cognitive functions of participants. Mean value (± standard error of the mean) for the different tests run for the two groups of participants (control readers, dyslexic readers). P values are also reported.

	Controls **N = 18**	**Dyslexics** **N = 14**	**P values**
Age (years)	21.1 ± 0.5	21.2 ± 0.6	0.895
No-meaning text reading (words correctly read/minute)	143 ± 5.9	102 ± 4.3	< .001
No-meaning text reading (Reading efficiency Score, CTL)	430 ± 18	305 ± 13	< .001
Text reading (words correctly read/minute)	205 ± 5.8	148 ± 7.8	< .001
Regular word reading (score/20)	19.3 ± 0.2	18.7 ± 0.3	0.066
Regular word reading (time in seconds)	11.0 ± 0.6	19.9 ± 1.9	< .001
Irregular word reading (score/20)	18.8 ± 0.4	17.6 ± 0.5	0.055
Irregular word reading (time in seconds)	10.6 ± 0.6	18.1 ± 1.7	< .001
Pseudoword reading (score/ 20)	18.6 ± 0.3	17.0 ± 0.6	0.015
Pseudoword reading (time in seconds)	16.2 ± 1.4	33.2 ± 2.5	< .001
Initial phoneme deletion (score/ 10)	8.9 ± 0.3	7.9 ± 0.7	0.151
Initial phoneme deletion (time in seconds)	38.8 ± 2.8	50.3 ± 2.4	0.005
Spoonerisms (score/ 20)	18.7 ± 0.3	14.1 ± 1.2	< .001
Spoonerisms (time in seconds)	89.2 ± 8.5	216 ± 31	< .001
Non-word repetition (score/ 20)	19.0 ± 0.1	18.6 ± 0.3	0.220
Non-word repetition (time in seconds)	68.8 ± 2.2	78.6 ± 3.2	0.014
Rapid automatized naming (RAN) letter (score/ 50)	49.6 ± 0.1	47.7 ± 1.7	0.211
Rapid automatized naming (RAN) letter (time in seconds)	16.1 ± 0.7	22.4 ± 1.5	< .001
Visuo-attentional span (score/ 100)	93.1 ± 1.4	75.9 ± 4.2	< .001
Similarities subtest WAIS IV	10.8 ± 0.5	10.1 ± 0.6	0.390
Matrices subtest WAIS IV	10.5 ± 0.6	10.1 ± 0.3	0.614

However, we cannot exclude the existence of a phonological deficit. Besides, our behavioral data indicated a significant difference between dyslexic and control participants in tests measuring phonological awareness (i.e., initial phoneme deletion, spoonerisms; see also Table 1). The fact that dyslexics made fewer single fixations (and more double fixations) may indicate that their reading abilities are deficient, and they use the sublexical grapheme-to-phoneme conversion procedure more, whatever the type of stimulus to be read, in comparison to control readers who may use the lexical route more, since they fixate stimuli only once [34,36].

Similar results were found in dyslexic children by De Luca et al. [24] who reported more frequent fixations during reading short pseudowords and longer stimuli (words and pseudowords) in dyslexics as compared to controls, and by Hutzler et al. [27] who found a higher number of fixations in dyslexics as compared to normal children when reading pseudowords.

Furthermore, a similar result was found by Denis-Noël et al. [34] in dyslexic students; they reported longer fixation durations during the reading of inconsistent words, for which phonological processing is more demanding. Note, however, that in the present study fixation durations were not different in the two groups of participants; this could be due to the type of stimuli used, which were quite easily processed and short. We suggest that the lower occurrence of single fixations in dyslexics as compared to controls may indicate a delayed activation of the phonological code, expressed by the need to make more fixations in order to read words and word-like stimuli. Together the above-mentioned results could support the phonological deficit hypothesis.

The absence of a Group by Condition interaction with stimuli requiring a grapheme-to-phoneme conversion cannot lead to a straightforward indication in favor of the phonological deficit, but may indicate that the different eye movement patterns found in dyslexics may be attributed to both phonological and to visuo-attentional deficits. Furthermore, the observation that dyslexics made fewer single fixations irrespective of whether the stimulus contained lexical or sublexical information, strengthens the hypothesis of the presence of both phonological and visuo-attentional difficulties in dyslexics. Unfortunately, we are not able to discriminate whether this abnormal oculomotor pattern is the origin or the cause of dyslexia [37]. This could be highlighted by an interaction with the type of stimulus, that could better indicate whether a deficit has a phonological or a visuo-attentional cause.

With respect to the duration of double fixations and the number and amplitude of saccades, we found a similar oculomotor pattern in both groups. More precisely, in the case of double fixations, both groups showed longer durations during the first rather than during the second fixation; this finding is in line with Rayner [38] who suggested that during the first fixation the reader processes the visual features of the word, such as its length, letter shape, and spacing, which can take longer than subsequent fixations. The absence of any difference in oculomotor pattern between the two groups of subjects could also be attributed to the use of short stimuli in our experiment. Earlier studies examining eye movements when reading short and long words [24] reported similar findings for short words while for longer stimuli more fixations were needed [24,25].

In our study, we found more frequent single fixations in the word than in the pseudohomophone and symbol condition. This result can be partially explained by the fact that reading words is acquired through the direct route of reading [39], whereas reading pseudohomophones, which are stimuli with no orthographic representation, need the application of grapheme-to-phoneme conversion rules. In the case of the comparison between the word and symbol, the lower occurrence of single fixations reported in symbols could be due to the fact that this type of stimulus was quite simple to distinguish with respect to words.

Surprisingly, our data did not show any significant group difference in terms of the occurrence of fixations and in fixation duration when reading stimuli that required a grapheme-to-phoneme conversion (pseudowords and pseudohomophones). A similar result was reported by De Luca et al. [24] in children when short words and pseudowords were presented. In the present study, this can most likely be attributed to the fact that the stimuli used were short and were high-frequency concrete nouns and the dyslexics tested were university students who had completed several years of remediation.

Limitations

The short stimuli used in the study together with the fact that subjects were university students who had completed several years of remediation and had acquired strategies to compensate their reading difficulties may be the cause of the similarities in the oculomotor pattern observed between dyslexic and non-dyslexic subjects. In addition, our experimental design may have been too simple, since the stimuli were presented alone in the center of the screen after the presentation of a center fixation cross; consequently, the subject was already fixating the center of the screen. Future research in a more ecological situation of reading a text will be needed in order to explore oculomotor patterns in dyslexic students as a function of the amount of remediation.

Conclusion

To sum up, our study focused on comparing eye movements of French dyslexic adults and non-dyslexic controls during a phonological lexical decision task, in order to better distinguish the role of the phonological and/or the visuo-attentional deficit in dyslexia. Fewer single than double fixations in dyslexic subjects confirm a deficit in their decoding abilities and a less automatic processing during reading. At the same time, the reduced visual attentional span reported in dyslexics could be the cause of their need to make more fixations in order to process stimuli. Taken together, the present results support the coexistence of a phonological and visuo-attentional deficit in dyslexic participants. However, it still remains an open question whether these abnormal eye movements are the cause or the consequence of dyslexia. We believe that phonological together with visuo-attentional remediation could be useful tools to improve phonological and visual-attentional span performances in dyslexics.

Methods

Participants

We tested fourteen native French university students with dyslexia (6 males; mean age = 21.2 ± 0.6 years) and eighteen control subjects (5 males; mean age = 21.1 ± 0.5 years). All participants had normal or corrected-to-normal vision (more than 8/10 in each eye according to Parinaud's optometric scale [40]. Dyslexic individuals had been diagnosed during childhood (mean age of diagnosis = 7.5 ± 2.1 years) by a specialized therapist and control participants had no history of spelling or reading difficulties. They all reported no neurological or cognitive problems. All dyslexic subjects had undergone several years of remediation with a speech therapist (mean = 8.4 ± 3.5 years).

Screening Tests

As reported in Table 1, reading skills, phonological awareness, visuo-attentional skills and non-verbal intelligence were evaluated with a battery of standardized tests. To assess reading abilities, we used the French reading test L'Alouette [41], and we took into consideration accuracy and speed of reading as measured by the words correctly read per meaning and the reading efficiency score (CTL) [42]. The ECLA 16 + Battery Test [43] was employed to measure several reading abilities (text reading (Pollueur; ECLA-16 + [43]), regular and irregular word reading and pseudoword reading, phonological skills (initial phoneme deletion, spoonerisms, non-word repetition), and rapid letter naming. A five-consonant global report task [9] was used to assess visuo-attentional skills and the matrices and the similarities subtest of the Wechsler Adult Intelligence Scale IV (WAIS-IV) [44] was used to assess nonverbal intelligence.

The study was approved by the local ethics committee of the Institutional human Experimentation committee of Lille University, France and was carried out in accordance with the Declaration of Helsinki (Comité Ethique de l'Université de Lille, N° 2020-441-S87).

All participants gave their written consent to participate in the experiment and were paid 15 euros per hour for their participation.

Linguistic materials

Five experimental conditions were used for the stimulus type: (1) *words* (W) (e.g., *chaise* [chair]) taken from the French database *Lexique 3* [45]; all the words were 5- to 6-letter monosyllabic concrete nouns (mean length of word stimuli = 5.3, ± 0.5) with a high frequency of occurence (*M* = 148.1, *SD* = 110.9). Orthographic (*M* = 4.8, *SD* = 3.8) and phonological (*M* = 10.9, *SD* = 6.6) neighbors, number of homographs (*M* = 1.4, *SD* = 0.6) and homophones (*M* = 3.5, *SD* = 1.9) were taken into account when selecting the words. (2) *Pseudohomophones* (PH; stimuli having a phonological but not an orthographic representation in French, or in other words, non-lexicalized stimuli in French but pronounced in the same way as French words; **chèse* [same pronunciation as "chaise" (chair)]); Pseudohomophones were created from the list of words by replacing one grapheme at a time with another grapheme corresponding to the same phoneme, by adding or eliminating a double consonant or a silent letter [46]; (3) *Pseudowords* (PW; stimuli that are orthographically and phonologically plausible but having neither a phonological nor an orthographic representation in French. They were created from words by changing one grapheme at a time; **chuse*); (4) *Consonant strings* (CS; sequences that are orthographically illegal and phonologically unpronounceable, since they contain no vowels and therefore no syllables; **nbvrzc*). Consonant strings were matched with words based on their form, with respect to the ascender or descender graphemes that they contain; (5)

Symbol strings (SS; non-alphabetic stimuli; *§ ¥Ð‡*). Symbol strings were matched for the number of characters with high frequency words. The 12 symbols used in our study were taken from a previous study by Mahé et al. [47]. In total, 300 stimuli were used, 60 stimuli in each condition.

Eye movement recordings

All participants were tested individually in a soundproof room. They were seated 92 cm from the screen, with a chinrest and a forehead rest. Eye movements were recorded using the Eyelink 1000 eye tracker (Eyelink 1000 Desktop Mount distributed by SR Research Ltd., Mississauga, Ontario, Canada). Before each session, nine-point gaze calibration was performed and repeated until the validation error was less than 1° on average and less than 1.5° at the worst point. After the calibration session a phonological lexical decision task was proposed to the 32 participants (see Procedure section below). We recorded only the dominant eye of each participant, since previous studies reported no apparent association between ocular dominance and reading skills [48,49].

Procedure

Participants performed a phonological lexical decision task. Each trial started with a fixation cross flashing in the center of a grey screen for 400 ms. The cross was followed by a grey screen flashing for 150 ms and followed by the stimulus, which remained on screen for 700 ms. After presentation of the stimulus, a question mark appeared on the screen and subjects had to reply as accurately as possible whether the stimulus that was presented sounded like a real word in French or not, by pressing a yes or no key on the computer keyboard. Stimuli were presented in “Arial Narrow” black font, with 47-point lower case letters in the center of the monitor, on a grey background. All 300 stimuli were distributed in equal numbers in 5 blocks, each of which contained 60 trials. The stimuli in each block were pseudorandomized based on the following constraints: no more than two stimuli of the same condition were presented successively; no more than three stimuli requiring the same response were displayed in succession. Words and their corresponding pseudohomophones were not presented within the same block; the 12 corresponding pseudohomophones of each word within a block were distributed among the four remaining blocks. Eye movements were recorded during the phonological lexical decision task, and calibration was repeated at the beginning of each block presentation.

Data analysis

During performance of the phonological decision task by the participants, we measured the occurrence and the duration of single and double fixations for each stimulus presented on the screen. In the case of double fixations, we measured the occurrence and the duration of the first and the second fixation. The occurrence and the amplitude of the first saccade were also measured.

Eye movement analyses were performed using the Data Viewer software (SR Research Ltd.). We analyzed eye movements solely during the period of stimulus appearance on the screen (maximum time 700 ms). We excluded from the data trials of incorrect responses, when fixations and saccades fell outside the area of interest, and trials including blinks.

Statistical analysis

The Student t-test was used to compare reading and cognitive skills in dyslexic and non-dyslexic participants. A two-way ANOVA was run to compare the response accuracy in the phonological lexical decision task in the two groups of participants.

For the analysis of fixation duration, repeated measures ANOVAs were conducted for each dependent oculomotor parameter (single, first and second fixation duration, saccade amplitude, single saccade occurrence) between the different stimuli (5 levels: word, pseudohomophone, pseudoword, consonant string, symbol string) as a within-subjects factor and the two groups of participants (dyslexic, control) as a between-subjects factor. For the analysis of the occurrence of single and double fixations, repeated measures ANOVAs were conducted between the different stimuli (5 levels: word, pseudohomophone, pseudoword, consonant string, symbol string) and the number of fixations per item (2 levels: single, double) as a within-subjects factor and the two groups of subjects (dyslexic, control) as a between-subjects factor.

Post-hoc pairwise comparisons were made using a modified Holm procedure. The threshold of statistical significance was set at $p < 0.05$. All statistical analyses were processed using JASP software (a free open-source program for statistical analysis supported by the University of Amsterdam).

Declarations

Acknowledgements

The authors thank the subjects who participated in the study.

Authors' contributions

F.I. and M.P.B. acquired funding and conceptualized, supervised, reviewed, and edited the manuscript. A.P. curated the data, analyzed formal data and wrote, revised and edited the manuscript. F.I. and M.P.B. curated the data and reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors have no financial and personal relationships with other people or organizations that could inappropriately influence or bias their work in this study.

Funding

Aikaterini Premeti is funded by a Ph.D. grant from Paris Nanterre University, France.

References

1. Bruck, M. Persistence of dyslexics' phonological awareness deficits. *Developmental Psychology* **28**, 874–886 (1992).
2. Brady, S., Shankweiler, D. & Mann, V. Speech perception and memory coding in relation to reading ability. *Journal of Experimental Child Psychology* **35**, 345–367 (1983).
3. Snowling, M. J. Phonological processing and developmental dyslexia. *Journal of Research in Reading* **18**, 132–138 (1995).
4. Elliott, J. G. It's Time to Be Scientific About Dyslexia. *Reading Research Quarterly* **55**, S61–S75 (2020).
5. Stein, J. The visual basis of reading and reading difficulties. *Frontiers in Neuroscience* **16**, (2022).
6. Stein, J. Theories about Developmental Dyslexia. *Brain Sciences* **13**, 208 (2023).
7. Tallal, P. Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language* **9**, 182–198 (1980).
8. Smith-Spark, J. H. & Fisk, J. E. Working memory functioning in developmental dyslexia. *Memory* **15**, 34–56 (2007).
9. Bosse, M.-L., Tainturier, M. J. & Valdois, S. Developmental dyslexia: The visual attention span deficit hypothesis. *Cognition* **104**, 198–230 (2007).
10. Livingstone, M. S., Rosen, G. D., Drislane, F. W. & Galaburda, A. M. Physiological and anatomical evidence for a magnocellular defect in developmental dyslexia. *Proceedings of the National Academy of Sciences* **88**, 7943–7947 (1991).
11. Biscaldi, M., Gezeck, S. & Stuhr, V. Poor saccadic control correlates with dyslexia. *Neuropsychologia* **36**, 1189–1202 (1998).
12. Biscaldi, M., Fischer, B. & Hartnegg, K. Voluntary Saccadic Control in Dyslexia. *Perception* **29**, 509–521 (2000).
13. De Luca, M., Di Pace, E., Judica, A., Spinelli, D. & Zoccolotti, P. Eye movement patterns in linguistic and non-linguistic tasks in developmental surface dyslexia. *Neuropsychologia* **37**, 1407–1420 (1999).
14. Eden, G., Stein, J., Wood, H. M. & Wood, F. Differences in eye movements and reading problems in dyslexic and normal children. *Vision research* **34**, 1345–58 (1994).
15. Fischer, B., Biscaldi, M. & Otto, P. Saccadic eye movements of dyslexic adult subjects. *Neuropsychologia* **31**, 887–906 (1993).
16. Martos, F. J. & Vila, J. Differences in eye movements control among dyslexic, retarded and normal readers in the Spanish population. *Read Writ* **2**, 175–188 (1990).

17. Rayner, K. Do faulty eye movements cause dyslexia? *Developmental Neuropsychology* **1**, 3–15 (1985).
18. Seassau, M., Gérard, C. L., Bui-Quoc, E. & Bucci, M. P. Binocular saccade coordination in reading and visual search: a developmental study in typical reader and dyslexic children. *Front. Integr. Neurosci.* **8**, (2014).
19. Pavlidis, G. T. Eye movement differences between dyslexics, normal, and retarded readers while sequentially fixating digits. *Am J Optom Physiol Opt* **62**, 820–832 (1985).
20. Pavlidis, G. Th. Do eye movements hold the key to dyslexia? *Neuropsychologia* **19**, 57–64 (1981).
21. Zangwill, O. L. & Blakemore, C. Dyslexia: Reversal of eye-movements during reading. *Neuropsychologia* **10**, 371–373 (1972).
22. Premeti, A., Bucci, M. P. & Isel, F. Evidence from ERP and Eye Movements as Markers of Language Dysfunction in Dyslexia. *Brain Sciences* **12**, 73 (2022).
23. Hutzler, F. & Wimmer, H. Eye movements of dyslexic children when reading in a regular orthography. *Brain and Language* **89**, 235–242 (2004).
24. De Luca, M., Borrelli, M., Judica, A., Spinelli, D. & Zoccolotti, P. Reading Words and Pseudowords: An Eye Movement Study of Developmental Dyslexia. *Brain and Language* **80**, 617–626 (2002).
25. MacKeben, M. *et al.* Eye movement control during single-word reading in dyslexics. *Journal of Vision* **4**, 4 (2004).
26. Hatzidaki, A., Gianneli, M., Petrakis, E., Makaronas, N. & Aslanides, I. M. Reading and visual processing in Greek dyslexic children: an eye-movement study. *Dyslexia* **17**, 85–104 (2011).
27. Hutzler, F., Kronbichler, M., Jacobs, A. M. & Wimmer, H. Perhaps correlational but not causal: No effect of dyslexic readers' magnocellular system on their eye movements during reading. *Neuropsychologia* **44**, 637–648 (2006).
28. Kirkby, J. A., Blythe, H. I., Drieghe, D. & Liversedge, S. P. Reading Text Increases Binocular Disparity in Dyslexic Children. *PLOS ONE* **6**, e27105 (2011).
29. Trauzettel-Klosinski, S. *et al.* Pictogram naming in dyslexic and normal children assessed by SLO. *Vision Research* **42**, 789–799 (2002).
30. Bucci, M. P., Brémond-Gignac, D. & Kapoula, Z. Poor binocular coordination of saccades in dyslexic children. *Graefes Arch Clin Exp Ophthalmol* **246**, 417–428 (2008).
31. Bucci, M. P., Nassibi, N., Gerard, C.-L., Bui-Quoc, E. & Seassau, M. Immaturity of the Oculomotor Saccade and Vergence Interaction in Dyslexic Children: Evidence from a Reading and Visual Search Study. *PLOS ONE* **7**, e33458 (2012).
32. Jainta, S. & Kapoula, Z. Dyslexic Children Are Confronted with Unstable Binocular Fixation while Reading. *PLOS ONE* **6**, e18694 (2011).
33. Prado, C., Dubois, M. & Valdois, S. The eye movements of dyslexic children during reading and visual search: Impact of the visual attention span. *Vision Research* **47**, 2521–2530 (2007).

34. Denis-Noël, A., Pattamadilok, C., Castet, É. & Colé, P. Activation time-course of phonological code in silent word recognition in adult readers with and without dyslexia. *Ann. of Dyslexia* **70**, 313–338 (2020).
35. Ziegler, J. C., Jacobs, A. M. & Stone, G. O. Statistical analysis of the bidirectional inconsistency of spelling and sound in French. *Behavior Research Methods, Instruments, & Computers* **28**, 504–515 (1996).
36. Hawelka, S., Gagl, B. & Wimmer, H. A dual-route perspective on eye movements of dyslexic readers. *Cognition* **115**, 367–379 (2010).
37. Werth, R. Dyslexia: Causes and Concomitant Impairments. *Brain Sciences* **13**, 472 (2023).
38. Rayner, K. Eye movements and attention in reading, scene perception, and visual search. *Q J Exp Psychol (Hove)* **62**, 1457–1506 (2009).
39. Coltheart, M., Rastle, K., Perry, C., Langdon, R. & Ziegler, J. DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review* **108**, 204–256 (2001).
40. Parinaud, H. *Échelle optométrique: acuité visuelle, perception de la lumière et des couleurs*. (Roulot, 1888).
41. Lefavrais, P. *Test de l'Alouette*. (Editions du Centre de Psychologie Appliquée, 1965).
42. Cavalli, E. *et al.* Screening for Dyslexia in French-Speaking University Students: An Evaluation of the Detection Accuracy of the Alouette Test. *J Learn Disabil* **51**, 268–282 (2018).
43. Gola-Asmussen, C., Lequette, C., Pouget, G., Rouyer, C. & Zorman, M. *ÉCLA-16+: Évaluation des Compétences de Lecture chez l'Adulte de plus de 16 ans.* (CogniSciences, 2010).
44. Wechsler, D. *The Wechsler Adult Intelligence Scales. 4th ed. (WAIS-IV).* (Pearson Assessment, 2009).
45. New, B., Pallier, C., Ferrand, L. & Matos, R. Une base de données lexicales du français contemporain sur internet : LEXIQUE. *L'Année psychologique* **101**, 447–462 (2001).
46. Farioli, F., Grainger, J. & Ferrand, L. PHOM : une base de données de 14 000 pseudo-homophones. *L'Année psychologique* **111**, 725–751 (2011).
47. Mahé, G., Bonnefond, A., Gavens, N., Dufour, A. & Doignon-Camus, N. Impaired visual expertise for print in French adults with dyslexia as shown by N170 tuning. *Neuropsychologia* **50**, 3200–3206 (2012).
48. Fagard, J., Monzalvo-Lopez, K. & Mamassian, P. Relationship between eye preference and binocular rivalry, and between eye-hand preference and reading ability in children. *Developmental Psychobiology* **50**, 789–798 (2008).
49. Newman, S. P., Wadsworth, J. F., Archer, R. & Hockly, R. Ocular dominance, reading, and spelling ability in schoolchildren. *British Journal of Ophthalmology* **69**, 228–232 (1985).

Figures

Figure 1

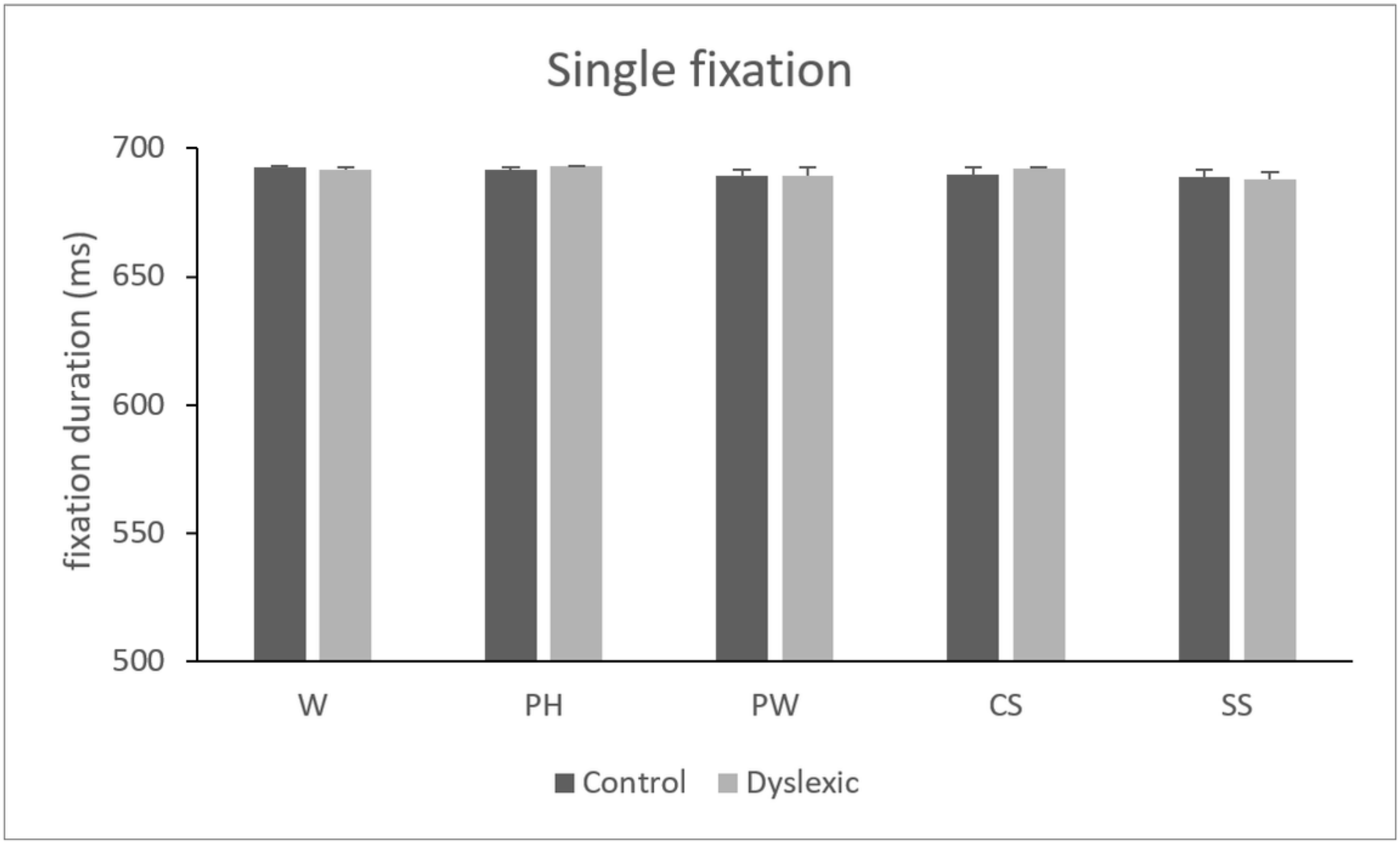

Figure 1

Mean duration of fixation (in ms) and the standard error of the mean (SEM) when reading words (W), pseudohomophones (PH), pseudowords (PW), consonant strings (CS) and symbol strings (SS) in the two groups of subjects (controls, dyslexics).

Figure 2A

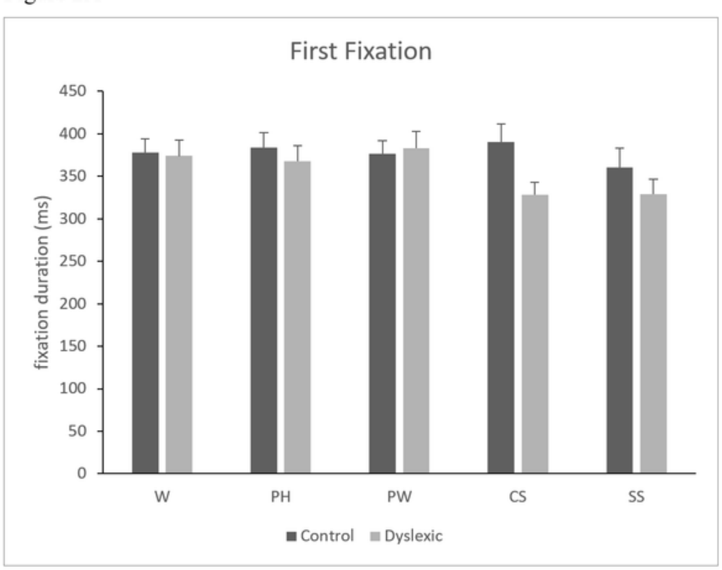

Figure 2B

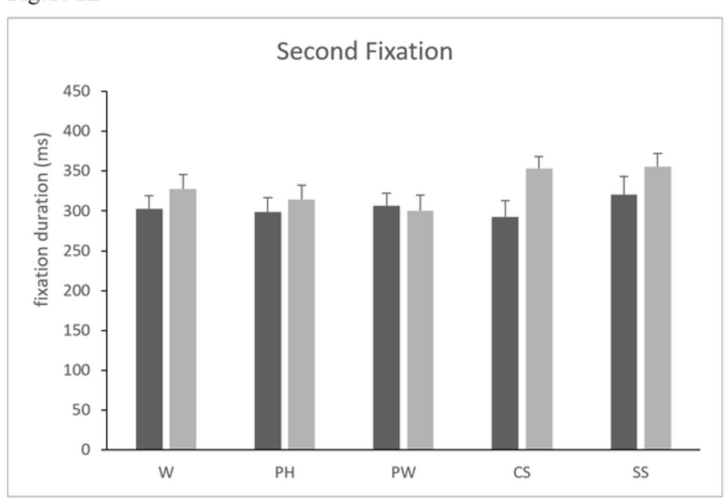

Figure 2

Mean duration of the first (A) and second (B) fixation (in ms) and the standard error of the mean (SEM) when reading words (W), pseudohomophones (PH), pseudowords (PW), consonant strings (CS) and symbol strings (SS) in the two groups of subjects (controls, dyslexics).

Figure 3A

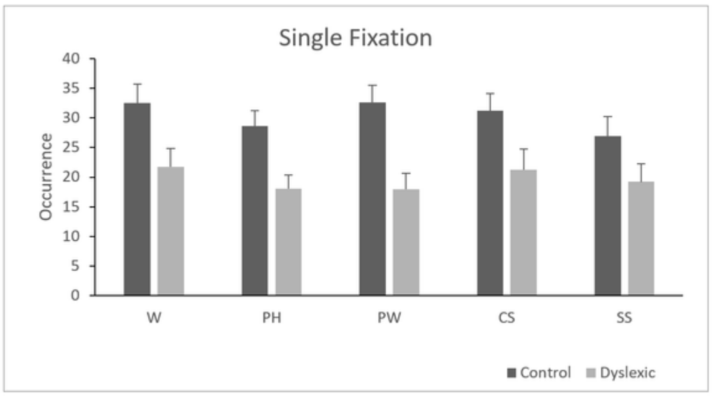

Figure 3B

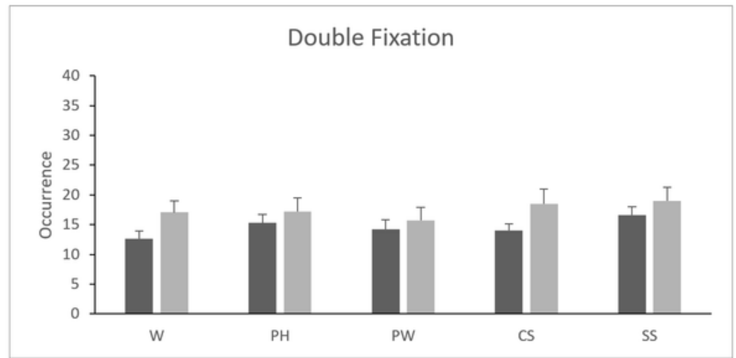

Figure 3

Occurrence of appearance of single (A) and double fixations (B) and the standard error of the mean (SEM) when reading words (W), pseudohomophones (PH), pseudowords (PW), consonant strings (CS), and symbol strings (SS) in the two groups of subjects (controls, dyslexics).

Figure 4A

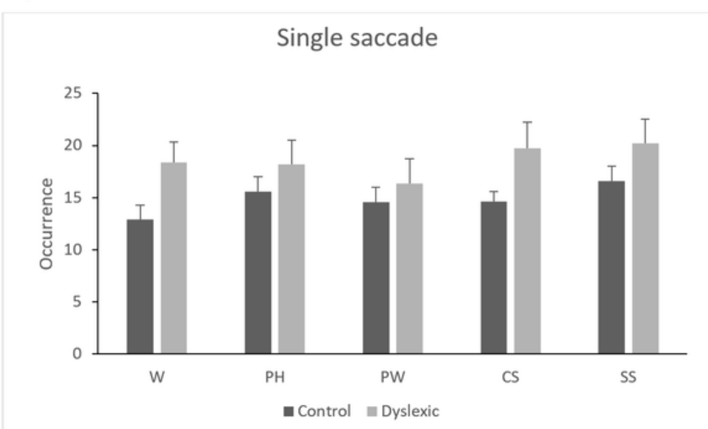

Figure 4B

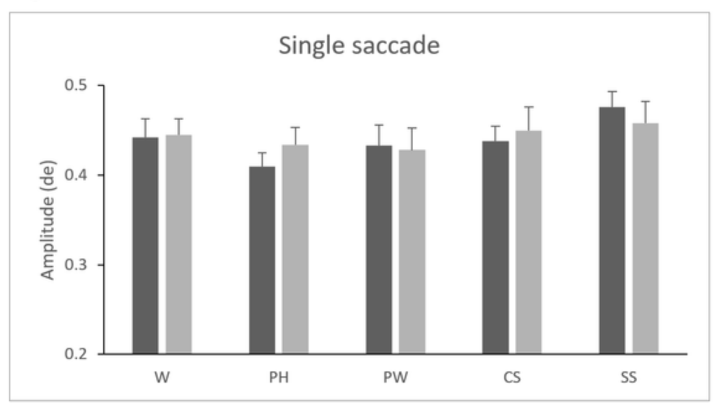

Figure 4

Occurrence of appearance (A) and amplitude (B) of single saccades and the standard error of the mean (SEM) measured when reading words (W), pseudohomophones (PH), pseudowords (PW), consonant strings (CS), and symbol strings (SS) in the two groups of subjects (controls, dyslexics).