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# Can pulsed lighting help adults with dyslexia to read better: Testing LeFloch and Ropars's hypothesis

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# Abstract

The aim of the present study was to test Le Floch and Ropars' hypothesis according to which dyslexia is mainly triggered by visual processing deficits, namely an absence of eye dominance, which induce the aberrant perception of afterimages for individual letters. According to these authors, dyslexic readers would be expected to produce reading performances very similar to those of controls under pulsed lighting conditions. 23 participants with dyslexia and 19 control readers were recruited and asked to perform two reading tasks under three different lighting conditions; standard lighting, pulsed lighting and a combination of the two. We used two reading measures for each participant and each lighting condition: (1) a reading accessibility index (using the MNREAD test) and (2) a text reading comprehension score. To control for individual differences in reading skills, all participants also completed a series of French standardized tests which were used to compute an individual reading impairment score. Finally, visual acuity and eye dominance were measured to control for participants' visual function. We found no effect of lighting conditions on either of the two reading measures. This was true for all reading impairment score values and irrespective of whether participants showed eye dominance or not. Furthermore, even under pulsed lighting, individuals with dyslexia did not reach the reading performance of skilled adult readers, regardless of their eye dominance. In conclusion, we failed to show a clear positive impact of pulsed lighting on the reading skills of adults with dyslexia. This set of results does not support the visual hypothesis of dyslexia proposed by Le Floch and Ropars.


# Introduction

Developmental dyslexia (hereafter, dyslexia) is the most frequent neurodevelopmental disorder, affecting approximately 7% of the population (Peterson & Pennington, 2012). Significant and persistent decoding and word-reading difficulties, which may also impair reading comprehension and result in poor spelling performance, are the main symptoms of dyslexia (Lyons et al., 2003). Deficit hypotheses, such as the auditory hypothesis (Tallal, 1980), the phonological hypothesis (Denis-Noël et al., 2020), the visual hypothesis (Franceschini et al., 2022) or the cerebellar/motor hypothesis (Nicolson et al., 2001) have been proposed as possible causal explanations of dyslexia, leading to a huge number of studies (for a review, see (Colé & Sprenger-Charolles, 2021)). The aim of the present study was to test the hypothesis recently proposed by Le Floch and Ropars (2017), who developed a Hebbian pulse-width modulated lighting set-up to ease dyslexia symptoms.

Several visual hypotheses of dyslexia had previously been proposed. These include: the visual-attention span deficit hypothesis (Bosse, Tainturier & Valdois, 2007), the orientation of visual attention deficit hypothesis (Facoetti et al., 2010; Franceschini et al., 2022) and, more recently, the iconic memory and visual-short-term memory transfer deficit hypothesis ( Castet et al., 2017; Castet et al., 2020). The common idea to all these hypotheses is that the associated visual deficit would disrupt the generation of the orthographic codes of the words being read, resulting in impaired multi-letter string processing (Martelli et al., 2009). As far as orthographic coding is concerned, letter orientation is an important feature of any orthographic system and makes it possible to distinguish between different letters of an alphabet,

such as *b* and *d* (Colé & Sprenger-Charolles, 2021). This is not the case for images. Thus, Dehaene, Nakamura, et al., (2010) reported that, in adults, prior presentation of a left-right inverted item facilitates its recognition when it is a picture (e.g., a horse) but not when it is a French word written backwards (e.g., *mon* vs. *nom*; *my* vs.*name* in English). In their review on mirror image processing, (Fernandes & Leite, 2017) emphasize the processing specificity of left-to-right inverted letters (*b, d*) compared to those inverted vertically (*b*, *p*). When learning to read in a given orthographic system, children must therefore inhibit previously acquired automatisms, leading to competition in the visual word form area (Dehaene, et al., 2010).

Physicists Le Floch and Ropars (2017) proposed another visual hypothesis of dyslexia, positing that this disorder may be attributed to a specificity in the anatomy of the eye. They suggested that individuals with dyslexia may present a weak ocular dominance due to a lack of asymmetry in the central region of their retinas. This lack of asymmetry would result in an undetermined afterimage dominance, with the primary and mirror images coexisting and possibly causing confusion regarding the identification of mirror letters (e.g., *b* and *d)*. They consequently reported that the blue cone-free areas at the center of each retina (retinal Maxwell's centroids) in skilled adult readers with established eye dominance are asymmetrical. Using a foveascope of their design, they outlined a noise-stimulated afterimage of Maxwell's centroids, revealing dissimilar blue cone-free areas in skilled readers: a circular one in the dominant eye and an elliptical one in the non-dominant eye. In contrast, this asymmetry was absent in adults with dyslexia, for whom the authors reported circular blue cone-free areas in both eyes and no eye dominance, despite them having normal ocular status. The authors hypothesized that the lack of asymmetry they found in individuals with dyslexia might prevent them from having the expected ocular dominance.

While the typical brain receives visual information from both optic nerves, it relies preferentially on the input from the dominant eye (Hubel & Kuehni, 1988). It is only at the end of the developmental period (~ 8 years) that children's eye dominance stabilizes, bringing about a decrease in mirror reversal errors (Cornell, 1985). According to Le Floch and Ropars' hypothesis, the lack of asymmetry found in individuals with dyslexia would prevent the brain from focusing preferentially on one input, leading to perturbations in the brain's central connectivity. This supports the idea of a poor lateralization of the brain in individuals with dyslexia (Bishop, 2013). Again according to this hypothesis, instead of correctly perceiving only one input, individuals would receive two equally strong inputs and may therefore be unable to properly decode visual inputs such as letters (Le Floch & Ropars, 2020). Indeed, under natural lighting, individuals with dyslexia would perceive both the primary and the afterimage of the stimulus that is presented to them.

There is some evidence that temporal modulations of light frequency and luminance can influence perception of visual afterimages (Fiorentini & Ercoles, 1960; Gerling & Spillmann, 1987; Matteson, 1965). Based on such mechanisms, Le Floch and Ropars developed a set-up using Hebbian pulse-width modulated lighting in order to erase the disturbing afterimage perceived by individuals with dyslexia, thus removing the mirror image (Le Floch & Ropars, 2017). After running a letter identification task on five dyslexic participants, they concluded that pulse-width modulated lighting can compensate for the lack of binocular rivalry in this population and thus improve overall reading skills. However, this result may be

subject to caution for several reasons. First, only a very small sample of participants with dyslexia was tested and no description of the diagnosis or functional deficit of these participants was provided. Second, the authors only tested letter recognition performance, which does not necessarily transfer to the higher-level skill of reading. Lastly, the authors gave very little detail about the characteristics of the lighting conditions that they used, making it impossible to replicate their results.

Therefore, the goal of the present work was to assess the impact of pulsed lighting on the reading skills of a larger sample of individuals with dyslexia. Importantly, throughout this work, dyslexia was considered as a multifactorial condition, ranked along a continuous scale rather than a dichotomic one (controls vs. dyslexics). Indeed, according to current understanding, dyslexia appears to result from a multifactorial disorder involving many genes, which may result in a reading deficit under unfavorable environmental conditions (e.g., opacity of the orthographic system) (Pennington, 2006; Pennington et al., 2012; van Bergen et al., 2014). This framework allows us to better understand and account for the reported heterogeneity in reading profiles of adults with dyslexia (Cavalli et al., 2018; Laasonen et al., 2009; Parrila et al., 2007). Thus, in Cavalli et al. (2018), 18% of a sample of university students with dyslexia achieved normative text reading fluency performances, while exhibiting a performance deficit in single-word and pseudoword reading. Another example of the heterogeneity of reading profiles in the dyslexic population comes from Parrila et al. (2007), who reported that 75% of their sample of adults with dyslexia achieved reading comprehension scores within the norms (when reading without time pressure), while 93% continued to show deficits in written word recognition and decoding skills. This heterogeneity in the manifestations of dyslexia (possibly due to compensatory mechanisms, (see Colé et al., (2020) for a discussion) led us to calculate an overall reading impairment score for each participant. This measure, based on four reading test scores (namely, an isolated-word reading test, a pseudoword reading test and two reading fluency tests), ranged from 0 (no impairment) to 4 (pathological threshold reached on all tests). In line with the current conception of dyslexia developed by Pennington (2006), this score allowed us to consider reading performance on a continuum rather than on a dichotomous scale and to evaluate the impact of each lighting condition as a function of individual reading profiles.

According to Le Floch and Ropars' (2017) hypothesis, the likelihood of observing an absence of eye dominance in adults with dyslexia should be greater than in skilled readers. Therefore, individuals with high reading impairment scores would be more likely to show an absence of eye dominance than skilled readers with no reading impairment. Furthermore, using pulsed lighting would significantly enhance reading performance in the dyslexic group by erasing the perception of disturbing afterimages of some of the letters present in the words being read. Hence, Le Floch and Ropars' hypothesis suggests that there should be a positive effect of pulsed lighting on reading performance, which would interact with the reading impairment score (the greater the impairment, the larger the facilitating effect) and/or the presence of ocular dominance (the facilitating effect would only be present in the absence of eye dominance).

# Methods

# Participants

We tested 23 participants with developmental dyslexia (9 males) and 19 chronological age-matched control readers (8 males) with no reported reading difficulties. Age ranged from 19 to 27 years, with a mean (±SD) of 21±2 years in both groups. All participants were native French speakers, with normal or corrected-to-normal vision and normal audition. All were university students with equivalent school-leaving qualifications and ranged from first-year postgraduate to fifth-year postgraduate. Participants with dyslexia were recruited from the Aix-Marseille University Disability Service and had all been diagnosed by a speech therapist earlier in life. Comorbidities with dyslexia were distributed as follows: dysorthographia (67%), specific oral language disorder (22%), dyscalculia (19%), developmental coordination disorder (15%) and attention deficit hyperactivity disorder (11%). Written consent was obtained from all participants when they were enrolled. All received monetary compensation for their participation. The experiment followed the tenets of the Declaration of Helsinki and was approved by the local ethics committee of Aix-Marseille University.

# Experimental protocol

Each participant came to the laboratory for two 90-minute sessions: a pre-test session, followed within a month by the experimental testing session. All tests were administered by a single experimenter in an empty experimental room (e.g., no windows or shelves) to avoid any distractions. During the pre-test session, a series of pre-tests was run followed by a series of tests intended to assess the individual reading impairment score. During the experimental session, the influence of pulsed lighting on two main components of reading performance was estimated: sentence reading speed, estimated using the MNREAD chart (Mansfield et al., 1993), and text reading comprehension, measured with a French standardized test (Brèthes et al., 2022). Details of the experimental protocol are detailed below and summarized in Fig. 1.

# Pre-tests

All participants completed a series of French tests, which were administered using a standard procedure (Fig. 1) (Brèthes et al, 2022). The French version of the Adult Reading History Questionnaire (ARHQ) and Anamnesis (Lefly & Pennington, 2000) were used to screen for dyslexia. IQ levels were estimated both verbally using the French version of the Peabody Picture Vocabulary Test (PPVT, EVIP in French) (Dunn et al., 1993) and non-verbally with Raven's Matrices (Raven et al., 2003). Phonological short-term memory and phonemic awareness were also tested with the EVALEC toolset (Sprenger-Charolles et al., 2005). The Alouette test (Lefavrais, 1967) was used to assess reading skills. Because, it consists of a series of real words embedded in meaningless but grammatically and syntactically correct sentences, dyslexic and poor readers cannot use contextual information to compensate for their written word recognition difficulties. Here, we used a standardized version of the test developed for adults by Cavalli et al., (2018). Participants were asked to read the 265-word text aloud as rapidly and as accurately as possible within a maximum of 3 minutes. The results allowed us to derive a reading efficiency score combining speed and

accuracy. Finally, three more standardized reading tests were run (Brèthes et al., 2022): an isolated word reading test (to measure the efficiency of the orthographic procedure), a pseudoword reading test (to assess the efficiency of the decoding procedure) and a reading fluency test. As shown in Table 1, readers with dyslexia performed significantly worse than controls on every skill, except for verbal IQ.

Table 1. Comparison of our two sample populations (readers with and without dyslexia) for each of the inclusion pre-tests. Mean and standard deviation are given for each test, along with the p-value of the Kolmogorov–Smirnov test comparing our two sample distributions. The test results showing no significant difference between the two groups are highlighted in grey. The tests used to estimate the reading impairment score are highlighted in green.

| | Control readers (mean ± SD) | Readers with dyslexia (mean ± SD) | p-value |
|---|---|---|---|
| ARHQ | 0.29 ± 0.10 | 0.61 ± 0.12 | <0.0001 |
| Verbal IQ (EVIP) | 38 ± 5 | 34 ± 5 | 0.25 |
| Non-verbal IQ (Raven) | 50 ± 6 | 46 ± 4 | 0.01 |
| honological short-term memory | 0.97 ± 0.13 | 0.72 ± 0.14 | <0.001 |
| Phonemic awareness | 1.02 ± 0.14 | 0.61 ± 0.21 | <0.0001 |
| Alouette test | 545 ± 85 | 376 ± 67 | <0.0001 |
| Pseudoword reading test | 134 ± 36 | 81 ± 30 | <0.0001 |
| Word reading test | 111 ± 21 | 81 ± 24 | <0.001 |
| Text reading fluency | 225 ± 41 | 154 ± 34 | <0.001 |

# Reading Impairment Score estimation

For each participant, we used the Alouette test and three additional reading tests (Fig. 1, Table 1) to estimate an overall reading impairment score. The four tests have normative cut-off values (https://osf.io/zmf82/ and see Brèthes et al. (2022) and Cavalli et al. (2018) for the Alouette test with a cut-off value of 402.2). A standardized test of isolated word reading was used to measure the efficiency of the orthographic procedure, and scores below the cut-off value of 99 were considered pathological. An analogous standardized test of pseudoword reading was used to assess the efficiency of the decoding procedure and scores below the cut-off value of 105 were considered pathological. Lastly, a reading fluency test was run and scores below 186 were considered pathological. A score was computed for each test and compared to the normative cut-off value. A new score was then obtained: 0 (normal) or 1 (pathological for dyslexia). For each participant, all four scores were summed, providing a final Reading Impairment Score ranging between 0 (i.e. normal scores in all tests) and 4 (i.e. pathological scores in all tests).

# Visual tests

For each participant, binocular visual acuity was measured with prescribed correction, if any, using the ETDRS letter chart (Ferris et al., 1982). Corrected visual acuity was normal for all participants, with a mean value of 0.0 ± 0.1 logMAR. Eye dominance was estimated using a simple dominant eye test, derived from the distance hole-in-the-card test (Miles, 1930). Participants were asked to extend their arms

and place their hands together at a 45-degree angle to create a triangular opening between their thumbs and forefingers. The hand opening was centered on a distant object and the participants had both eyes open. Closing each eye one at a time, the dominant eye was defined as the one that made it possible to keep the target object centered within the opening. Overall, 83.3% of our participants showed a strong ocular dominance, 9.5% showed a weak ocular dominance and 4.7% showed no ocular dominance. Detailed results are given in Fig. 2 and Appendix 1.

# Sentence reading speed assessment

MNREAD is a standardized reading test designed to estimate reading speed as a function of print size through a series of short sentences. Participants are presented with 60-character sentences (~ 10 words) and asked to read them out loud, one at a time and as fast and accurately as possible. Each new sentence is presented in a smaller type size than the previous one until it becomes so small that reading is impossible. All sentences were printed on cardboard in Times font on three lines of justified text. In our study, MNREAD was presented at a distance of 80 cm in its regular polarity (black print on a white background). The reading time (in seconds) and accuracy (in number of misread words) of each presented sentence were measured and used to derive a reading speed value in words per minute. For each test, a Reading Accessibility Index value was then derived as follows: mean reading speed across the 10 largest physical print sizes on the chart, normalized by the value for a group of normally sighted young adults (Calabrèse, Owsley, et al., 2016; Calabrèse et al., 2019). This first outcome measure is a single-valued score that represents each participant's visual access to commonly encountered printed material, where 0.0 means no access to print, 1.0 represents average normal performance and values greater than 1.0 indicate that individuals exceed the mean for normally sighted young adults.

# Text reading comprehension assessment

Our second outcome measure was text reading comprehension performance, assessed with a new French standardized task which consists in the silent reading of a newspaper article from the French newspaper, Le Monde (~ 500 words). The text is read without time constraints and is followed by a set of questions (Brèthes et al., 2022; https://osf.io/zmf82/). This newly validated test makes it possible to evaluate literal comprehension as well as inferential comprehension skills, namely text-connecting inference skills (which require the participant to integrate text information in order to establish local cohesiveness) and knowledge-based inference skills (which make it possible to establish links between the text content and the reader's personal knowledge). Once participants had finished reading, they answered a series of oral multiple-choice or open questions. They were not allowed to go back to the text when answering the questions. A comprehension score was assessed, ranging from 0 (i.e, no comprehension) to 100 (perfect comprehension).

# Lighting conditions

In order to assess the influence of lighting on the two outcome measures (reading accessibility index and text reading comprehension score), each reading test was administered using different test versions

under three lighting conditions: (1) a control condition with regular lighting, (2) a pulsed light condition, and (3) a combination condition with both regular and pulsed light. Control lighting was provided by a standard desk lamp, set to its standard luminance (136 lumens measured in the laboratory with a Konica Minolta LS-150 photometer). Pulsed lighting was provided using the Lili Lamp, designed by the *Lili for life* company and based on the patented technology from Le Floch and Ropars. Lili projects a pulsed luminous flux that can be customized in terms of both pulsation frequency and on/off time balance. Frequency and balance parameters were optimally chosen for each participant before the experiment. Settings were considered optimal when participants felt comfortable reading a mock text presented in front of them on a sheet of paper. The settings chosen for each participant are reported in Appendix 1. The luminance of Lili (116 lumens) was noticeably lower than in our control condition. To avoid any luminance bias, we added a third condition, combining both light settings, in which the luminance (131 lumens) matched our control condition, while pulsed lighting with optimal settings was also provided. The order of the lighting conditions was randomized across participants and the lighting arrangements hid the different lamps from the participants' view.

# Statistical analysis

Statistical analysis was performed using R statistics (R core team 2020, version 4.0.2). Linear mixed-effects (LME) models were used to assess the effect of the lighting conditions on each of our outcome measures (i.e., reading accessibility index and comprehension score). LME models are especially appropriate here, since they make it possible to consider the random effects associated with individual participants and their repeated measures. Two LME models were fitted, one for each outcome measure, which was set as the dependent variable. In both models, reading impairment score, ocular dominance strength and lighting condition were used as independent variables (i.e., fixed effects). Their interactions were also included in the models. Non-verbal IQ score (Raven) was initially included in the models, but was then discarded from final models because it showed no significant influence on the effect of lighting condition. The random structure of both models included a random intercept for participants, which assumed a different baseline performance level for each individual. Both the reading accessibility index and comprehension score were transformed into natural logarithm (ln) units to satisfy the assumptions of parametric statistical tests (Howell, 2009; Tabachnick et al., 2007). Optimal model structures were assessed using the Akaike Information Criterion (AIC) and likelihood-ratio tests (Zuur et al., 2010). The significance of the fixed effects was estimated using t-values. Results were considered significant for t-values larger than 2 or smaller than − 2, corresponding to a 5% significance level in a two-tailed test (Baayen et al., 2008; Gelman & Hill, 2007). In the Results section, fixed-effects estimates are reported along with their t-values and 95 percent confidence intervals (Bates et al., 2015).

An *a posteriori* power analysis was conducted with the mixedpower package in R (Kumle et al., 2021). This indicated that a sample size of 40 participants would provide a statistical power above 80%.

# Results

# Analysis 1 – Reading Accessibility Index (ACC)

According to model 1, the average ACC of expert readers (Reading Impairment = 0) with a strong ocular dominance and under control lighting was 0.97 (exp(-0.032) – Table 2). For these same readers, switching to pulsed + control lighting led to a non-significant increase in ACC by a factor of 1.008 (exp(0.008); t = 0.361; 95% CI = [-0.033;0.048]), with an average index value of 0.98 exp(-0.032 + 0.008). Similarly, switching to pulsed lighting only led to a non-significant change (t = -0.139; Fig. 3). This was also true for expert readers with weak ocular dominance, for whom switching to pulsed + control lighting or pulsed lighting did not significantly modify ACC (t = -0.809; 95% CI = [-0.105;0.042] and t = -1.324; 95% CI = [-0.125;0.023], respectively). In the control lighting condition, increasing readers' reading impairment score by 1 decreased ACC significantly by a factor of 0.91 (exp(-0.097); t = -9.336; 95% CI = [-0.117;-0.077]), leading to an average ACC of 0.88 for individuals with impairment = 1 (exp(-0.032-0.097)), 0.80 for individuals with impairment = 2 (exp(-0.032+(2*-0.097))), 0.72 for individuals with impairment = 3 (exp(-0.032+(3*-0.097))), and 0.66 for individuals with impairment = 4 (exp(-0.032+(4*-0.097)) – Fig. 3). This is consistent with well-established reports of impaired reading speed in individuals with dyslexia. It also suggests that, for any given individual, the more skills affected by dyslexia are labelled as impaired, the more reading speed is impaired. Still according to model 1, we found no significant change in ACC when going from control lighting to pulsed + control for any individual with a reading impairment of 1 or above, (t = 1.337; 95% CI = [-0.004;0.025]), and observed only a barely significant increase in ACC (by a factor of 1.018 - *exp(0.008)*) when switching to pulsed lighting only (t = 2.273; 95% CI = [0.003;0.033]).

Table 2. Fixed effects estimates from LME model 1. The intercept estimate represents the log-transformed accessibility index when all factors included in the model are at their reference level (categorical variable) or at 0 (continuous variable). Reference levels are: *control* lighting condition, *strong* ocular dominance and reading impairment score of 0. Interactions are represented by the symbol ":". Factors showing a significant effect on reading time are in bold font.

| | Estimate | St. Error | t-value | 95% CI |
|---|---|---|---|---|
| (Intercept) | -0.032 | 0.029 | -1.118 | [-0.087;0.023] |
| Pulsed + control | 0.008 | 0.021 | 0.361 | [-0.033;0.048] |
| Pulsed | -0.003 | 0.021 | -0.139 | [-0.044;0.038] |
| Weak ocular dominance | -0.001 | 0.052 | -0.019 | [-0.1;0.098] |
| **Reading impairment** | **-0.097** | **0.01** | **-9.336** | **[-0.117;-0.077]** |
| Pulsed + control: Weak ocular dominance | -0.031 | 0.038 | -0.809 | [-0.105;0.042] |
| Pulsed : Weak ocular dominance | -0.051 | 0.039 | -1.324 | [-0.125;0.023] |
| Pulsed + control: Reading impairment | 0.01 | 0.008 | 1.337 | [-0.004;0.025] |
| Pulsed : Reading impairment | 0.018 | 0.008 | 2.273 | [0.003;0.033] |

# Analysis 2 – Text reading comprehension score

According to this second model, the average score of expert readers (Reading Impairment = 0) with strong ocular dominance under control lighting condition was 56.9 (exp(4.042) – Table 3). When the same participants were switched to the other conditions, the average scores were unchanged: 56.8 (exp(4.042 – 0.001); t=-0.003) in the pulsed + control condition and 56.6 (exp (4.042 – 0.006); t=-0.029) in the pulsed condition. This was also true for expert readers with weak ocular dominance, for whom switching to pulsed + control lighting or pulsed lighting did not significantly modify ACC (t = -0.106 and t = -0.481 respectively). Similarly, changing lighting conditions did not significantly modify the comprehension scores of readers with a reading impairment of 1 or above (t = 0.74 and t = 0.811). Finally, changes in reading impairment score did not significantly alter the comprehension score (t = -1.956; Fig. 4).

Table 3. Fixed effects estimates from LME model 2. The dependent variable is the log-transformed comprehension score. The intercept estimate represents the log-transformed comprehension score when all factors included in the model are at their reference level (categorical variable) or at 0 (continuous variable). Reference levels are: *control* lighting condition, *strong* ocular dominance and reading impairment score of 0. Interactions are represented by the symbol ":". Factors showing a significant effect on comprehension score are in bold font.

| | Estimate | St. Error | t-value | 95% CI |
|---|---|---|---|---|
| (Intercept) | 4.042 | 0.175 | 23.09 | [3.709;4.375] |
| Pulsed + control | -0.001 | 0.224 | -0.003 | [-0.428;0.427] |
| Pulsed | -0.006 | 0.224 | -0.029 | [-0.434;0.421] |
| Weak ocular dominance | 0.154 | 0.317 | 0.486 | [-0.448;0.756] |
| Reading impairment | -0.124 | 0.063 | -1.956 | [-0.244;-0.003] |
| Pulsed + control: Weak ocular dominance | -0.043 | 0.405 | -0.106 | [-0.816;0.73] |
| Pulsed : Weak ocular dominance | -0.195 | 0.406 | -0.481 | [-0.969;0.579] |
| Pulsed + control: Reading impairment | 0.06 | 0.081 | 0.74 | [-0.095;0.215] |
| Pulsed : Reading impairment | 0.066 | 0.082 | 0.811 | [-0.09;0.222] |

# Discussion

The aim of the present study was to test Le Floch and Ropars' hypothesis according to which dyslexia is mainly triggered by visual processing deficits, namely an absence of eye dominance, which induce the aberrant perception of afterimages for individual letters (Le Floch & Ropars, 2017). According to these authors, dyslexic readers would be expected to achieve reading performances similar to those of controls under pulsed lighting conditions. To test this hypothesis, we assessed the reading performance of young

adults with and without dyslexia reading under pulsed lighting, while taking into account the presence (or absence) of eye dominance as well as the functional impact of dyslexia on their reading abilities. Our main result is that we found no effect of pulsed lighting on the two reading scores we used, namely the MNREAD reading accessibility index (ACC) and a text reading comprehension score. This was true for all values of the reading impairment score, irrespective of whether participants showed eye dominance or not. In other words, we failed to show a clear positive impact of pulsed lighting on the reading performance of a group of young adults with dyslexia.

Indeed, individuals with dyslexia did not reach control readers' performance, even in the pulsed lighting condition. This suggests that pulsed lighting is not sufficient to alleviate the reading deficit experienced by dyslexics and to restore reading skills. Over the years, different visual remediation strategies have also been explored to eliminate and/or reduce visual impairment, through visual aids or training. For instance, colored overlays have been used to alleviate visual stress (i.e., distortions) in dyslexic reader, but no clear-cut effects have been observed (Evans & Allen, 2016; Henderson et al., 2013). Lawton and Shelley-Temblay (2017) administered visual training to dyslexic children in order to restore the functioning of the magnocellular pathway (activated by eye movement), which is thought to be deficient and responsible for a lack of synchronization with the parvocellular pathway (activated during fixations). Using exercises focusing on movement detection and its direction, such training is intended to improve the sensitivity and synchronization of magnocellular processing. Another type of training currently being investigated involves the use of action video games. These games, which feature fast-moving elements and targets, along with numerous spatially and temporally unpredictable events, place considerable emphasis on the peripheral visual field as well as on the global visual processing of elements and impose a high motor load. Thanks to these features, they strongly solicit the player's attentional, visual and visual-attentional capacities, improvements which would then transfer to reading. In particular, action video games might increase the useful size of the visual field and improve the discrimination of rapid sequences of visual stimuli, of the sort that occur in reading. Letters in words must be accurately selected from surrounding graphemes through the rapid orientation of visual attention before their correct letter-sound translation for word decoding can occur. Effective visual attention would improve the perception of visual stimuli and increase the development of letter-sound connections. Using action video games with children with dyslexia (Franceschini et al., 2013), reported a significant improvement in these children's reading fluency skills. However, (Łuniewska et al., 2018) failed to replicate this effect. Overall, even though a number of studies have reported that individuals with dyslexia may use a different visual sampling strategy to read texts (e.g., longer fixation durations, shorter saccades and fewer skipped words during first-pass reading (Franzen et al., 2021)), the question of which visual deficit causes this phenomenon remains unanswered.

The second important result of this study is that the majority of the participants with dyslexia (87%) showed strong ocular dominance and this was true even of those with the highest reading impairment score of 4. This proportion is higher than in Le Floch & Ropars, (2017), who reported that only 53% of their participants with dyslexia showed ocular dominance (also measured with the hole-in-the-card test). While it may be argued that our sample did not respond differently to pulsed lighting because it mainly showed

strong ocular dominance, this result actually implies that dyslexia may not be related to a lack of eye dominance, contrary to the suggestion made by Le Floch & Ropars, (2017). In the 60's, a number of authors had already suggested that the absence of ocular dominance might play a pathogenetic role in developmental dyslexia (Benton et al., 1965; Bettman et al., 1967). However, conflicting results led this hypothesis to fall out of favor until it was lent renewed interest through the work of Stein & Fowler, (1981). More recently, Zeri et al. (2011) postulated that these conflicting results may be due to a lack of consistency between the results of different dominance tests, which assess different dimensions of eye dominance. For instance, while the hole-in-the-card test estimates sighting eye dominance (i.e., the preferential choice of one eye during monocular tasks), other tests, such as the Dunlop test, evaluate motor ocular dominance (related to binocular conflict in binocular vision) (Evans, 2001). In their thorough investigation of the relationship between ocular dominance and reading performance, Zeri et al., (2011) confirmed that different tests yield different stability measures and concluded that test selection is critical when assessing eye dominance stability. However, their results lent no support to the idea that there is a link between stability of ocular dominance and reading performance for any of the tests they considered. The present results, obtained with a standard test of monocular vision (chosen to match Le Floch and Ropars' methodology and to simplify the comparison of the results), are in line with these findings.

Finally, we used a continuous reading impairment score in order to grade the overall deficit experienced by dyslexic readers. This score is intended to represent a reader's level of impairment on the basis of a certain number of reading skills, namely, reading speed and accuracy, reading fluency, orthographic reading procedure and reading decoding procedure. Our results show that individuals with a high reading impairment score have a poorer reading accessibility index than readers with higher scores. In other words, the more pathological markers of dyslexia a reader has, the harder it is to achieve a reading accessibility index comparable to that of expert readers. This result suggests that considering dyslexic readers' impairment level on a continuous scale using a reading impairment score of this type may be an efficient and sensitive way to grade the overall deficit experienced by such readers. In addition, the present work highlights the use of the reading accessibility index (ACC) to assess the specific impact of dyslexia on reading speed. While, the MNREAD test was first designed to assess reading performance in normally sighted and visually impaired individuals, our results suggest that ACC may be sensitive enough to provide a measure of reading speed impairment in individuals with dyslexia. Interestingly, the significant body of literature available on MNREAD for control readers of all ages would allow researchers to measure the impact of developmental dyslexia on reading performance through comparisons with age-specific normative data (Baskaran et al., in press; Calabrèse, Cheong, et al., 2016).

As in Le Floch and Ropars, the present study investigated reading using the French orthographic system. It is known that the characteristics of orthographic systems may have an influence on the impairment of reading processes in dyslexia. For instance, it has been shown that brain activity during reading or reading-related tasks differs in people classified as dyslexic compared to skilled readers (Maisog et al., 2008; Richlan et al., 2009) and that the amplitude of this difference is modulated by orthographic depth (Martin et al., 2016). Therefore, it remains to be tested whether our results can be applied to other

orthographic systems, the orthographic depth of which may differ from French. Furthermore, while our focus was on sentence and text reading skills, further investigation of the effect reported by Le Floch and Ropars should be conducted using simpler tasks. For instance, it would be possible to use isolated words and pseudowords, the identification of which requires precise orthographic coding and cannot be accomplished using semantic or contextual knowledge, unlike in the case of text reading. This may shed some light on the specificity of any potential benefits of pulsed lighting in dyslexia. Finally, while this study focuses on young adults, future investigations should consider assessing the impact of pulsed lighting on a cohort of children of different ages and reading expertise.

# Declarations

### Author contributions

AC and PC conceived and designed the analysis. EL and JBM collected the data. EL and AC performed the data analysis. EL, PC and AC wrote the manuscript.

### Data availability statement

Data will be fully available upon request to the corresponding author (AC) at aurelie.calabrese@univ-amu.fr

### Additional Information

### Competing Interests Statement

The authors declare no competing interest.

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# Figures

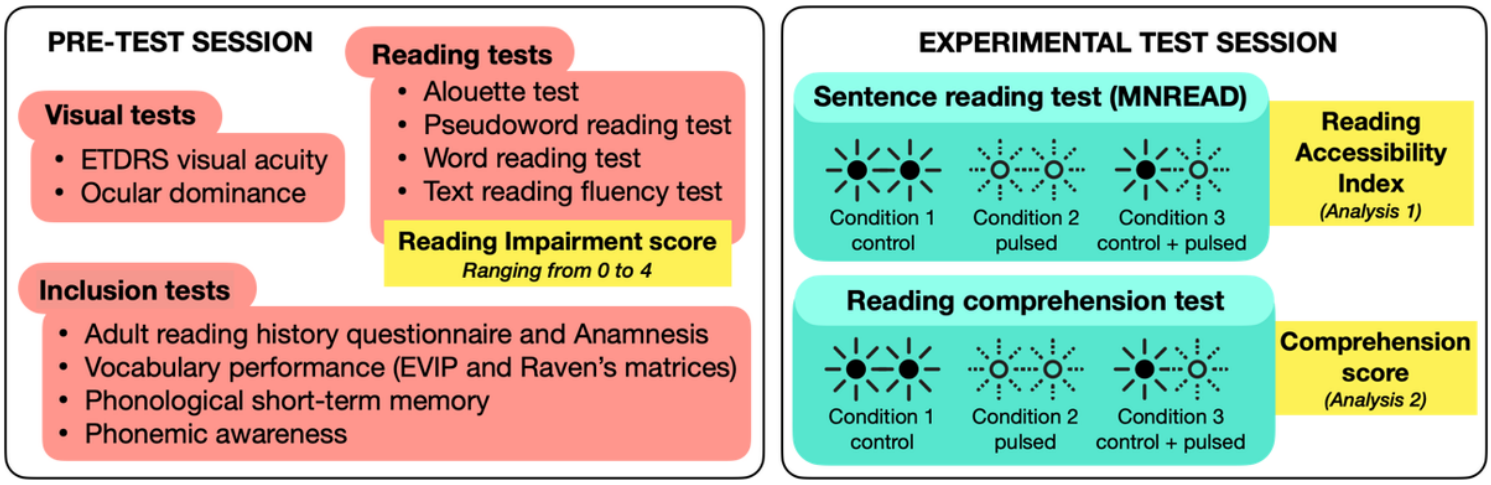


Figure 1

Overview of all tests run during the pre-test and experimental test sessions.

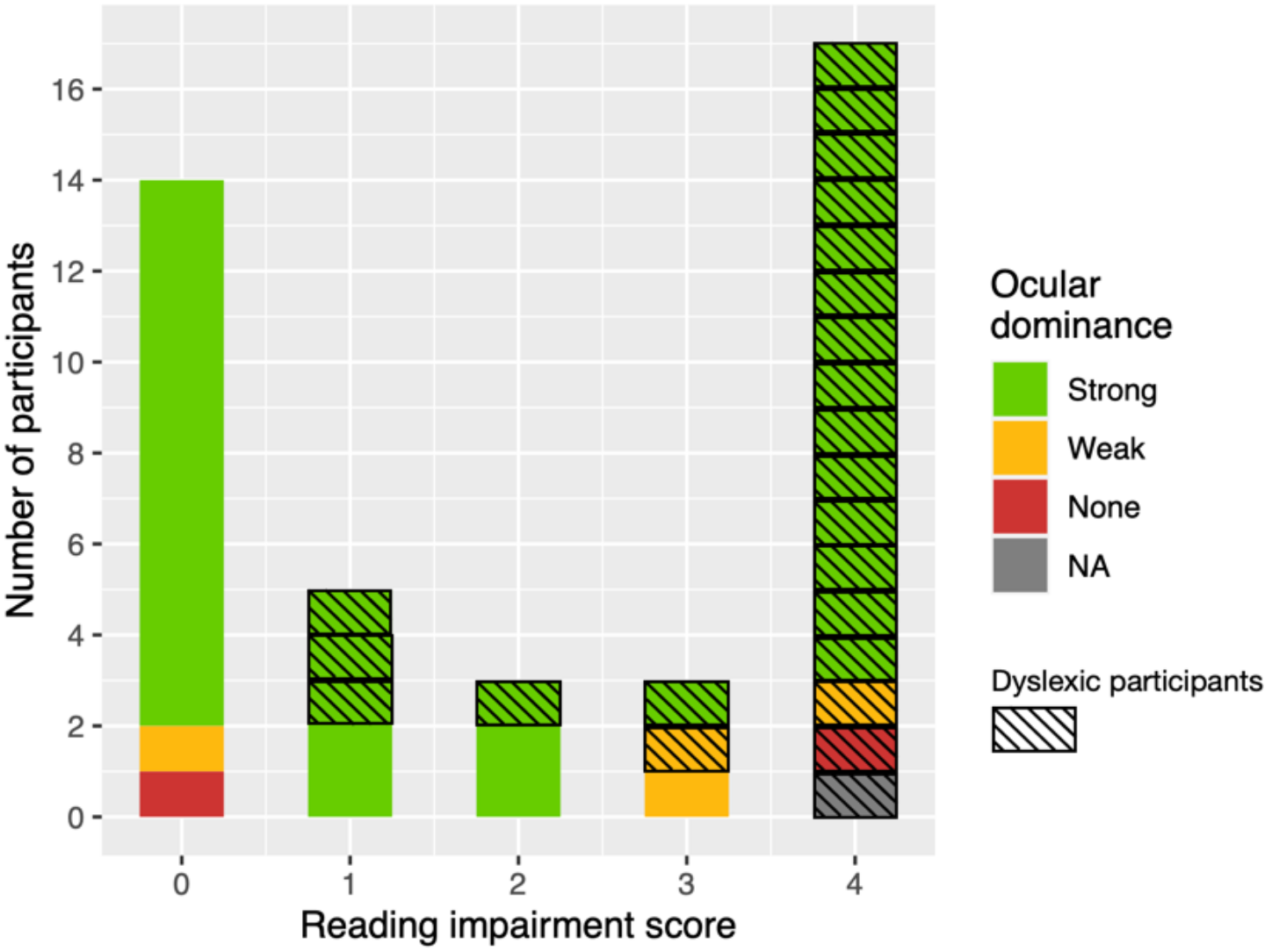


Figure 2

Distribution of our population's ocular dominance strength, broken down by reading impairment score value. Participants enrolled as dyslexic are shown with hatching.

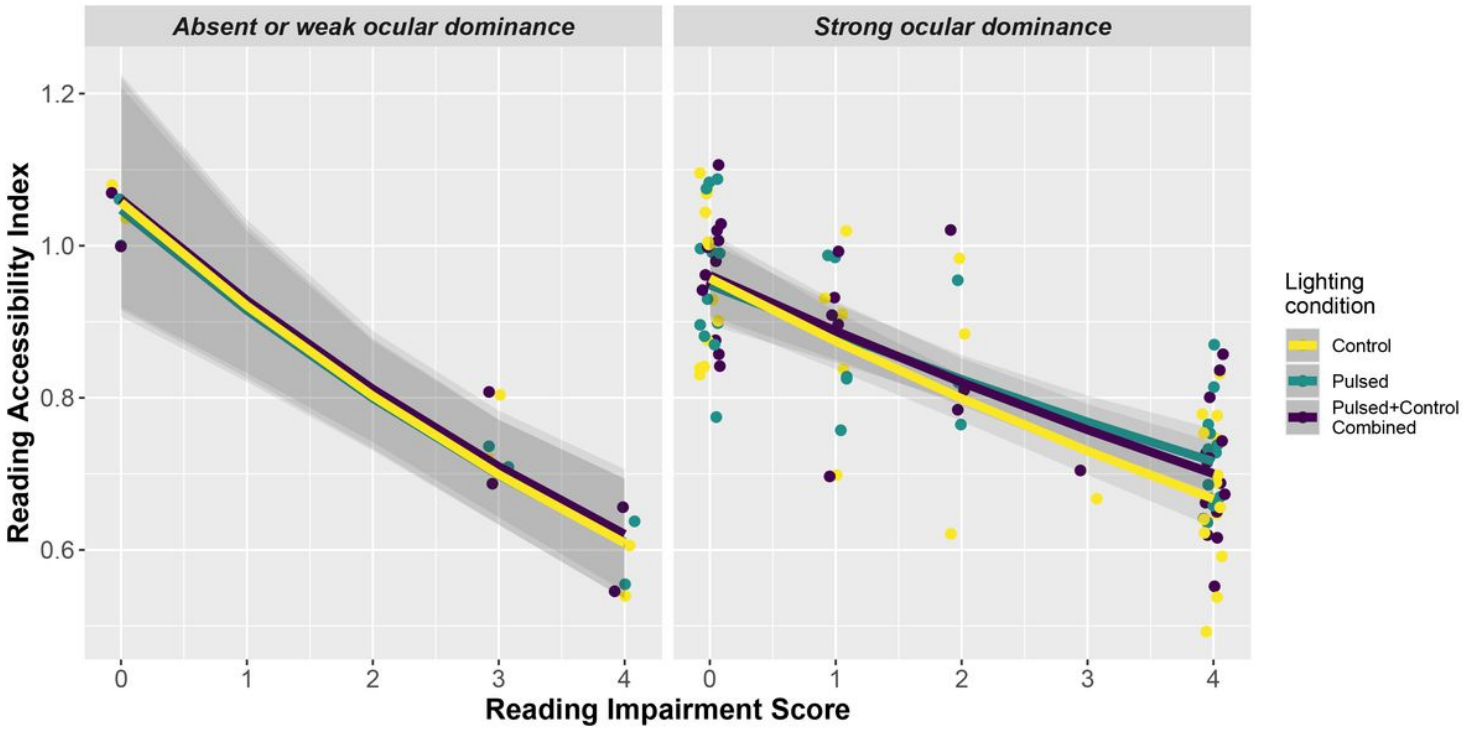


**Figure 3**

Effect of reading impairment on reading accessibility index for three different lighting conditions. Data points show the raw data. Lines represent the fits estimated by model 1 and shaded areas their 95% confidence intervals. Lighting conditions are color-coded as follows: control condition is represented in yellow, pulsed condition in green and pulsed + control in purple.

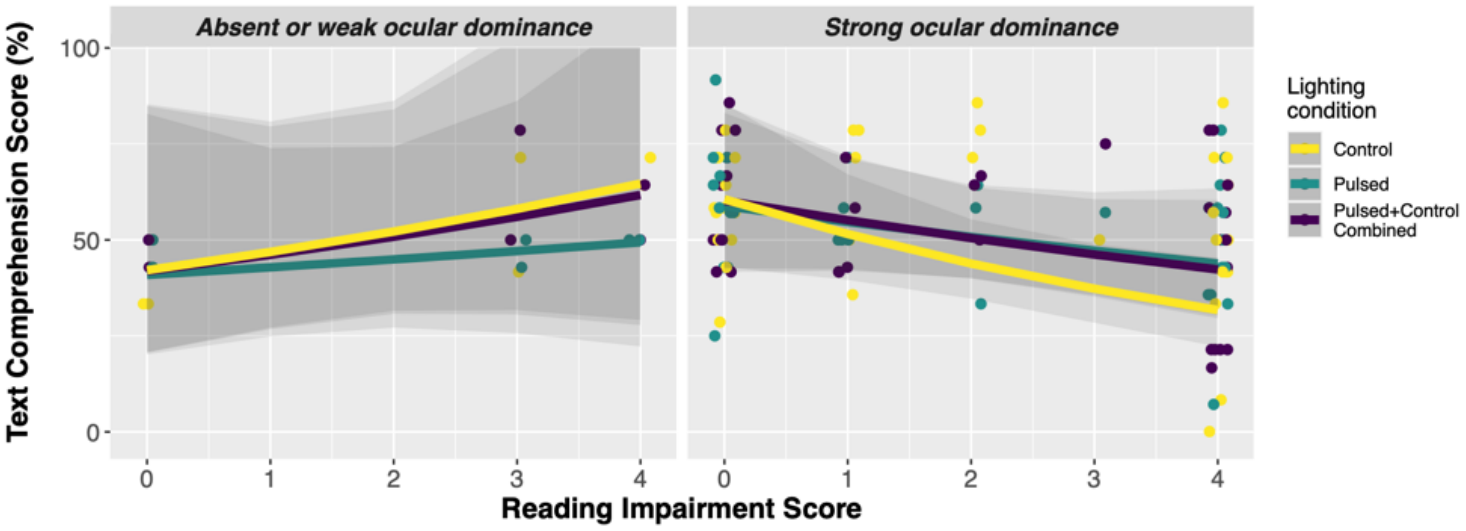


**Figure 4**

Effect of reading impairment score on comprehension score for three different lighting conditions. Data points show the raw data. Lines represent the fits estimated by model 2 and shaded areas their 95% confidence intervals. Lighting conditions are color-coded as follows: control condition is represented in yellow, pulsed condition in green and pulsed + control in purple.

## Supplementary Files

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