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Eole Lapeyre, Jean-Baptiste Melmi, Pascale Colé & Aurélie Calabrèse✉

The goal of this study is to evaluate the impact of pulsed lighting on the reading performance of young adults with dyslexia. A total of 42 participants were recruited, including individuals diagnosed with developmental dyslexia and adults without reported reading difficulties. The severity of each participant's reading deficit was assessed on a continuous scale using a reading impairment score, derived from four reading tests: an isolated-word reading test, a pseudoword reading test, and two reading fluency tests. The impairment score ranged from 0 (no impairment) to 4 (severe impairment across all tests). To examine the potential effect of pulsed lighting, we measured (1) sentence reading speed, expressed as a reading accessibility index (ACC), and (2) text comprehension, expressed as a comprehension score. These measures were taken under three lighting conditions: standard lighting, pulsed lighting, and a combination of the two. Linear mixed-effects models were applied to assess the effects of lighting on ACC and comprehension, controlling for the reading impairment score. We found no effect of lighting conditions on either ACC or comprehension, except in the most impaired readers, who showed a small but significant increase of 7% in ACC. However, even with pulsed lighting, impaired readers did not reach the performance level of skilled adult readers. In conclusion, the study did not demonstrate a clear positive impact of pulsed lighting on the reading skills of adults with dyslexia.

Developmental dyslexia (hereafter, dyslexia) is the most frequent neurodevelopmental disorder, affecting approximately 7% of the population[1]. According to the *Diagnostic and Statistical Manual of Mental Disorders* 5th Ed[2]. , dyslexia is a specific learning disorder characterized by inaccurate (or slow and effortful) decoding and word reading that may impair reading comprehension, as well as poor spelling skills, despite normal intelligence and appropriate educational opportunities. In the literature, several deficit hypotheses have been proposed as possible causal explanations of dyslexia. These include the auditory hypothesis[3], the phonological hypothesis[4], the cerebellar/motor hypothesis[5] or the visual hypothesis[6] (for a review, see[7]). Several visual hypotheses of dyslexia have already been proposed: the visual-attention span deficit hypothesis[8], the orientation of visual attention deficit hypothesis[9,10] and, more recently, the iconic memory and visual-short-term memory transfer deficit hypothesis[11,12]. The common idea to all these hypotheses is that the associated visual deficit would disrupt the generation of words orthographic coding, resulting in impaired multi-letter string processing[13].

Recently, physicists Le Floch and Ropars proposed another visual hypothesis, attributing dyslexia to a specificity in the Maxwell's centroids (the blue cone-free areas at the center of each retina)[14]. Using a foveascope of their design, these authors were able to map Maxwell's centroids in both eyes of skilled readers and dyslexic adults. They reported dissimilar blue cone-free areas in skilled readers (a circular area in the dominant eye and an elliptical one in the non-dominant eye), associated with an established eye dominance. This asymmetry was absent in adults with dyslexia, who experienced circular blue cone-free areas in both eyes and no eye dominance (despite a normal ocular status). The authors hypothesized that this lack of asymmetry might prevent dyslexic individuals from having ocular dominance. While the typical brain receives visual information from both optic nerves, it relies preferentially on the input from the dominant eye[15]. 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[16]. 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 would result in an undetermined afterimage dominance, with the primary and mirror images

Aix-Marseille Univ, CNRS, CRPN, Marseille, France. ✉email: aurelie.calabrese@univ-amu.fr

coexisting and possibly causing confusion regarding the identification of mirror letters (e.g., *b* and d). However, this hypothesis is still subject to strong controversy[17].

There is some evidence that temporal modulations of light frequency and luminance can influence perception of visual afterimages[18–20]. 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[21]. 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 hard to replicate their results.

Therefore, the goal of the present work is to assess the impact of pulsed lighting on the reading skills of a larger sample of individuals with dyslexia. Importantly, throughout this work, dyslexia is considered as a multifactorial condition ranging along a continuous spectrum rather than as a dichotomic status (control vs. dyslexic). This framework allows us to better understand and account for the reported heterogeneity in reading profiles of adults with dyslexia[22–24]. Thus, in Cavalli et al. (2018)[22], 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)[24]. These authors 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[25] 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)[26], this score allowed us to consider reading performance on a continuum rather than on a dichotomous scale and to evaluate the impact of different lighting conditions (pulsed versus control) as a function of individual reading profiles.

Methods

Participants

We tested 42 young adults (17 males) aged 19 to 27 years old (mean±SD = 21±2), including individuals with no reported reading difficulties and individuals with diagnosed developmental dyslexia. 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 a previous diagnosis of dyslexia (established earlier in life by a speech therapist, either during childhood or adolescence) were recruited from the Aix-Marseille University Disability Service. 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 Informed 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 test session (Fig. 1). All tests were administered by a single experimenter in an empty room (e.g., no windows or shelves) to avoid any distractions.

Pre-test session

Screening tests

All participants completed a series of French tests to screen for individual reading skills. The French version of the Adult Reading History Questionnaire (ARHQ) and Anamnesis[27] 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)[28] and non-verbally with Raven's Matrices[29]. Phonological short-term memory and phonemic awareness were also tested with the EVALEC toolset[30]. Individual results are reported in the Supplementary Material.

Reading tests

Four standardized reading tests were run to estimate a reading impairment score for each participant. First, we used a standardized version of the Alouette test[31] developed for adults[22] to assess reading skills. This test consists of a series of real words embedded in meaningless but grammatically and syntactically correct sentences. Hence, dyslexic and poor readers cannot use contextual information to compensate for their written word recognition difficulties. Participants were asked to read the 265-word text aloud as rapidly and as accurately as possible within a maximum of 3 min. A reading efficiency score combining speed and accuracy was computed for each participant and considered pathological below the cut-off value of 402.2[22]. A standardized test of isolated word reading was used to measure the efficiency of the orthographic procedure (pathological cut-off value of 99 (https://osf.io/zmf82/)[32]. The efficiency of the decoding procedure was tested with an analogous standardized pseudoword reading test (pathological cut-off value of 105). Last, a reading fluency test (pathological cut-off

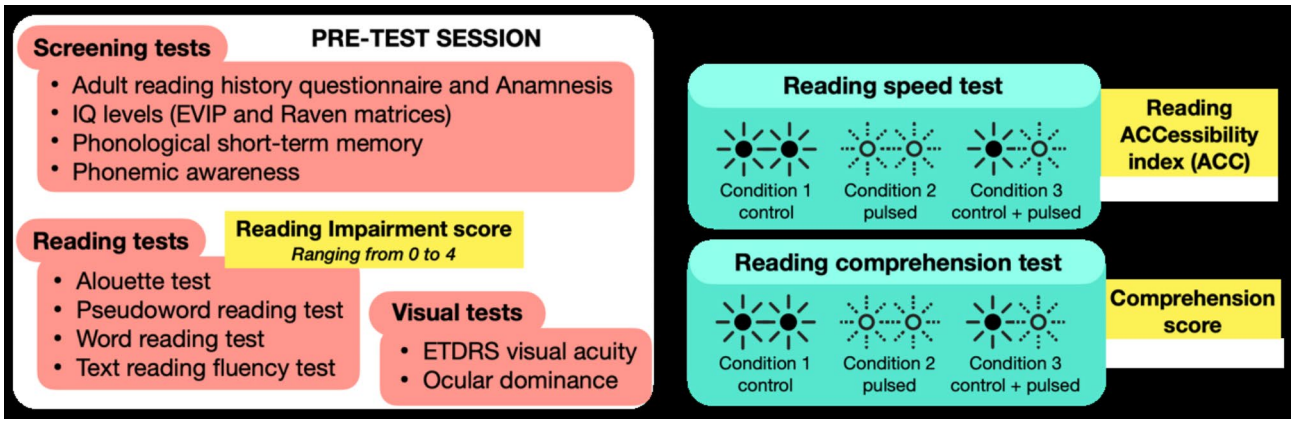

Fig. 1. Overview of all tests run during the pre-test and experimental test sessions. Highlighted in yellow are the outcome measures used for the analyses.

value of 186) was also used. For each test, a score was computed: 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[33]. Corrected visual acuity was normal for all participants, with a mean value of 0.0 ± 0.1 logMAR. Sighting eye dominance was estimated as follows: 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. The test was repeated four times. Eye dominance was estimated as: *strong* if participants responded consistently from test #1 to test #4; *weak* if they did not identify their dominant eye from test #1 but responded consistently once they did; *none* if the target object disappeared from the opening when closing both their left and right eye on all 4 tests. Based on this test, 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 Supplementary Material.

Experimental test session

During this session, two different tests were run to estimate the influence of pulsed lighting on reading performance: a sentence reading test and a reading comprehension test. Both tests were performed under several lighting conditions detailed below.

Reading speed test

The MNREAD chart[34] 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, 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. 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. As per the MNREAD guidelines, the reading ACCessibility index (ACC) was then derived for each test[35,36]. The ACC 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.

Reading comprehension test

Text reading comprehension was measured with a new French standardized test (https://osf.io/zmf82/)[32]. Newspaper articles (~500 words each), selected from the French newspaper Le Monde, were read silently without time constraints and followed by a series of questions. This newly validated test allows 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).

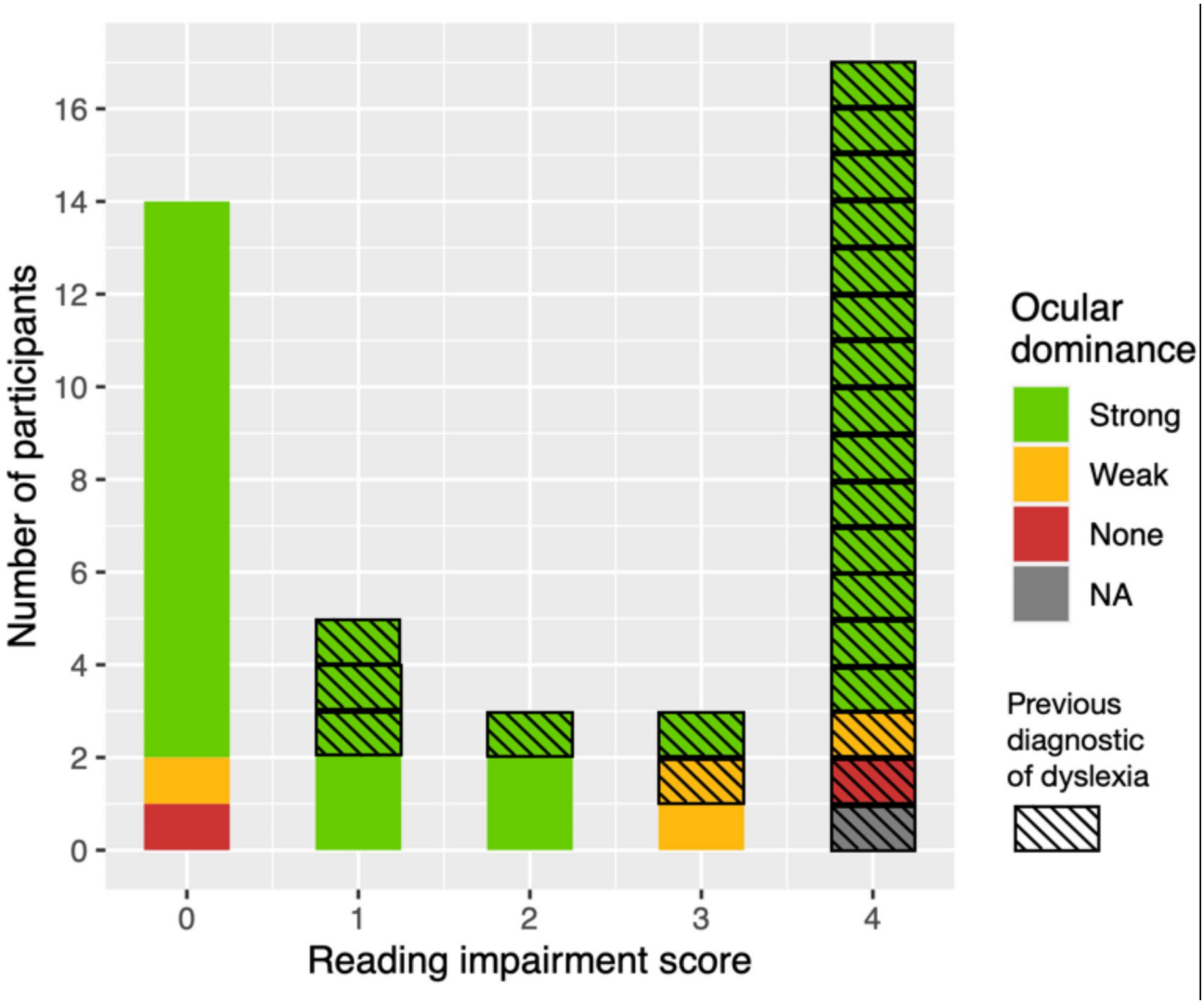

Fig. 2. Distribution of our population's ocular dominance strength, broken down by reading impairment score value. Participants with a previous diagnosis of dyslexia are shown with hatching.

Lighting conditions

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, using high-frequency flickering, 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 (between 60 and 120 Hz) and on/off time balance. Frequency and balance parameters were optimally chosen by 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[37]. Linear mixed-effects (LME) models were used to assess the effect of lighting conditions on the measure of reading speed (ACC) and the measure of reading comprehension (comprehension score), while also taking into account individual values of impairment 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. A first LME model was fitted with ACC as the dependent variable and

the following independent variables (i.e., fixed effects): reading impairment score, lighting condition and their interaction. A second model with the same fixed-effects structure was also fitted with comprehension score as the dependent variable. Non-verbal IQ score (Raven) and ocular dominance strength were initially included in both models. They were discarded from the final models as they showed no significant influence on the effect of lighting. Both models included a random intercept for participants, assuming a different baseline performance level for each individual. Both dependent variables (ACC and comprehension score) were normalized using natural logarithm (ln) transformation to satisfy the assumptions of parametric statistical tests[38,39]. Optimal model structures were assessed using the Akaike Information Criterion (AIC) and likelihood-ratio tests[40]. 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[41,42]. In the Results section, fixed-effects estimates are reported along with their t-values and 95% confidence intervals[43].

An *a posteriori* power analysis was conducted with the mixedpower package in R (Kumle et al., 2021). It indicated that a sample size of 40 participants was sufficient to obtain a statistical power above 80% for all effects included in the model.

Results

Reading speed (ACC)

According to the LME model, average ACC value of expert readers (Reading Impairment = 0) under control lighting was 0.97 (exp(-0.033) – Table 1). For these same readers, reading with pulsed + control lighting led to a non-significant increase in ACC by a factor of 1.003 (exp(0.003); t = 0.137; 95% CI = [-0.044 ; 0.050]), and an average ACC value of 0.97 exp(-0.033 + 0.003). Pulsed lighting also led to a non-significant change (t = -0.248; Fig. 3). Under control lighting, ACC decreased as reading impairment score increased. For instance, an increase in impairment score from 0 to 4 leads to a significant decrease in ACC by a factor of 0.68 (exp(-0.382); t = -8.840; 95% CI = [-0.468 ; -0.297]), i.e., an average ACC of 0.66 (exp(-0.033-0.382) – Fig. 3). This suggests that, for any given individual, the more skills affected by dyslexia are labelled as impaired, the more reading speed is impaired. For any impairment scores, we found no significant difference in ACC when reading under pulsed + control lighting compared to control lighting. Likewise, there was no significant change in ACC when reading under pulsed lighting, compared to control lighting, for dyslexic individuals with an impairment score between 1 and 3. However, in the group with the most severe reading skill deficits (impairment score of 4), we observed a significant 7% increase in ACC (exp(0.070); t = 2.172; 95% CI = [0.006; 0.134]), raising ACC from 0.66 under control lighting to 0.70 under pulsed lighting.

	Effects on ACC			
Predictors	***Estimate***	***Std. Error***	***95% CI***	***t-value***
(Intercept)	−0.033	0.032	−0.096–0.031	−1.018
Pulsed	−0.006	0.024	−0.053–0.041	−0.248
Pulsed + control	0.003	0.024	−0.044–0.050	0.137
Impairment score 1	−0.104	0.062	−0.228–0.020	−1.665
Impairment score 2	**−0.173**	**0.076**	**−0.324 – −0.022**	**−2.267**
Impairment score 3	**−0.284**	**0.076**	**−0.436 – −0.133**	**−3.732**
Impairment score 4	**−0.382**	**0.043**	**−0.468 – −0.297**	**−8.840**
Pulsed : Impairment score 1	0.005	0.046	−0.086–0.096	0.106
Pulsed + control : Impairment score 1	0.004	0.046	−0.087–0.096	0.094
Pulsed : Impairment score 2	0.040	0.056	−0.071–0.152	0.715
Pulsed + control : Impairment score 2	0.058	0.056	−0.054–0.169	1.027
Pulsed : Impairment score 3	0.015	0.056	−0.096–0.127	0.268
Pulsed + control : Impairment score 3	0.001	0.056	−0.111–0.112	0.014
Pulsed : Impairment score 4	**0.070**	**0.032**	**0.006–0.134**	**2.172**
Pulsed + control : Impairment score 4	0.040	0.032	−0.023–0.104	1.266
Observations	125			
Marginal R^2 / Conditional R^2	0.626 / 0.898			

Table 1. Fixed effects estimates from the LME model. The intercept estimate represents the log-transformed ACC when all factors included in the model are at their reference level (categorical variable) or at 0 (discrete variable). Reference levels are: control lighting condition and reading impairment score of 0. Interactions are represented by the symbol ":". Factors showing a significant effect on reading time are in bold font. Marginal R^2 (variance of the fixed effects) and conditional R^2 (variance of the fixed and random effects) are provided.

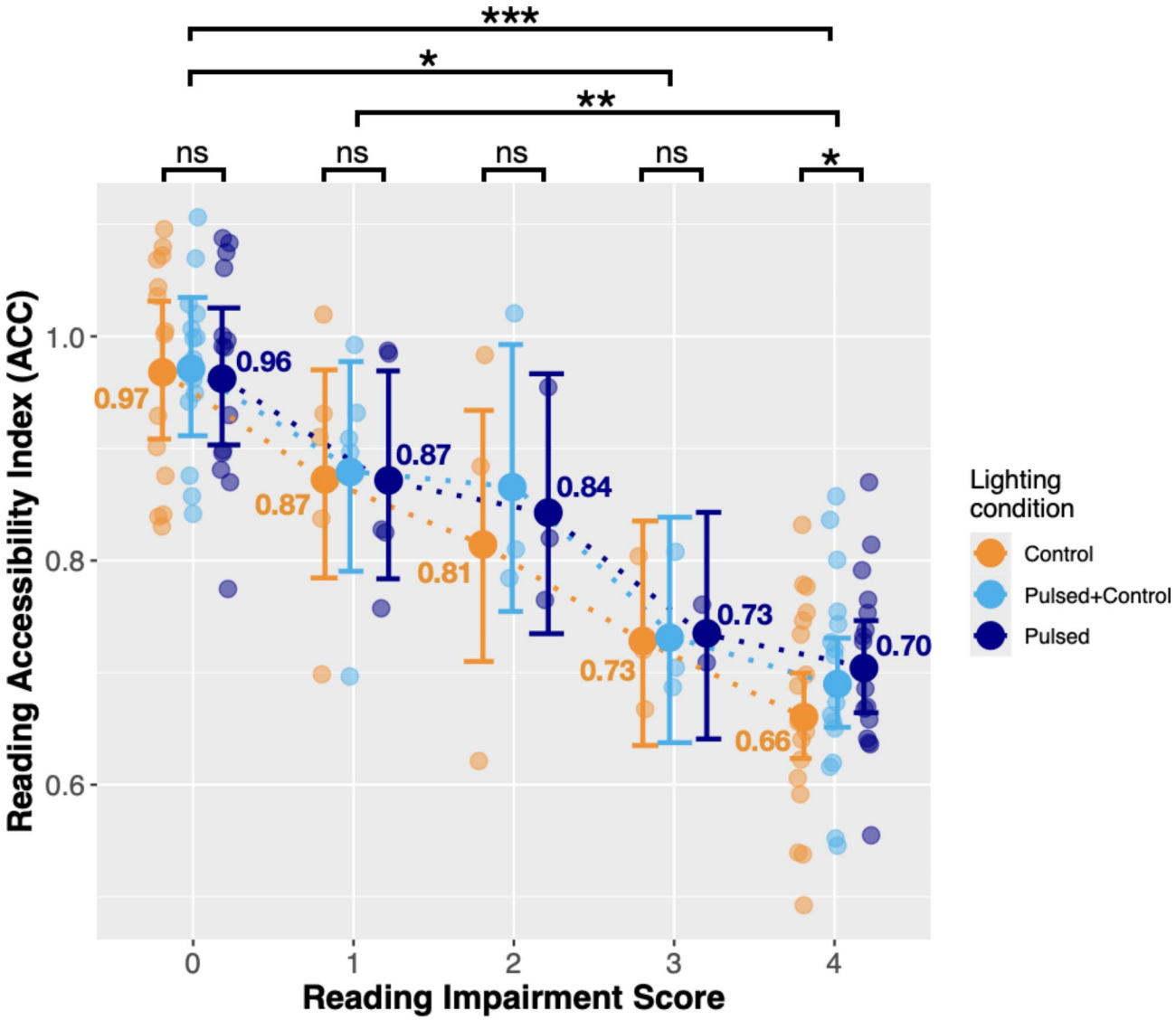

Fig. 3. ACC grouped by reading impairment score for three different lighting conditions. Small data points show the raw data. Large data points represent the model estimates for each score and their 95% confidence intervals. Lighting conditions are color-coded as follows: control condition is represented in orange, pulsed+control condition in light blue and pulsed only in dark blue.

Reading comprehension

According to the LME model, the average comprehension score of expert readers (Reading Impairment = 0) under control lighting condition was 51.7 (exp(3.945) – Table 2 - Fig. 4). The score did not significantly changed under pulsed + control lighting (56.9 (exp(3.945 + 0.097); t = 0.389) or pulsed lighting only (55.5 (exp(3.945 + 0.072); t = 0.292). Similarly, changing lighting conditions did not significantly modify the comprehension scores of readers with a reading impairment of 1 or above (t = -0.321; t = -0.585; t = -0.883; t = -0.620; t = -0.233; t = 0.222; t = 0.725 and t = 0.329). Finally, changes in reading impairment score did not significantly alter the comprehension score (t = 0.405; t = 0.910; t = 0.054 and t = -1.763).

Discussion

The aim of the present study was to test whether pulsed lighting can improve reading performance in individuals with dyslexia. To sum up, 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, except for the most impaired readers. Indeed, for individuals with the higher reading impairment score, we found a small but significant positive effect of pulsed lighting, increasing ACC from 0.66 to 0.70. However, this increase should be taken with caution for two reasons. First, because it barely reached an arbitrary significance threshold (t = 2.17), meaning that it may not hold with data collected from a different sample of individuals. Second, and foremost, because its amplitude can be considered quite small, which may not translate into functionally relevant reading performance changes in real-life and/or clinical settings. As a matter of fact, the increase in ACC yield by pulsed

Predictors	Effects on comprehension score			
	Estimate	*Sth. Error*	*95% CI*	*t-value*
(Intercept)	**3.945**	**0.192**	**3.565–4.326**	**20.544**
Pulsed	0.072	0.248	-0.419–0.564	0.292
Pulsed + control	0.097	0.248	-0.395–0.588	0.389
Impairment score 1	0.151	0.374	-0.591–0.894	0.405
Impairment score 2	0.416	0.457	-0.490–1.322	0.910
Impairment score 3	0.025	0.457	-0.881–0.931	0.054
Impairment score 4	-0.457	0.259	-0.971–0.057	-1.763
Pulsed : Impairment score 1	-0.155	0.484	-1.113–0.803	-0.321
Pulsed + control : Impairment score 1	-0.283	0.484	-1.241–0.675	-0.585
Pulsed : Impairment score 2	-0.522	0.590	-1.692–0.649	-0.883
Pulsed + control : Impairment score 2	-0.366	0.590	-1.537–0.804	-0.620
Pulsed : Impairment score 3	-0.137	0.590	-1.308–1.033	-0.233
Pulsed + control : Impairment score 3	0.131	0.590	-1.039–1.301	0.222
Pulsed : Impairment score 4	0.245	0.338	-0.425–0.914	0.725
Pulsed + control : Impairment score 4	0.110	0.335	-0.554–0.774	0.329
Observations	125			
Marginal R^2 / Conditional R^2	0.079 / 0.231			

Table 2. Fixed effects estimates from the LME model. 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 (discrete variable). Reference levels are: control lighting condition and reading impairment score of 0. Interactions are represented by the symbol ":". Factors showing a significant effect on comprehension score are in bold font.

lighting in individuals with a reading impairment score of 4 was not sufficient to bring them up to the average ACC of those with less severe deficits (impairment score of 3). However, it is worth noting that the small (if effective) improvement yield by pulsed lighting in these severely impaired readers was immediate, whereas current effective dyslexia interventions, such as phonics training, typically show modest gains and require dozens of hours of practice[46].

As for the comprehension score, it should be noted that the absence of a significant difference across reading impairment scores, even in the control light condition, reduces the possibility of finding an improvement effect under pulsed lighting. This lack of difference in reading comprehension performance between university-level dyslexic adults and control skilled readers has been reported in several studies before[24,32,47,48]. The reason for this similarity is probably two-fold. On one hand, the test is administered without time pressure, and on the other hand, these individuals with dyslexia may have developed compensatory text comprehension procedures[32]. However, it can also be noted that these performances (for all groups) are far from ceiling level, and the most impaired individuals could potentially benefit from the effect of pulsed lighting.

Overall, we failed to show a clear positive impact of pulsed lighting on the reading performance of a group of young adults with dyslexia. This conclusion is consistent with recent results from a different group, who found no significant effect of pulsed lighting (as provided by both a lamp and glasses) on the reading performance of children and adults with dyslexia[49]. These authors inspected the effect of high-frequency light flickering on letter naming, isolated word reading and text reading fluency on 35 dyslexic students. Experiments were run with the Lexilight lamp, another commercialized lamp providing pulsed light, set to a frequency of 80 Hz. This value is close to the setting chosen by most of our participants, who had to select a comfortable setting between 60 and 120 Hz. For all of the three reading tasks tested, Lubineau et al., 2023 reported no detectable impact of pulsed lighting compared to natural light.

According to Le Floch and Ropars, reading difficulties encountered by dyslexics can be (at least partially) attributed to "internal visual crowding"[50]. Because this phenomenon can be controlled through Hebb mechanisms, these authors uphold the potential benefit of pulsed lighting for letter or word identification[14]. The present work however, focused on text-reading fluency, which differs from word-reading fluency as it relies on high-level literacy skills, such as vocabulary and grammatical knowledge in children and adolescents[51,52]. One may argue that even if pulsed lighting can remove low-level internal visual crowding, fluent text reading would still require long-lasting remedial work to correct for the impaired lexicons. While this reasoning does support the absence of effect reported in the present study, it does not account for the fact that our sample of participants shows (oral) vocabulary skills comparable to those of skilled readers. In addition, recent results from Brèthes et al. (2022), showed that text-reading fluency performance is only explained by word reading, pseudoword reading and spelling skills (i.e., low-level literacy skills) in adult readers with and without dyslexia.

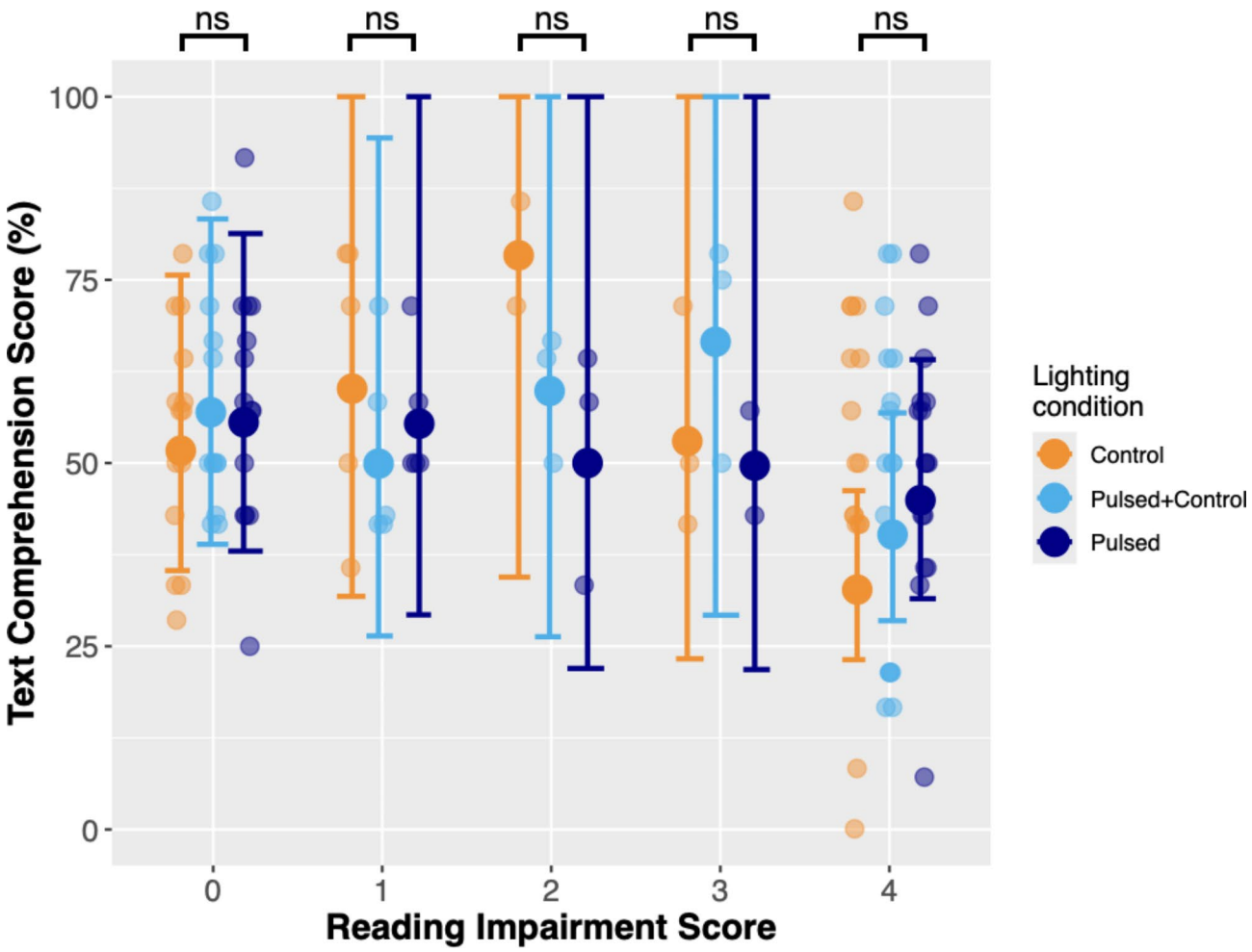

Fig. 4. Comprehension score grouped by reading impairment score for three different lighting conditions. Small data points show the raw data. Large data points represent the model estimates for each score and their 95% confidence intervals. Lighting conditions are color-coded as follows: control condition is represented in orange, pulsed+control condition in light blue and pulsed only in dark blue.

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 individuals with dyslexia. 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[53,54]. 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)[55]. 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[56], reported a significant improvement in these children's reading fluency skills. However[57], 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[58]), the question of which visual deficit causes this phenomenon remains unanswered. Indeed, the meta-analysis by

Peters et al. (2019), comparing three types of visuo-attentional interventions[59], and that of Puccio et al. (2023) on the effects of action video games[60], suggest that several types of visuo-attentional deficits could explain the reading difficulties in dyslexia.

In this study, we used a discrete reading impairment score to grade the overall deficit experienced by dyslexic readers. This score represents a reader's level of impairment over a range of reading skills, namely: speed and accuracy, fluency, decoding procedure and orthographic reading procedure. Our results show that the reading impairment score is significantly related to ACC: the higher the score, the smaller the ACC (Fig. 3; Table 1). In other words, the more pathological markers of dyslexia a reader has, the harder it is to achieve an ACC comparable to that of expert readers. This result suggests that considering dyslexic readers' impairment level on a continuum 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 ACC as a potential measure of the 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 provide an additional 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[61,62].

Finally, 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[63,64] and that the amplitude of this difference is modulated by orthographic depth[65]. 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, future investigations should 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, as in Lubineau et al., (2023)[49].

Data availability

Data will be fully available upon request to the corresponding author (AC).

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Author contributions

A.C. and P.C. conceived and designed the analysis. E.L. and J.-B.M. collected the data. E.L. and A.C. performed the data analysis. E.L., P.C. and A.C. wrote the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to A.C.

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