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Visual training could be useful for improving reading capabilities in dyslexia

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ABSTRACT
The term dyslexia originated in 1887 when an ophthalmologist described the difficulty of learning to read. After more than a century of research, we still do not know the etiology of such pathology. Several hypotheses have been suggested to explain dyslexia and in the present article we will describe in detail the visual attentional deficits reported in dyslexia. Reading is a complex cognitive process during which several mechanisms are involved (visual perception, eye movements -saccades and fixations-, semantic and linguistic abilities); consequently, a deficit in one of these different components could cause impairment in reading acquisition. In children with dyslexia, we observed abnormal oculomotor patterns during reading: frequent saccades of small amplitude, long-term fixation, high number of saccades to the left (retro-saccades), and poor binocular coordination during and after the saccades. These results suggest a deficit of visual information processing as well as an immaturity of the interaction between the saccade and vergence systems. In the present review, we will discuss different methods that use short periods of visual rehabilitation or text manipulation, and by using an eye tracker in order to obtain objective information on eye movement's performance during reading, assist in improved reading performance of dyslexic children.

KEYWORDS
Filters; fixations; reading; saccades; visual training

Introduction

The term dyslexia was proposed in 1887 by Rudolf Berlin, an ophthalmologist, who described the reading disorder (Berlin, 1887). Dyslexia is a specific learning difficulty in reading without compromising oral or nonverbal reasoning skills and it affects between 5 and 15% of the school-age population (Pennington, 2009). The origin of dyslexia is still not well known; it is a complex reading disorder involving genetic and environmental factors (Bishop, 2015). Researchers have suggested several theories of dyslexia and the hypothesis of a phonological deficit in dyslexia has been shared by several authors (Brady, Shankweiler, & Mann, 1983; Bruck, 1992; Snowling, 1995). Recent imaging studies reported that phonological deficiencies in dyslexics are correlated with important abnormalities in the cortical structure of the left hemisphere (Hampson et al., 2006; Xia, Hoeft, Zhang, & Shu, 2016). Taken together, these results suggest that a phonological theory is partially correct but that it cannot explain all deficiencies reported in dyslexia. Other theories have been proposed such as auditory, visual perception, working memory, and attentional abnormalities (Brosnan et al., 2002; Facoetti et al., 2003; Nicolson & Fawcett, 1990; Stein, Riddell, & Fowler, 1988; Tallal, 1980). Further functional magnetic resonance imaging (fMRI) studies (Demb, Boynton, & Heeger, 1997, 1998; Eden et al., 1996) reported abnormal processing of visual motion, particularly in the extrastriate middle temporal brain areas, supporting the hypothesis of an M-cell pathway visual abnormality in subjects with dyslexia. Gori, Seitz, Ronconi, Franceschini, and Facoetti (2016) showed, with different experiments, the impairment of the magnocellular system in dyslexia and highlighted the role of this system in developing normal visual capabilities. A recent work (Le Floch & Ropars, 2017) underlined visual abnormalities in dyslexics, based on the absence of asymmetry of the two foveas (Maxwell's spot centroid) that seems to play an important role for brain connectivity in normal child development. In relationship with the hypothesis of a visual deficit in dyslexia, Stein (2018) advanced the theory of an impaired dorsal stream function, even if several researchers do not share this hypothesis and the existence of a deficit of the dorsal pathway in

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dyslexia is still under debate (Blythe, Kirkby, & Liversedge, 2018).

It is important to point out that for reading, a good control of eye movement (saccades, fixation and vergence) is required, and several studies reported poor eye movement control in dyslexic children independently of language. Indeed, during reading Greek, dyslexic children showed longer and increased numbers of fixations, pro-saccades with shorter amplitude, and frequent retro-saccades (Palvidis, 1981), suggesting that such oculomotor abnormalities could be responsible for slow-reading abilities in these children. Successively, a similar abnormal oculomotor pattern has also been reported in English (Rayner, 1985), Italian (De Luca, Di Pace, Judica, Spinelli, & Zoccoloti, 1999), German (Trauzettel-Klosinski et al., 2010), Chinese (Li et al., 2009), and French (Seassau, Gerard, Bui-Quoc, & Bucci, 2014) dyslexic children. Furthermore, our group (Bucci, Nassibi, Gerard, Bui-Quoc, & Seassau, 2012; Tiadi, Gerard, Peyre, Bui-Quoc, & Bucci, 2016) suggested a deficiency in the visual attentional processing, as well as an immaturity in the interaction between the saccade and the vergence system, leading to poor motor control during reading by French dyslexic children. Note, however, that it is not yet clear whether atypical eye movement performance is the cause or the consequence of reading difficulties in dyslexia. Independently of the fact that visuo-oculomotor problems observed in dyslexics are the result or the cause of their reading problems, several studies have been performed to test the possibility of improving reading capabilities in the dyslexia population via "visual training." Indeed, by performing a PubMed research, one can find about 363 papers focused on "visual training in dyslexia," suggesting that this research issue is important and it has great interest for scientists.

Recently, Peters and collaborators (Peters, De Losa, Bavin, & Crewther, 2019) reviewed the effect of several types of visuo-attentional interventions for reading in dyslexic children; however, they did not describe studies in which eye movements were recorded during reading. Next, we will describe new studies on rehabilitation techniques that reduce reading deficits in dyslexia that are relevant to studies dealing with eye movements in dyslexia.

A study done in 2012 (Chouake, Levy, Javitt, & Lavidor, 2012) reported that basic visual networks, such as the magnocellular system, might play a crucial role in reading deficits observed in dyslexia. These researchers showed that reading abilities significantly improved in dyslexics after five days of training using a motion detection task (magnocellular training); in contrast, dyslexics trained with a control task of pattern detection (parvocellular training) did not showed any reading improvement. This study advanced the importance of basic visual systems in reading and had potential implications for reading rehabilitation in the dyslexic population. In the same line of thinking, Ebrahimi, Pouretemad, Khatibi, and Stein (2019) explored the effect of magnocellular based visual motion training on reading performance in Persian speaking dyslexic children. The training consisted on 12 sessions, twice a week over 6 weeks. They found an improvement of reading capabilities that persisted also after training (at least 1 month later). The authors advanced the hypothesis that a simple test on magnocellular function could be also used as screening tool for detecting dyslexia early before that child starts to read.

It has been also shown that several dyslexics suffer from crowding phenomenon, that is, impaired recognition of the word due to the presence of neighboring letters (Bouma, 1970) and dyslexics could take advantage of reading a text with larger spaced letters (Zorzi et al., 2012).

Meng, Lin, Wang, Jiang, and Song (2014) also reported that visual perceptual training can improve reading performance in Chinese children and that such improvement persisted for up to 2 months, suggesting that visual perceptual processing and reading ability could, at least partially, rely on overlapping mechanisms. Gori and Facoetti (2014) also reported that perceptual learning could improve visual capabilities in dyslexic children that are the consequence of a magnocellular impairment and poor visual attention, given that as suggested by Rizzolatti, Riggio, Dascola, and Umiltá (1987), there is a relationship among visual input, eye movement, and attention. Furthermore, it has been also explored whether playing action video games (without reading or phonological content) could improve reading abilities in dyslexia (Franceschini et al., 2013, 2017). These authors reported that 12 hours of playing action video games (AVG), in contrast to nonaction video games (NAVG), significantly improved the reading abilities in French dyslexic children (Franceschini et al., 2013) as well as English dyslexic children (Franceschini et al., 2017). The AVGs have specific characteristics: "1) extraordinary speed both in terms of very transient events and in terms of the velocity of moving objects; 2) a high degree of perceptual, cognitive, and motor load in the service of an accurate motor plan; 3) unpredictability both temporal and spatial; 4) an emphasis on peripheral processing (Green, Li, & Bavelier, 2010, page 203). Based on the description of the AVG characteristics, a possible distinction between the two treatments could be that the AVG increase stimulation of the Magnocellular-Dorsal or Action stream in comparison with the NAVG (Vidyasagar & Pammer, 2010). Recently, Franceschini and Bertoni (2018) reported that AVG intervention in dyslexic children improved both phonological decoding speed and phonological short-term memory. Note, however, that such improvement has been reported in a small group of dyslexic Italian children that obtained a good video game score.

Finally, the possible benefits of reading text through colored filters have also been suggested to facilitate reading in dyslexia, even if it is an extremely controversial subject (see the review of Uccula, Enna, & Mulatti, 2014, and more recent Stein, 2018). For instance, Ritchie, Sala, and McIntosh (2011) failed to show a significant effect of colored filters on reading performance in dyslexia population and Denton and Meindl (2016) did not report either significant improvements in reading from the use of colored filters in three individuals with dyslexia (7-, 11-, and 32-year-old). In contrast, Ray, Fowler, and Stein (2005) showed reading improvement after yellow filters used for 3 months compared with the use of no filter in children with reading difficulties. Those authors suggested that the yellow color increased input to the magnocellular system by selectively stimulating both L- and M-cones. One major problem with studies exploring the colored filter effect during reading is the lack of standardization during the trials. For example, the procedures used to investigate reading performance with and without filters should be strictly controlled, such as maintaining the same experimental setup; preventing any noise and/or distractions; randomizing the trials with and without filters; and, most importantly, presenting different texts in each condition to prevent learning effects. Finally, it is important to record eye movements during the reading with filters in order to obtain objective data on eye movement. Based on these findings, the current study further explores the effect of colored filters on reading performance in dyslexic and nondyslexic children.

The following sections describe some recent studies made by our group in which we explored some techniques to improve reading performance in dyslexic children. Eye movements were recorded during reading text in order to objectively quantify the eventual benefit of these rehabilitations.

Children population

Dyslexic children participated in the studies were recruited from the Center for Language Disorders and Learning, at the Robert Debré pediatric hospital (Paris), to which they had been referred for a complete evaluation of their dyslexia including an extensive examination of their neurological/psychological and phonological capabilities. For each child, we measured the time they required to read a text passage, assessed their general text comprehension, and evaluated their ability to read words and pseudowords using the L2MA battery (oral Language, written Language, Memory, Attention; Chevrie-Muller, Simon, & Fournier, 1997). This is the standard test in France developed by the "Center de Psychologie appliquée de Paris" and is used to detect dyslexic populations. Inclusion criteria were: score on the L2MA thhat was more than two standard deviations from the mean, a normal mean intelligence quotient (IQ, evaluated using the Wechsler Intelligence Scale for Children-Fourth edition [WISC-IV], 2004), namely between 85 and 115 and normal visual acuity at near vision (both eyes $\geq$10/10). The reading age of all children was assessed using the ELFE test (www.cognisciences.com, Grenoble). Children with comorbid diagnosis such as ADHD and dyslexia were not included in our studies. Typically developing (TD) age-matched children group was compared to dyslexic group. The inclusion criteria for TD children were as follows: no known neurological or psychiatric abnormalities, no history of reading difficulty (reading score was assessed by ELFE test), no visual impairment, or difficulty with near vision. Also, IQ in TD children was estimated on two subtests, one assessing their verbal capability (similarities test) and one assessing their logic capability (matrix reasoning test). Normal range for both tests is 10 ± 3 (WISC-IV). The number and the age of the population participating in each of the studies are reported in the following section.

Eye movement recording during reading text

We used an eye tracker (Mobile EBT, from e(ye)BRAIN, SuriCog, Paris, France), to record eye movements from both eyes. This system is a CE-marked medical eye- tracking device (Figure 1); its frequency is 300 Hz and its precision is 0.25°.

Children were asked to read a text of four lines from a children's book projected on a PC screen at 60 cm in front of the child. The text consisted of 40 words and 174 characters, it was 29° wide and 6.4° high and the mean character width was 0.5°. The words were written on a white background in black "courier" font. During reading, eye movements were recorded at the same time; for oculomotor data, calibration factors for each eye were determined from the eye positions during a calibration procedure done before the reading task. The number and the amplitude of progressive saccades (pro-saccades, from left to right) and regressive saccades (retro-saccades, from right to left) and the duration of fixations between each saccade were analyzed. The time to perform reading task was also measured.

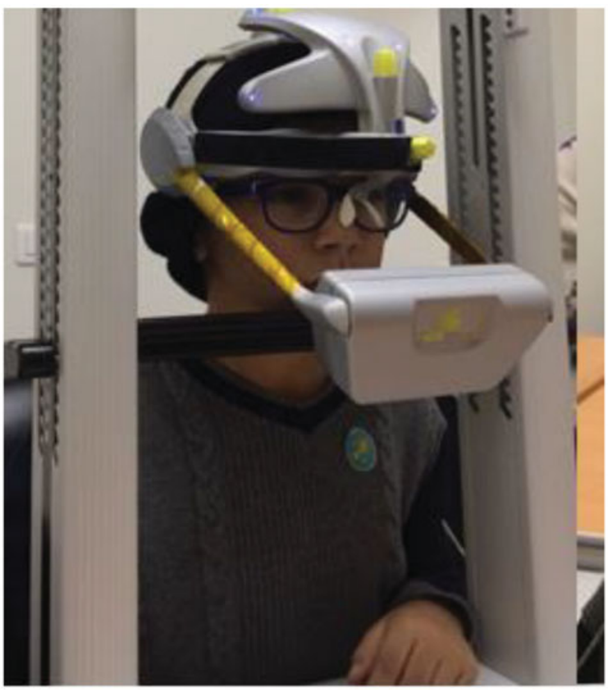

Figure 1. Mobile Eyebrain tracker used to record eye movements.

Statistical analysis

Analysis of variance (ANOVA) was performed in the two groups of children (dyslexic and TD children) on the different oculomotor parameters. The level of significance was maintained at 0.05.

Effect of green filters

Further exploration of the effect of filters on reading performance in dyslexic children was deemed important, based on the work of Irlen (1983) who patented a set of colored-filter lenses for visual stress treatment, which is linked to problems of seeing a distorted page of words or perceiving the environment in a distorted fashion. Such visual difficulties (also called Meares-Irlen syndrome) can affect reading, writing, spelling, math, copying, reading music, working on a computer, night driving, driving, sports performance, and comfort under fluorescent lights, among other effects. However, the use of colored-filtered lenses to reduce the effects of visual stress on reading is controversial, and the scientific community remains skeptical about their benefits.

In one study (Razuk et al., 2018), we recorded eye movements while 18 dyslexic (mean age 9.8 ± 1.2 years) and 18 IQ- and age-matched nondyslexic children read different texts (with similar difficulties) in three different filter conditions: no filter, yellow filter, and green filter. We reported that the total reading time and the duration of fixations, which were significantly longer in dyslexic versus TD children while reading without filters, significantly shortened in dyslexic children only when they were reading with green filters on (see Figure 2A and B), respectively), suggesting that visual word recognition/

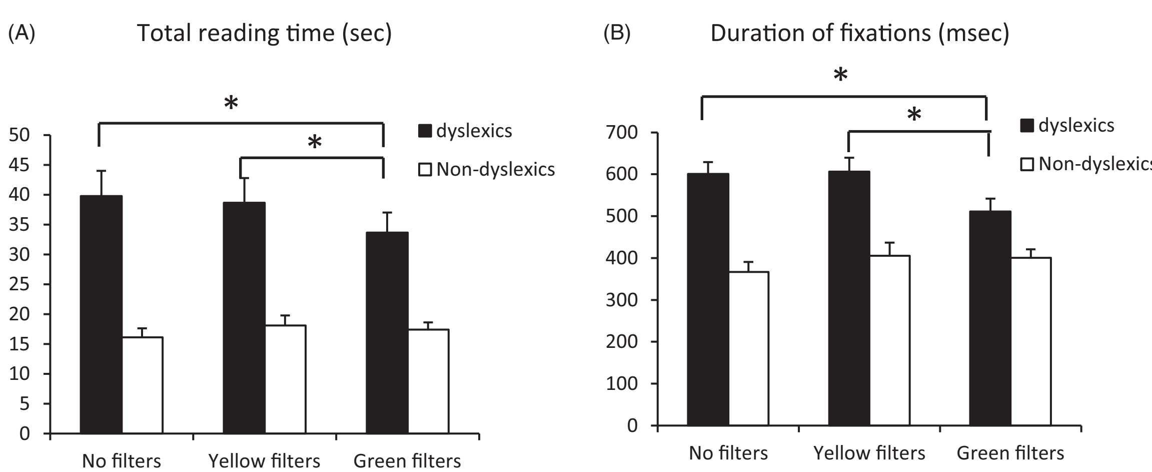

Figure 2. Mean of the total reading time (A) and of the duration of fixations (B), while reading without filters and with yellow and green filters for dyslexic and nondyslexic children. Vertical bars indicate the standard error. Horizontal bars indicate significant difference in dyslexic groups.

identification was facilitated by changing the color of the visual stimulus. In contrast, in TD children, filters did not affect these parameters (i.e., reading time and the duration of fixation).

The results of this study indicated no significant discrepancies in the number of pro- and retro-saccades across the visual conditions. These results may suggest that the oculomotor pattern of children with dyslexia, which consists of smaller and more frequent pro- and retro-saccades, could be due to a reduced visual attention window (Friederici, Rüschemeyer, Hahne, & Fiebach, 2003) and that neither the green nor the yellow filter was sufficient to change and improve such abnormal behavior. We suggest that colored filters minimize the distortions and apparent text motion and that they could be considered useful as assistive technology for people with learning disabilities according to previous studies (Hall, Ray, Harries, & Stein, 2013; Henderson, Tsogka, & Snowling, 2013). Interestingly, an imaging study (Kim, Seo, Ha, & Kim, 2015) investigated sentence reading before and after the use of color filters in patients with Meares-Irlen syndrome. The results showed that 20% of patients wearing blue filters improved their reading speed. Moreover, the fMRI showed that the activity of the left middle and superior temporal cortices significantly increased while reading with filters compared to sentence reading without filters. Recall these regions are involved in comprehension and, more specifically, semantic and syntactic integration; thus, despite the controversy, the use of filters seems to change activation in cortical structures related to the reading process. This finding is interesting and definitely indicates the need for more studies to confirm the benefits of colored filters on the reading performance in dyslexic children. Although many questions and doubts remain, our study suggests that green filters can be used as an additional tool at school and home to improve the academic performance of children with dyslexia.

Effect of font sizes and of spaces between words

The goal of the study by Masulli et al. (2018) was to explore the eventual change in eye movements performance in a group of 15 dyslexic (mean age: 9.4 ± 0.2 years) and 15 IQ- and age-matched nondyslexic children reading a text with different font sizes and spaces between the words. As previously mentioned in the Introduction, the crowding effect in dyslexic subjects can be reduced by adding space between letters (Bouma & Legein, 1977). Interestingly, spacing between the words influences word comprehension and oculomotor performances (Slattery & Rayner, 2013), but, in contrast to the previous findings (Zorzi et al., 2012), for some researchers such improvement is also observed among nondyslexic subjects (Skotun & Skoyles, 2012). Indeed, several other studies observed a reading improvement in terms of speed or accuracy that was not specific to individuals with dyslexia only (Hakvoort, van den Boer, Leenaars, Bos, & Tijms, 2017; Perea & Gomez, 2012). In order to gain more insight on the effect of different sizes and spaced words on reading we recorded objectively eye movements in dyslexic and nondyslexic children during reading three different texts with different corpus and/or inter-letter space (Text 1: Corpus: 25 pt; Inter-letter space: 1 pt; Text 2: Corpus: 25 pt; Inter-letter space: 2.5 pt; Text 3: Corpus: 30 pt; Inter-letter space: 2.5 pt). The child was asked to read aloud in order to register the number of errors he/she made; after reading each text we asked few questions to the child to assess he/she text comprehension.

We reported that increasing font size and character spacing changed eye movement's performance. In more detail, the duration of the fixations (Figure 3A), independently to the text read, was significantly longer in dyslexic than in TD children, but in dyslexic group it reduced significantly while reading Text 2 and 3. The number of pro-saccades (Figure 3B) in all three types of text was significantly larger in dyslexic than in TD children group, but it increased with the increase of the font size and space between the words. Note that this occurred also for TD children. Finally, the amplitude of pro-saccades (Figure 3C) was similar between the two groups of children, but it increased significantly while reading Text 2 and 3 for both groups of children (dyslexics as well as TD).

Taken together, these results suggest that the size and the interspace of the letters of a text can affect oculomotor pattern: the duration of fixations, the number, and the amplitude of pro-saccades changed depending of the type of the text read.

Finally, the total duration for reading the text was not affected by the type of the text read. Reading a text in which the size and the interspace of the letters increased facilitates reading capabilities, even if the total time for reading did not change given that even if the duration of fixation is shortened, the child make several saccades of large amplitude. It should be noted that the three texts were balanced in terms of number and length of words and that they differed only in font size and letter spacing. Consequently, the greater number of

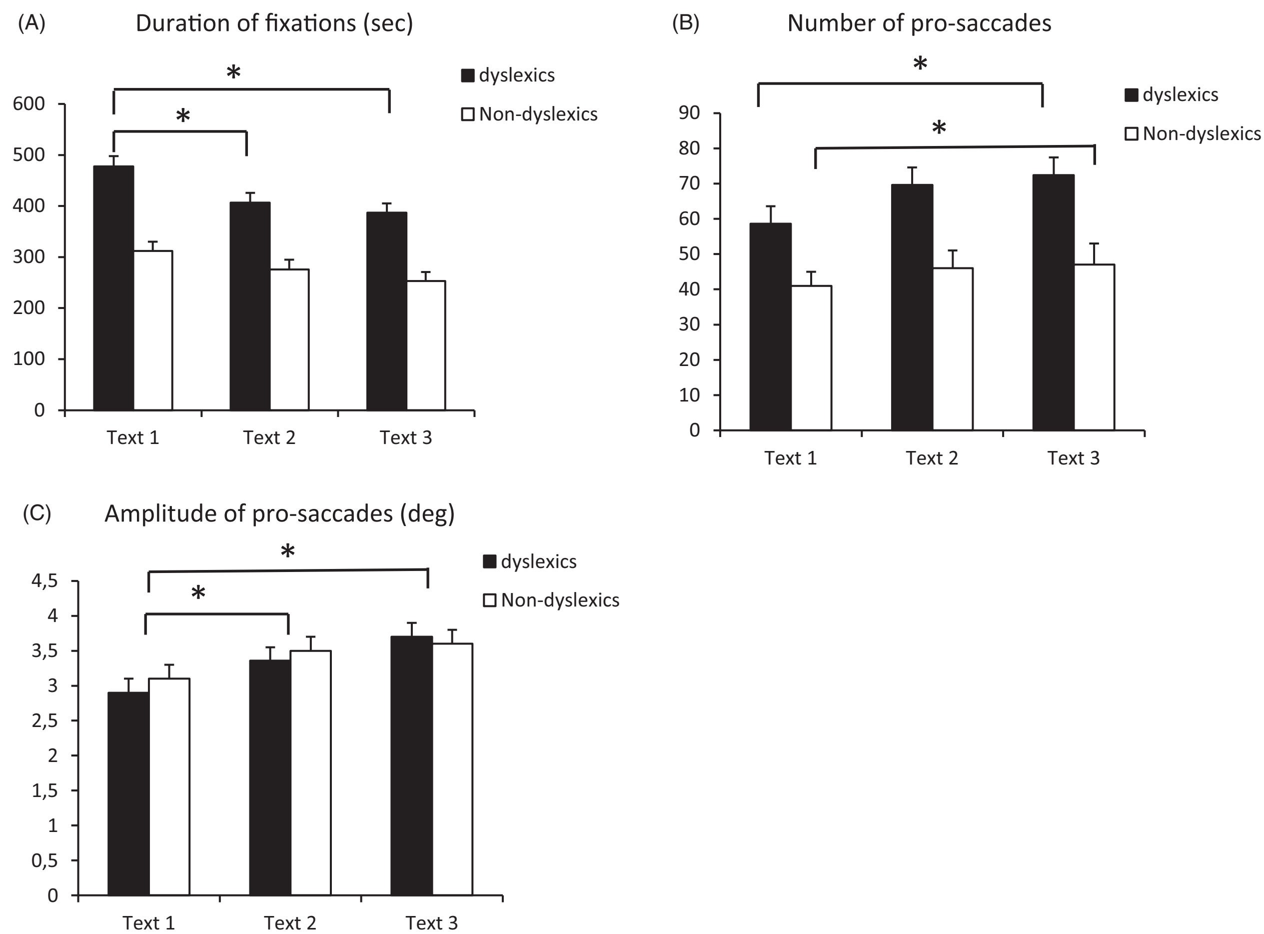

Figure 3. The mean of duration of the fixations (A), of the number (B), and of the amplitude (C) of pro-saccades in both groups of children tested (dyslexic and nondyslexic), while reading the three different types of text (Text 1: 25 pt with 1 pt inter-letter; Text 2: 25 pt with 2.5 inter-letter; Text 3: 30 pt with 2.5 pt inter-letter). Vertical bars indicate the standard error. Horizontal bars indicate significant differences.

pro-saccades made by both groups of children while reading Texts 2 and 3, with respect to the Text 1 could be due to the typographical characteristics. Indeed, larger font size led the child to make more saccades in order to look at the word of interest and to put it on the fovea. By increasing both letter size and interletter spaces, the crowding effect could also be reduced, which leads to a better reading performance in both groups of children, most likely due to visual attention capabilities that play an important role in phonological decoding.

Even if this study did not directly test a visual reeducation technic for improving reading in dyslexic children, the present findings could be useful for the facilitation of reading in such a population. Indeed, based on these results, we could develop applications on tablets or e-readers that allow text size changes and other features that help dyslexic (and nondyslexic) children ameliorate their reading performance.

Effect of computer based oculomotor training

Finally, based on the hypothesis of eye movements difficulties in dyslexia, we aimed at validating a computer-based program for remediation of reading deficits in French (Peyre et al., 2018) and Italian dyslexic children (Bucci, Carzola, Fiucci, Potente, & Caruso, 2018). The training used in these two studies consists of four different exercises (rapid naming task, Stroop task, motion perception and saccades) performed 15 minutes a day, 5 days a week, for 8 weeks. In France, we conducted a crossover randomized trial on 11 children (from 7 to 12 years old); participants were assessed on reading and writing skills as well as phonological skills, visuo-attentional skills, and verbal

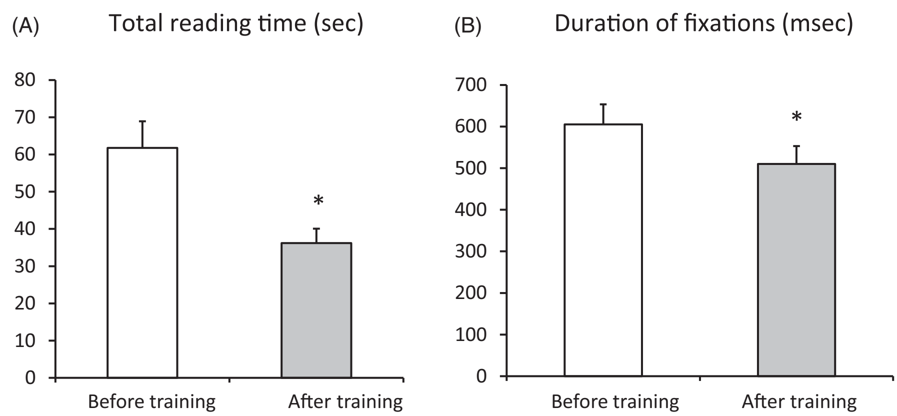

Figure 4. Total time of reading (A) and the duration of fixations (B) in dyslexic children tested before and after training. Vertical bars indicate the standard error. Horizontal bars indicate significant difference.

memory using the French Batterie Analytique du Langage Ecrit (BALE). Eye movements during reading a text were recorded before and after training. French dyslexic children did not show effects of training on reading capabilities. However, after training they showed a significant improvement on several tests measuring phonological skills (syllabic suppression), visuo-attentional skills (search of anarchic verbal cues), verbal memory (digit span backward), and writing skills (regular words). The same study was than conducted on a group of 16 Italian dyslexic children (mean age: 10.2 ± 0.3 years), but with an important difference with respect to the study previously performed: each of the four exercises was composed of eight levels with increasing difficulty, developed using the Unity game engine (Unity Technologies, Paris, France). After the training, we observed that the majority of dyslexic children (69%) significantly improved the number of syllables read per second. Moreover, as shown in Figure 4, the total time of reading (4A) and the duration of fixations (4B) significantly decreased after training (in 77% of children tested). These results are interesting, even if they need to be confirmed by a study comparing a population of dyslexic and nondyslexic children. Additionally, a follow-up study will be necessary in order to verify the permanence of the beneficial effect of training in reading capabilities.

Such training benefits suggest that a computer-based oculomotor program could be an easy and practical tool for improving reading performance in dyslexic children. The based oculomotor rehabilitation proposed in this study allowed to train visuo-attentional capacities as well magnocellular abilities. We suggest that both mechanisms occur given that visuo-attention and saccades are strictly linked to each other and that the magnocellular visual pathway is also involved in oculomotor performance (Leigh & Zee, 2015).

Finally, an important point to be discussed is the individual home training performance follow-up used in this study. Indeed, to the best of our knowledge, this is the first time that a training performed at home is controlled and supervised, and user performance continuous monitoring is an important step in the development of training programs. Indeed, children with unsatisfactory performance in different levels of each one of the four exercises did not present a shortening in fixations. This finding is in line with the study of Franceschini and Bertoni (2018) showing that only children who performed well in the video games training obtained a significant improvement in reading, highlighting the importance of training supervision by the clinician and/or therapist. Further research on such issues will be necessary to confirm these previous findings; however, a computerized oculomotor training could be helpful for improving reading capabilities in dyslexic children.

General discussion

For several years, researchers posited that a phonological deficit is the mean cause of dyslexia (Peterson & Pennington, 2012). However, it is well known that when one child is reading a word, he/she needs to have good fixation and correct position of the visual axis on the word that is read. Consequently, the eye movement's capability that in dyslexia is known to be impaired needs to be considered independently of language (Bucci et al., 2012; De Luca et al., 1999; Li et al., 2009; Palvidis, 1981; Rayner, 1985; Seassau et al., 2014; Tiadi et al., 2016; Trauzettel-Klosinski et al., 2010). Several studies previously cited confirmed the hypothesis of a visual deficit in dyslexia in relationship with poor magnocellular system organization and difficulty to focalize visual attention (see review of Stein (2018)). Our studies are in line with this hypothesis, because their goal was to test new visual attentional techniques in order to improve reading abilities in dyslexic children. Indeed, the use of filters for reading, and/or the use of larger letter size and interletter spaces, could improve the magnocellular activity leading to a better visual input at the cortical level for better and faster word identification. The new computer-based oculomotor program tested was created to improve visual attention span, as well as oculomotor and magnocellular performance in dyslexia as these mechanisms have also been shown to be impaired in subjects with dyslexia (Bosse, Tainturier, & Valdois, 2007; Eden, Stein, Wood, & Wood, 1994; Gori et al., 2016 Valdois, Bosse, & Tainturier, 2004).

Conclusion

Taken together, these results suggest dyslexic children could benefit from visual oculomotor training to improve their reading capabilities. Further studies are necessary to be performed in order to confirm such findings on a large population of dyslexic children from different countries. Also important is the use of an eye tracker, which allows precise and objective quantification of reading improvement after training, with precise information on oculomotor patterns during reading and not only the reading performance of children. Finally, several types of dyslexia exist, and it is not yet well known the role of visual, attentional, phonological, and auditory deficiencies in such pathology. A focus on training that deals with these deficits will be useful for dyslexic children.

Statement of ethics

The investigation adhered to the principles of the Declaration of Helsinki and was approved by the Institutional Human Experimentation Committee of CPP Ile de France I (Hotel-Dieu Hospital).

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Disclosure statement

The authors declare no competing interests exist.

References

Berlin, R. (1887). *Eine besondere art der Wortblindheit (Dyslexie)*. Wiesbaden: J.F. Bergmann.

Bishop, N. D. V. (2015). The interface between genetics and psychology: Lessons from developmental dyslexia. *Proceedings of the Royal Society B: Biological Sciences*, *282*(1806), 20143139. doi:10.1098/rspb.2014.3139

Blythe, H. I., Kirkby, J. A., & Liversedge, S. P. (2018). Comments on: "What is developmental dyslexia?" *Brain Sciences*, *8*(6), 100. doi:10.3390/brainsci8060100

Bosse, M. L., Tainturier, M. J., & Valdois, S. (2007). Developmental dyslexia: The visual attention span deficit hypothesis. *Cognition*, *104*(2), 198–230. doi:10.1016/j.cognition.2006.05.009

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature*, *226*(5241), 177–178. doi:10.1038/226177a0

Bouma, H., & Legein, C. P. (1977). Foveal and parafoveal recognition of letters and words by dyslexics and by average readers. *Neuropsychologia*, *15*(1), 69–80. doi:10.1016/0028-3932(77)90116-6

Brady, S., Shankweiler, D., & Mann, V. (1983). Speech perception and memory coding in relation to reading ability. *Journal of Experimental Child Psychology*, *35*(2), 345–367. doi:10.1016/0022-0965(83)90087-5

Brosnan, M., Demetre, J., Hamill, S., Robson, K., Shepherd, H., & Cody, G. (2002). Executive functioning in adults and children with developmental dyslexia. *Neuropsychologia*, *40*(12), 2144–2155. doi:10.1016/S0028-3932(02)00046-5

Bruck, M. (1992). Persistence of dyslexics phonological awareness deficits. *Developmental Psychology*, *28*(5), 874–886. doi:10.1037/0012-1649.28.5.874

Bucci, M. P., Carzola, B., Fiucci, G., Potente, C., & Caruso, L. (2018). Computer based oculomotor training improves reading abilities in dyslexic children: Results from A Pilot Study. *Sports Injuries & Medicine*, *2018*(1), 1–6. doi:10.29011/2576-9596/100030

Bucci, M. P., Nassibi, N., Gerard, C. L., Bui-Quoc, E., & Seassau, M. (2012). Immaturity of the oculomotor saccade and vergence interaction in dyslexic children: Evidence from a reading and visual search study. *PLoS One*, *7*(3), e33458. doi:10.1371/journal.pone.0033458

Chevrie-Muller, C., Simon, A. M., & Fournier, S. (1997). *Batterie Langage oral ecrit. Memoire. Attention (L2MA)* Paris, Editions du Centre de Psychologie Appliquée.

Chouake, T., Levy, T., Javitt, D. C. D., & Lavidor, M. (2012). Magnocellular training improves visual word recognition. *Frontiers Human Neuroscience*, *6*, 14.

De Luca, M., Di Pace, E., Judica, A., Spinelli, D., & Zoccoloti, P. (1999). Eye movement patterns in linguistic and non-linguistic tasks in developmental surface dyslexia. *Neuropsychologia*, *37*(12), 1407–1420. doi:10.1016/S0028-3932(99)00038-X

Demb, J. B., Boynton, G. M., & Heeger, D. J. (1997). Brain activity in visual cortex predicts individual differences in reading performance. *Proceedings of the National*

Academy of Sciences of Sciences, *94*(24), 13363–13366. doi:10.1073/pnas.94.24.13363

Demb, J. B., Boynton, G. M., & Heeger, D. J. (1998). Functional magnetic resonance imaging of early visual pathways in dyslexia. *The Journal of Neuroscience*, *18*(17), 6939–6951. doi:10.1523/JNEUROSCI.18-17-06939.1998

Denton, T. F., & Meindl, J. N. (2016). The effect of colored overlays on reading fluency in individuals with dyslexia. *Behavior Analysis in Practice*, *9*(3), 191–198. doi:10.1007/s40617-015-0079-7

Ebrahimi, L., Pouretemad, H., Khatibi, A., & Stein, J. (2019). Magnocellular based visual motion training improves reading in Persian. *Scientific Reports*, *9*(1), 1142. doi:10.1038/s41598-018-37753-7

Eden, G. F., Stein, J. F., Wood, H. M., & Wood, F. B. (1994). Differences in eye movements and reading problems in dyslexic and non-dyslexic children. *Vision Research*, *34*(10), 1345–1358. doi:10.1016/0042-6989(94)90209-7

Eden, G. F., VanMeter, J. W., Rumsey, J. M., Maisog, J., Woods, R. P., & Zeffiro, T. A. (1996). Abnormal processing of visual motion in dyslexia revealed by functional brain imaging. *Nature*, *382*(6586), 66–69. doi:10.1038/382066a0

Facoetti, A., Lorusso, M. L., Paganoni, P., Cattaneo, C., Galli, R., & Mascetti, G. G. (2003). The time course of attentional focusing in dyslexic and normally reading children. *Brain and Cognition*, *53*(2), 181–184. doi:10.1016/S0278-2626(03)00105-2

Franceschini, S., & Bertoni, S. (2018). Improving action video games abilities increases the phonological decoding speed and phonological short-term memory in children with developmental dyslexia. *Neuropsychologia*, *130*, 100–106. 2018.10.023. doi:10.1016/j.neuropsychologia

Franceschini, S., Gori, S., Ruffino, M., Viola, S., Molteni, M., & Facoetti, A. (2013). Action video games make dyslexic children read better. *Current Biology*, *23*(6), 462–826. doi:10.1016/j.cub.2013.01.044

Franceschini, S., Trevisan, P., Ronconi, L., Bertoni, S., Colmar, S., Double, K., … Gori, S. (2017). Action video games improve reading abilities and visual-to-auditory attentional shifting in English-speaking children with dyslexia. *Scientific Reports*, *7*(1), 5863. doi:10.1038/s41598-017-05826-8

Friederici, A. D., Rüschemeyer, S. A., Hahne, A., & Fiebach, C. J. (2003). The role of left inferior frontal and superior temporal cortex in sentence comprehension: Localizing syntactic and senmantic processes. *Cerebral Cortex*, *13*(2), 170–177. doi:10.1093/cercor/13.2.170

Gori, S., & Facoetti, A. (2014). Perceptual learning as a possible new approach for remediation and prevention of developmental dyslexia. *Vision Research*, *99*, 78–87. doi:10.1016/j.visres.2013.11.011

Gori, S., Seitz, A. R., Ronconi, L., Franceschini, S., & Facoetti, A. (2016). Multiple causal links between magnocellular-dorsal pathway deficit and developmental dyslexia. *Cerebral Cortex*, *26*(11), 4356–4369. doi:10.1093/cercor/bhv206

Green, C. S., Li, R., & Bavelier, D. (2010). Perceptual learning during action video game playing. *Topics in Cognitive Science*, *2*(2), 202–216. doi:10.1111/j.1756-8765.2009.01054.x

Hakvoort, B., van den Boer, M., Leenaars, T., Bos, P., & Tijms, J. (2017). Improvements in reading accuracy as a result of increased interletter spacing are not specific to children with dyslexia. *Journal of Experimental Child Psychology*, *164*, 101–116. doi:10.1016/j.jecp.2017.07.010

Hall, R., Ray, N., Harries, P., & Stein, J. (2013). A comparison of two-coloured filter systems for treating visual reading difficulties. *Disability and Rehabilitation*, *35*(26), 2221–2226. doi:10.3109/09638288.2013.774440

Hampson, M., Tokoglu, F., Sun, Z., Schafer, R. J., Skudlarski, P., Gore, J. C., & Constable, R. T. (2006). Connectivity–behavior analysis reveals that functional connectivity between left BA39 and Broca's area varies with reading ability. *NeuroImage*, *31*(2), 513–519. doi:10.1016/j.neuroimage.2005.12.040

Henderson, L. M., Tsogka, N., & Snowling, M. J. (2013). Questioning the benefits that coloured overlays can have for reading in students with and without dyslexia. *Journal of Research in Special Educational Needs*, *13*(1), 57–65. doi:10.1111/j.1471-3802.2012.01237.x

Irlen, H. (1983). *Successful treatment of learning disabilities*. Paper presented at the annual convention of the American Psychological Association, Anaheim, CA.

Kim, J. H., Seo, H.-J., Ha, S.-G., & Kim, S.-H. (2015). Functional magnetic resonance imaging findings in meares-Irlen syndrome: A pilot study. *Korean Journal of Ophthalmology*, *29*(2), 121–125. doi:10.3341/kjo.2015.29.2.121

Le Floch, A., & Ropars, G. (2017). Left-right asymmetry of the Maxwell spot centroids in adults without and with dyslexia. *Proceedings of the Royal Society B: Biological Sciences*, *284*(1865), 20171380. doi:10.1098/rspb.2017.1380

Leigh, R. J., & Zee, D. S. (2015). *The neurology of eye movement* (5th ed.). New York, NY: Oxford University Press.

Li, X. H., Jing, J., Zou, X. B., Huang, X., Jin, Y., Wang, Q. X., … Yang, S. Y. (2009). Picture perception in Chinese dyslexic children: An eye-movement study. *Chinese Medical Journal*, *122*, 267–271. doi:10.1097/00029330-200809010-00004

Masulli, F., Galluccio, M., Gerard, C. L., Peyre, H., Rovetta, S., & Bucci, M. P. (2018). Effect of different font sizes and of spaces between words on eye movement performance: An eye tracker study in dyslexic and non-dyslexic children. *Vision Research*, *153*, 24–29. doi:10.1016/j.visres.2018.09.008

Meng, X., Lin, O., Wang, F., Jiang, Y., & Song, Y. (2014). Reading performance is enhanced by visual texture discrimination training in Chinese-speaking children with developmental dyslexia. *PLos One*, *9*(9), e108274. eCollection 2014. doi:10.1371/journal.pone.0108274

Nicolson, R. I., & Fawcett, A. J. (1990). Automaticity: A new framework for dyslexia research? *Cognition*, *35*(2), 159–182.

Palvidis, G. T. (1981). Do eye movements hold the key to dyslexia? *Neuropsychologia*, *19*, 57–64.

Pennington, B. F. (2009). *Diagnosing learning disorders: A neuropsychological framework* (2nd ed.). New York, NY: Guilford Press.

Perea, M., & Gomez, P. (2012). Subtle increases in interletter spacing facilitate the encoding of words during normal reading. *PLoS One*, *7*(10), e47568. doi:10.1371/journal.pone.0047568

Peters, J. L., De Losa, L., Bavin, E. L., & Crewther, S. G. (2019). Efficacy of dynamic visuo-attentional interventions for reading in dyslexic and neurotypical children: A systematic review. *Neuroscience & Biobehavioral Reviews*, *100*, 58–76. doi:10.1016/j.neubiorev.2019.02.015

Peterson, R. L., & Pennington, B. F. (2012). Developmental dyslexia. *The Lancet*, *26*, 1997–2007. doi:10.1016/S0140-6736(12)60198-6

Peyre, H., Gérard, C. L., Dupong Vanderhorst, I., Larger, S., Lemoussu, C., Vesta, J., … Bucci, M. P. (2018). Computerized oculomotor training in dyslexia: A randomized, crossover clinical trial in pediatric population. *L'Encéphale*, *44*(3), 247–255. doi:10.1016/j.encep.2017.03.004

Ray, N. J., Fowler, S., & Stein, J. F. (2005). Yellow filters can improve magnocellular function: Motion sensitivity, convergence, accommodation, and reading. *Annals of the New York Academy of Sciences*, *1039*(1), 283–293. doi:10.1196/annals.1325.027

Rayner, K. (1985). Do faulty eye movements cause dyslexia? *Developmental Neuropsychology*, *1*(1), 3–15. doi:10.1080/87565648509540294

Razuk, M., Perrin-Fievez, F., Gerard, C. L., Peyre, H., Barela, J. A., & Bucci, M. P. (2018). Effect of colored filters on reading capabilities in dyslexic children. *Research in Developmental Disabilities*, *83*, 1–7. doi:10.1016/j.ridd.2018.07.006

Ritchie, S. J., Sala, S. D., & McIntosh, R. D. (2011). Irlen colored overlays do not alleviate reading difficulties. *Pediatrics*, *128*(4), e932–e938. doi:10.1542/peds.2011-0314

Rizzolatti, G., Riggio, L., Dascola, I., & Umiltá, C. (1987). Reorienting attention across the horizontal and vertical meridians: Evidence in favor of a premotor theory of attention. *Neuropsychologia*, *25*(1), 31–40. doi:10.1016/0028-3932(87)90041-8

Seassau, M., Gerard, C. L., Bui-Quoc, E., & Bucci, M. P. (2014). Binocular saccade coordination in reading and visual search: A developmental study in typical reader and dyslexic children. *Frontiers in Integrative Neuroscience*, *30*(8), 85. doi:10.3389/fnint.2014.00085

Skottun, B. C., & Skoyles, R. (2012). Interletter spacing and dyslexia. *Proceedings of the National Academy of Sciences USA*, *09*(44), E2958. doi:10.1073/pnas.1212877109

Slattery, T. J., & Rayner, K. (2013). Effects of intraword and interword spacing on eye movements during reading: Exploring the optimal use of space in a line of text. *Attention, Perception, & Psychophysics*, *75*(6), 1275–1292. doi:10.3758/s13414-013-0463-8

Snowling, M. J. (1995). Phonological processing and developmental dyslexia. *Journal of Research in Reading*, *18*(2), 132–138. doi:10.1111/j.1467-9817.1995.tb00079.x

Stein, J. (2018). What is developmental dyslexia? *Brain Sciences*, *8*(2), 26. doi:10.3390/brainsci8020026

Stein, J. F., Riddell, P. M., & Fowler, S. (1988). Disordered vergence control in dyslexic children. *British Journal of Ophthalmology*, *72*(3), 162–166. doi:10.1136/bjo.72.3.162

Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language*, *9*(2), 182–198. doi:10.1016/0093-934X(80)90139-X

Tiadi, A., Gerard, C. L., Peyre, H., Bui-Quoc, E., & Bucci, M. P. (2016). Immaturity of visual fixations in dyslexic children. *Frontiers Human Neuroscience*, *10*, 58.

Trauzettel-Klosinski, S., Koitzsch, M., Durrwachter, U., Sokolov, A. N., Reinhard, J., & Klosinski, G. (2010). Eye movements in German-speaking children with and without dyslexia when reading aloud. *Acta Ophthalmologica*, *88*(6), 681–691. doi:10.1111/j.1755-3768.2009.01523.x

Uccula, A., Enna, M., & Mulatti, C. (2014). Colors, colored overlays, and reading skills. *Frontiers Psychology*, *5*, 833. doi:10.3389/fpsyg.2014.00833

Valdois, S., Bosse, M. L., & Tainturier, M. J. (2004). The cognitive deficits responsible for developmental dyslexia: Review of evidence for a selective visual attentional disorder. *Dyslexia*, *10*(4), 339–363. doi:10.1002/dys.284

Vidyasagar, T. R., & Pammer, K. (2010). Dyslexia: A deficit in visuo-spatial attention, not in phonological processing. *Trends in Cognitive Sciences*, *14*(2), 57–63. doi:10.1016/j.tics.2009.12.003

Xia, Z., Hoeft, F., Zhang, L., & Shu, H. (2016). Neuroanatomical anomalies of dyslexia: Disambiguating the effects of disorder, performance, and maturation. *Neuropsychologia*, *81*, 68–78. doi:10.1016/j.neuropsychologia.2015.12.003

Zorzi, M., Barbiero, C., Facoetti, A., Lonciari, I., Carrozzi, M., Montico, M., … Ziegler, J. C. (2012). Extra-large letter spacing improves reading in dyslexia. *Proceedings of the National Academy of Sciences USA*, *109*(28), 11455–11459. doi:10.1073/pnas.1205566109