Effect of colored filters on reading capabilities in dyslexic children

Milena Razuk, Faustine Perrin-Fievez, Christophe-Loic Gerard, Hugo Peyre, José Angelo Barela, Maria Pia Bucci

Effect of colored filters on reading capabilities in dyslexic children

Milena Razuk[a,b,*], Faustine Perrin-Fievez[a], Christophe Loic Gerard[d], Hugo Peyre[a,d], José Angelo Barela[b,c], Maria Pia Bucci[a]

[a] UMR 1141 Inserm - Paris Diderot University, Robert Debré Hospital, Paris, France
[b] Institute of Physical Activity and Sport Sciences, Cruzeiro do Sul University, São Paulo, São Paulo, Brazil
[c] Institute of Biosciences, São Paulo State University, Rio Claro, São Paulo, Brazil
[d] Child and Adolescent Psychiatry Department, Robert Debré Hospital, Paris, France

ABSTRACT

Aim: The aim of the present study was to examine the effects of colored filters on reading per-formance and eye movement control in children with and without dyslexia.
Methods: Eighteen children with dyslexia and 18 children without dyslexia were seated on a chair with their heads stabilized by a forehead and chin support. The children read different texts under the following three filter conditions: no filter, yellow filter, and green filter. The children's eye movements were recorded with a Mobile EyeBrain Tracker. Reading total time, duration of fixation between two successive saccades, pro-saccades amplitude and number of pro- and retro-saccades were obtained.
Results: Children with dyslexia read the fastest and had the shortest fixation time in the green filter condition compared with the other conditions. Furthermore, children with dyslexia showed the shortest fixation time in the green filter condition with respect to the other conditions. *Conclusions:* Taken together, these results suggested that the green filter improved reading per-formance in children with dyslexia because the filter most likely facilitated cortical activity and decreased visual distortions.

Keywords:
Children with dyslexia Eye movement Fixation Reading Colored filters

1. Introduction

Dyslexia seriously affects the academic development of children because most academic activities require reading and writing during the learning process. The results of a study conducted in the 1990s suggested that children at that time were spending up to 60% of their time reading and writing (McHale & Cermak, 1992). Although, no recent data have been collected on the time currently spent reading and writing, the percentage is expected to be even higher. As a result, the prevalence of visual stress is higher in individuals with dyslexia than in individuals without dyslexia (Singleton & Henderson, 2007; Singleton & Trotter, 2005).

To minimize and prevent visual stress, the use of colored filters have been beneficial for children with dyslexia (Denton & Meindl, 2016), autism (Ludlow, Wilkins, & Heaton, 2006; Ritchie, Della Sala, & McIntosh, 2011), and attention deficit/hyperactivity disorder (Iovino, Fletcher, Breitmeyer, & Foorman, 1998). In general, these children have frequently used colored filters during the school day and at home for remediation of reading difficulties (Denton & Meindl, 2016; Henderson, Tsogka, & Snowling, 2013).

The symptoms of sensory visual stress include feelings of eyestrain and excessive brightness and various perceptual distortions, such as fading, blurring, flickering, and movement of parts of the visual stimulus (Wilkins, 2002). Wilkins (2002) has suggested that

* Corresponding author at: Institute of Physical Activity and Sport Sciences, Cruzeiro do Sul University, Rua Galvão Bueno, 868, Liberdade, 01506-000, São Paulo, SP, Brazil.

E-mail address: milena.razuk@gmail.com (M. Razuk).

people with abnormal visual cortices are hypersensitive to coarse high-contrast stripes, such as lines of black text on a white background, which cause distortions and apparent text motion. Because colored filters are thought to minimize these distortions and apparent text motion, they are considered useful as assistive technology for people with learning disabilities (Hall, Ray, Harries, & Stein, 2013; Henderson et al., 2013). In 1983, Irlen was the first to patent a set of colored-filter lenses, which are also known as overlays, for treatment purposes, and she suggested that the beneficial colors might differ according to each child's needs. However, the use of colored-filtered spectacles to reduce the effects of visual stress on reading is controversial, and the scientific community remains skeptical about their benefits. For instance, Ritchie et al. (2011) tested the efficacy of the use of Irlen-colored overlays on reading difficulties in 60 children with ages ranging from 7 to 12 years in three different conditions: using an overlay with a prescribed color, using an overlay with no prescribed color, and using no overlay. They reported that using the Irlen-colored overlays did not have any immediate effects on the reading performances of the children with reading difficulties. Thus, the benefits of colored filters are debatable.

Despite this controversy, a candidate brain structure for understanding the relationship between colored filters and reading is the magnocellular system (Chase, Ashourzadeh, Kelly, Monfette, & Kinsey, 2003). Indeed, Stein (2001) and Stein and Walsh (1997) have suggested that magnocellular system malfunction is responsible for the behavioral reading deficits. The magnocellular theory, which has recently been reformulated as a general temporal processing deficit in dyslexia (Goswami, 2011; Lehongre, Ramus, Villiermet, Schwartz, & Giraud, 2011; Pammer, 2013; Tallal, 1980; Vidyasagar, 2013), suggests that individuals with dyslexia have specific deficits in the processing of rapid visual and auditory stimuli (McLean, Stuart, Coltheart, & Castles, 2011).

Although the magnocellular pathway is not involved in color vision, it receives input from the three types of cones that are sensitive to different wavelengths of light and that are therefore referred to as short (S; blue color), medium (M; green color), and long (L; red color) wavelength cones. Reading is compromised in red-light (long wavelength) environments compared to green-light (medium wavelength) environments because the red light inhibits the activity of the magnocellular system (Chase et al., 2003). Ray, Fowler, and Stein, (2005) have suggested that individuals with reading performance deficits might benefit not only from reduced S-cone input but also from compensation by the M- and L-cone inputs (Ray et al., 2005). Individuals with reading performance deficits are thought to have a strong overlap of L-cone input to the surrounds of M cells, which changes M- and L-cone functioning (Stromeyer et al., 2000).

Henderson et al. (2013) investigated the effects of the use of colored filters during reading in undergraduate students with and without dyslexia and found that both groups read more words per minute with colored filters than without. Moreover, the group with dyslexia showed marginally larger gains in its reading rate with the filters on than their non-dyslexic peers did. Ray et al. (2005) have shown that reading improved significantly after a yellow filter was used for three months compared with the use of no filter in children with reading difficulties. Those authors considered colored filters an effective intervention for delayed readers, and they suggested that the yellow color increased input to the magnocellular system by selectively stimulating both L- and M-cones (Hall et al., 2013). In contrast, Denton and Meindl (2016) did not find any significant improvements in reading from the use of colored filters in three individuals with dyslexia (a 7-, 11-, and 32-year-old).

Kim, Seo, and Ha, (2015) investigated sentence reading before and after the use of color filters using functional magnetic resonance imaging (fMRI) in patients with Meares-Irlen syndrome. The results showed that 80% of the patients selected a blue filter, and their reading speed improved over 20% after using it. Moreover, the fMRI showed significant regions of activation in the left middle and superior temporal cortices during sentence reading with filters compared to sentence reading without filters. These regions are involved in comprehension and, more specifically, semantic and syntactic integration (Friederici, Rüschemeyer, Hahne, & Fiebach, 2003; Vandenberghe, Nobre, & Price, 2002). Thus, despite the controversy, the use of filters seems to change activation in cortical structures related to the reading process.

One major problem with the studies of the use of colored filters during reading is the lack of standardization of the procedures used. The procedures used to investigate reading performance with and without a filter must be strictly controlled with methods, such as maintaining the same environmental organization and/or 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 and reveal any potential mechanisms underlying the reading improvements.

Studies have shown that reading performance was improved in yellow and blue filter conditions (Kim et al., 2015; Ray et al., 2005), however, there is no study in the literature that has investigated the intermediate of the color spectrum wavelengths between yellow and blue, for example, green color filter. Therefore, the aim of the present study was to examine the effects of colored filters on reading performance and eye movement control in children with and without dyslexia.

2. Materials and methods

2.1. Subjects

Eighteen children with dyslexia (mean age 9.8 ± 1.2 years) and 18 age-matched children without dyslexia (mean age 9.8 ± 1.3 years) with no reading difficulties participated in this study. The children with dyslexia were recruited from the Child and Adolescent Psychiatry Department of Robert Debré Hopital (Paris, France) where they were referred for a complete dyslexia evaluation and extensive examinations, including neurological/psychological and phonological capability assessments. For each child, the L2MA battery was used to evaluate the time required to read a text, their comprehension of the text, and their ability to read words and pseudo words (Chevrie-Muller et al., 1997). The L2MA, which is a standard test that was developed by the Centre de Psychologie

Table 1
Clinical characteristics of the age-matched children without and with dyslexia. Mean values of binocular vision (Stereoacuity test: TNO measured in seconds of arc; near point of convergence: NPC measured in cm, Vergence fusional amplitude (divergence and convergence) at near distance measured in prism diopters). Asterisks (*) indicate that value is significantly different compared to the group of dyslexic children ($p < 0.01$).

Children group	TNO (sec of arc)	NPC (cm)	Convergence (pD)	Divergence (pD)
Without Dyslexia	60 ± 1.7	3.6 ± 0.4	38 ± 3*	17 ± 4*
With Dyslexia	61 ± 2.4	3.8 ± 0.6	29 ± 4*	10 ± 3*

appliquée de Paris and that is often used in France, has been employed in our previous studies to select subjects with dyslexia (Bucci, Nassibi, Gerard, Bui-Quoc, & Seassau, 2012). The inclusion criteria were L2MA scores two standard deviations below the mean and a normal mean intelligence quotient, which was determined using the Wechsler Intelligence Scale for Children-IV and which was defined as scores between 80 and 115. All children underwent ophthalmologic examinations of their visual and motor function (mean values shown in Table 1). All children presented normal visual acuity (≥ 20/20) and normal binocular vision (mean of 60 s of arc or more), which was evaluated with the TNO random dot test for stereoscopic depth discrimination (Netherlands Organization, Good-Lite Company, Elgin, IL, USA). The near point of convergence was normal for all children (mean of 3 cm). Moreover, vergence fusion capability was evaluated using prisms and a Maddox rod and performed at near distance. The convergence and divergence amplitudes were significantly smaller in the children with dyslexia than in the children without dyslexia, and an analysis of variance (ANOVA) show significant effect of group on convergence and divergence [$F_{(1,34)} = 48.899$, $p < 0.01$ and $F_{(1,34)} = 21.764$, $p < 0.01$, respectively]. In summary, the orthoptic evaluations showed that the children with dyslexia had significantly worse convergence and divergence amplitudes.

These procedures adhered to the principles of the Declaration of Helsinki and were approved by our Institutional Human Experimentation Committee (CPP Ile de France I, Hôpital Hotel-Dieu). Written consent was obtained from the children's parents after the experimental procedures were explained.

2.2. Reading task

The reading tasks were similar to those used by Bucci et al. (2012) and are described below. Four lines of text from a book for children were presented on a computer screen in front of each child. The paragraph contained 40 words and 174 characters. The text was 29° wide and 6.4° high, and the mean character width was 0.5°. The text was written in black Courier font on a white background. It is important to note different texts were presented according to age (7–9 and 10–12 years). Fig. 1 (panels A, B and C)–depicts the texts that were presented to children with a reading age of 7–9 years (extract from Jojo Lapin fait des farces, Enid Blyton, Hachette Livre Group, Vanves, France). Reading was performed under three filter conditions: no filter, yellow filter, and green filter. The order of the use of each filter and text was randomly defined. Each child was asked to read the text silently, and, at the end of each reading condition, the experimenter asked each child a few questions to ensure that the child read and understood the text content. The filters used in this study were Irlen® filters. Given that the order of the visible colors from the shortest to the longest wavelength is violet, blue, green, yellow, orange, and red, the yellow and green filters were chosen because those colors are in the middle of the color spectrum wavelengths.

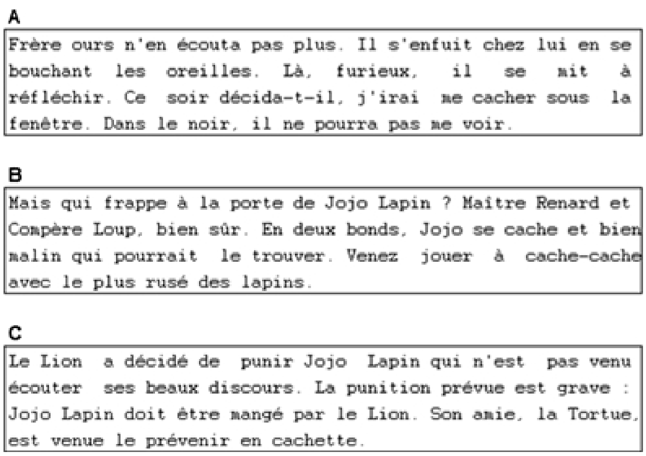

Fig. 1. Reading performance testing under three different conditions. Three different texts (A, B, and C) were projected onto the monitor screen to test reading performances without a filter and with a yellow or green filter.

2.3. Eye movement recordings

The eye movements were recorded with the Mobile EyeBrain Tracker® (SuriCog, Paris, France), which is an eye-tracking device that is Conformité Européene-marked for medical purposes. The Mobile EyeBrain Tracker® uses cameras that record the movements of each eye independently, with typical precision of 0.25° and no obstruction of the visual field by the recording system. The recording frequency was 300 Hz.

2.4. Procedure

Each child was seated on a chair with his/her head stabilized by a forehead and chin support. The binocular view distance (eye to the monitor) was 60 cm. Before the eye movements were recorded, calibration was performed by asking each child to fixate on a grid of 13 points (diameter, 0.5°) that mapped the screen. Each calibration point required a fixation of 250 ms to be validated. The meyeAnalysis® software was used to automatically detect saccades using a built-in saccade detection algorithm (for details, see (Lions, Bui-Quoc, Wiener-Vacher, Seassau, & Bucci, 2013). After the calibration procedure, the text to be read was presented to the child.

2.5. Data analysis

We analyzed all pro- and retro-horizontal saccades that started from or finished on a word. The oblique saccades were excluded from the analysis because this type of saccade is used when the reader moves to the following text line and is not related to word identification. The investigator verified all detected saccades. We also analyzed the total time taken to read the text (s), the duration of fixation between two successive saccades (ms), the pro-saccades amplitude and the number of pro- and retro-saccades.

Two-way ANOVAs with group (children with and without dyslexia) and condition (no filter, yellow filter, and green filter) as factors, this last one treated as repeated measure, were used to analyze each dependent variable (reading total time, duration of fixation, pro-saccades amplitude and number of pro- and retro-saccades). When necessary, Tukey Honestly Significant Difference post hoc comparisons were made. In all comparisons the alpha level was set at 0.05 and analyses were performed using SPSS software.

3. Results

Fig. 2 depicts the reading total time for the children with and without dyslexia in all three experimental conditions. An ANOVA showed a significant effect of group [$F_{(1,34)} = 26.15$, $p < 0.001$, $\eta^2 = 0.435$], which indicated that the children with dyslexia read slower than the children without dyslexia, and a significant effect of condition [$F_{(2,68)} = 3.068$, $p < 0.05$, $\eta^2 = 0.083$], which indicated that the children read fastest in the green filter condition compared to the yellow ($p < 0.02$) and no filter ($p < 0.05$) conditions. Finally, a significant interaction was found between group and condition [$F_{(2,34)} = 4.494$, $p < 0.015$, $\eta^2 = 0.117$]. Post hoc tests for the interaction showed that the children with dyslexia read faster in the green filter condition than in the yellow filter [$q_{(2,34)} = 6.168$, $p < 0.05$] and no filter conditions [$q_{(2,34)} = 7.536$, $p < 0.05$]. For the children without dyslexia, no difference in the reading total time was observed among all three conditions.

Fig. 3 depicts the duration of fixation for children with and without dyslexia in all three experimental conditions. An ANOVA showed a significant effect of group [$F_{(1,34)} = 28.622$, $p < 0.001$, $\eta^2 = 0.457$], indicating that children with dyslexia had longer fixation times than the children without dyslexia did, and a significant effect of condition [$F_{(2,68)} = 3.707$, $p < 0.03$, $\eta^2 = 0.098$],

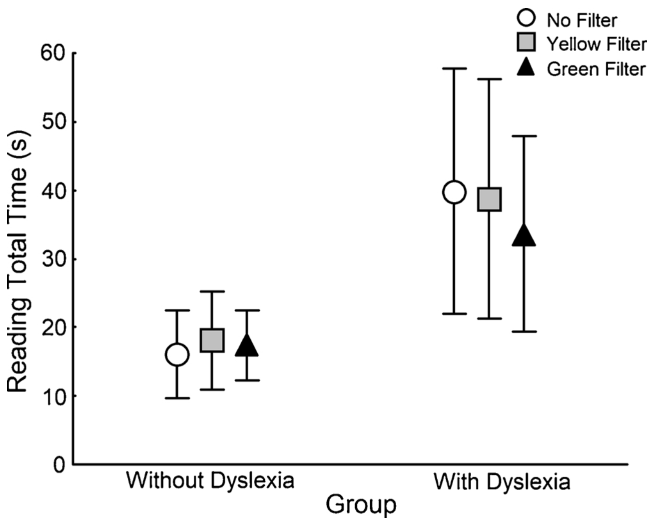

Fig. 2. Reading total time for children without and with dyslexia in the no filter and yellow and green filter conditions.

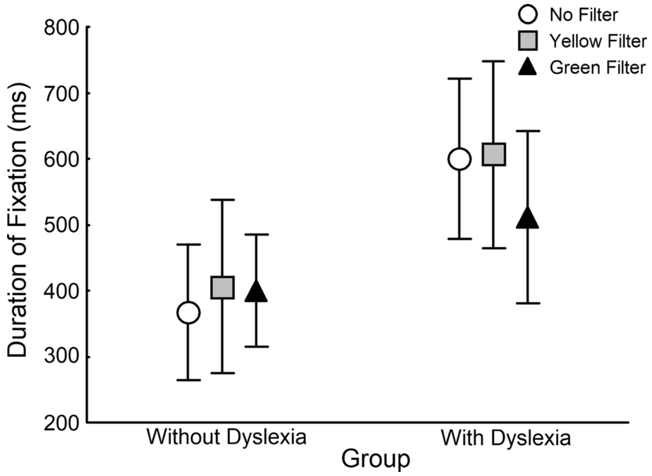

Fig. 3. Duration of fixation for the children without and with dyslexia in the no filter and yellow and green filter conditions.

indicating that the children had the shortest fixations in the green filter condition compared to the other conditions (all $p < 0.001$). Finally, a significant interaction was found between group and condition [$F_{(2,34)} = 6.012$, $p < 0.004$, $\eta^2 = 0.150$]. Post hoc tests showed that the mean duration of fixation for the children with dyslexia was shorter in the green filter condition than in the yellow [$q_{(2,34)} = 6.529$, $p < 0.05$] and no filter conditions [$q_{(2,34)} = 6.135$, $p < 0.05$]. For the children without dyslexia, no difference in the mean duration of fixation was observed among all three conditions.

For the pro-saccades amplitude, an ANOVA showed a significant effect only for group [$F_{(1,34)} = 12.126$, $p < 0.01$, $\eta^2 = 0.263$], which showed that the children with dyslexia made shorter pro-saccades (3.50 ± 0.87°) than the children without dyslexia (4.85 ± 1.69°). There was no effect of condition [$F_{(1,34)} = 0.582$, $p > 0.05$, $\eta^2 = 0.017$] and no group and condition interaction [$F_{(1,34)} = 0.074$, $p > 0.05$, $\eta^2 = 0.002$]. An ANOVA showed a significant effect only of group [$F_{(1,34)} = 13.010$, $p < 0.01$, $\eta^2 = 0.277$] on the number of pro-saccades, thus revealing that the children with dyslexia made more pro-saccades (35.94 ± 9.23) compared to the children without dyslexia (27.51 ± 7.49). There was no effect of condition [$F_{(1,34)} = 0.836$, $p > 0.05$, $\eta^2 = 0.005$] and no group and condition interaction [$F_{(1,34)} = 0.787$, $p > 0.05$, $\eta^2 = 0.007$]. Finally, an ANOVA showed a significant effect only of group [$F_{(1,34)} = 5.439$, $p < 0.05$, $\eta^2 = 0.138$] on the number of retro-saccades, thus indicating that the children with dyslexia made more retro-saccades (7.21 ± 5.18) compared to the children without dyslexia (5.47 ± 2.42). There was no effect of condition [$F_{(1,34)} = 0.53$, $p > 0.05$, $\eta^2 = 0.015$] and no group and condition interaction [$F_{(1,34)} = 0.689$, $p > 0.05$, $\eta^2 = 0.020$].

4. Discussion

The aim of this study was to evaluate the effects of colored filters on the reading performance and eye movement behavior of children with dyslexia while they read different texts. Our results indicated that children with dyslexia read faster and showed shorter eye fixation in the green filter condition compared with the yellow and no filter conditions. These findings are discussed below.

The results of this study showed that the reading time of children with dyslexia was significantly improved in the green filter condition. No such results were observed when the yellow filter was used. Therefore, despite the skepticism of the benefits of the use of filters, a comparison of the reading times among the conditions showed that the children with dyslexia benefited when the green filter was used. Despite this intriguing finding, the performance of the children without dyslexia was not improved by the use of the green filter. The children with dyslexia still read much slower than the children without dyslexia did, but they did better than they did in the no and yellow filter conditions.

The improvements in reading time that were observed with the use of the green filter might be due to changes in the visual stimuli that are available for central nervous system processing. Wilkins (2002) has suggested that colored filters reduce cortical hyper-excitability, which decreases the contrast of the visual stimulus and, consequently, improves reading performance. This suggestion is in line with the results of a recent fMRI study (Kim et al., 2015), that showed significant activation during reading with colored filters (80% of the subjects selected blue filters) than with no filters. Based on these results, it was hypothesized that the effects of magnocellular disorders, which result in visual stress and distortion and the resulting reading difficulties, are reduced by the use of colored filters, which improve visual processing and reading performance.

The results of this study provide new and important information on the potential effects of colored filters on reading performance. This study is a pioneer in the recording of eye movements of children with and without dyslexia while they performed reading tasks. Our results showed a dramatic decrease in the duration of fixation of the children with dyslexia with the use of a green filter. However, the improvements still did not reach the level of children without dyslexia. Children with dyslexia show impaired oculomotor functioning (Bucci et al., 2012; Rayner, 1986; Seassau, Gérard, Bui-Quoc, & Bucci, 2014; Stein & Walsh, 1997). Moreover, dyslexia might be related to difficulties clearly identifying the word on the fovea (Kliegl, Nuthmann, & Engbert, 2006; Rayner, 1998), most likely due to the poor vergence fusional capabilities and accommodative disorders that have been reported in the dyslexia population (Eden, Stein, Wood, & Wood, 1994). Fusional vergence amplitude could be also improved by wearing filters leading to better word identification as has been reported by Ray et al. (2005). Therefore, the shorter fixation time required by the children with dyslexia for word identification under the green filter condition indicated that visual recognition was facilitated by changing the color of the visual stimulus. Note however that in the present study we did not evaluate potential improvement of comprehension after wearing filters and other studies will need to explore further such issue.

Finally, our results did not show any changes in pro- and retro-saccades behavior. The numbers of pro- and retro-saccades were similar among all visual conditions. Moreover, pro-saccades amplitude, which differs between children with dyslexia and children without dyslexia (Bucci et al., 2012; Seassau et al., 2014), was not impacted by the green or yellow filters. These results 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 et al., 2003) and that neither the green nor the yellow filter was sufficient to change and improve such deviant behavior. A visual attention window is defined as the number of distinct visual elements that can be processed (Bosse, Tainturier, & Valdois, 2007), and the results showed that the children with dyslexia processed less visual elements than the children without dyslexia did.

Despite the controversy and limitations of these results, they clearly show a beneficial effect of the use of a green filter on reading performance in children with dyslexia. This finding is intriguing and definitely indicates the need for more studies to confirm the benefits of colored filters on the reading performance of children with dyslexia. Moreover, different analyses are needed in order to uncover the underlying mechanisms of these effects of colored filters and determine if any changes are acute or chronic. Also, in order to test whether magnocellular system could take advantage by wearing filters, further studies combining reading, motion detection task (Chouake, Levy, Javitt, & Lavidor, 2012) and filters will be necessary. Although many questions and doubts remain, our results suggest that green filters can be used as an additional tool at school and home to improve the academic performance of children with dyslexia.

5. Conclusion

In summary, the present findings provide evidence that green filters improve reading performance in children with dyslexia through changes in eye movement, which reduce the fixation duration required by the children with dyslexia during reading. However, for the children without dyslexia, no difference in the reading performance and the fixation duration was observed among all three conditions.

Funding

This study was supported by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) through a scholarship to Milena Razuk (grant number 2016/05602-7), FAPESP doctorate scholarship: 2013/25653-7.

Conflicts of interest

The authors have declared that no competing interests exist.

Acknowledgements

The authors are grateful to the children who participated in this study and their parents and to Claudia Zuber-Giorgio for generously providing the colored filters.

References

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

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*, e33458.

Chase, C., Ashourzadeh, A., Kelly, C., Monfette, S., & Kinsey, K. (2003). Can the magnocellular pathway read? Evidence from studies of color. *Vision Research, 43*, 1211–1222.

Chevrie-Muller, E. C., Simon, A. M., & Fournier, S. (1997). (Batterie Langage Oral, Langage écrit, Mémoire, Attention (L2MA). Paris: Editions du Centre de Psychologie Appliquée. ed.).

Chouake, T., Levy, T., Javitt, D. C., & Lavidor, M. (2012). Magnocellular training improves visual word recognition. *Frontiers in Human Neuroscience, 6*, 1–6.

Denton, T. F., & Meindl, J. N. (2016). The effect of colored overlays on Reading fluency in individuals with dyslexia. *Behavior Analysis in Practice, 9*, 191–198.

Eden, G. F., Stein, J. F., Wood, H. M., & Wood, F. B. (1994). Differences in eye movements and reading problems in dyslexic and normal children. *Vision Research, 34*, 1345–1358.

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*, 170–177.

Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in Cognitive Sciences, 15*, 3–10.

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*, 2221–2226.

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*, 57–65.

Iovino, I., Fletcher, J. M., Breitmeyer, B. G., & Foorman, B. R. (1998). Colored overlays for visual perceptual deficits in children with reading disability and attention deficit/hyperactivity disorder: Are they differentially effective? *Journal of Clinical and Experimental Neuropsychology, 20*, 791–806.

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

Kliegl, R., Nuthmann, A., & Engbert, R. (2006). Tracking the mind during reading: The influence of past, present, and future words on fixation durations. *Journal of Experimental Psychology: General, 135*, 12–35.

Lehongre, K., Ramus, F., Villiermet, N., Schwartz, D., & Giraud, A. L. (2011). Altered low-gamma sampling in auditory cortex accounts for the three main facets of dyslexia. *Neuron, 72*, 1080–1090.

Lions, C., Bui-Quoc, E., Wiener-Vacher, S., Seassau, M., & Bucci, M. P. (2013). Smooth pursuit eye movements in children with strabismus and in children with vergence deficits. *PloS One, 8*, e83972.

Ludlow, A. K., Wilkins, A. J., & Heaton, P. (2006). The effect of coloured overlays on reading ability in children with autism. *Journal of Autism and Developmental Disorders, 36*, 507–516.

McHale, K., & Cermak, S. A. (1992). Fine motor activities in elementary school: Preliminary findings and provisional implications for children with fine motor problems. *American Journal of Occupational Therapy, 469*, 898–903.

McLean, G. M., Stuart, G. W., Coltheart, V., & Castles, A. (2011). Visual temporal processing in dyslexia and the magnocellular deficit theory: The need for speed? *Journal of Experimental Psychology: Human Perception and Performance, 37*, 1957–1975.

Pammer, K. (2013). Temporal sampling in vision and the implications for dyslexia. *Frontiers in Human Neuroscience, 7*.

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*, 283–293.

Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers. *Journal of Experimental Child Psychology, 41*, 211–236.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*, 372–422.

Ritchie, S. J., Della Sala, S., & McIntosh, R. D. (2011). Irlen colored overlays do not alleviate reading difficulties. *Pediatrics, 128*, e932–e938.

Seassau, M., Gérard, 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, 8*.

Singleton, C., & Henderson, L. M. (2007). Computerized screening for visual stress in children with dyslexia. *Dyslexia, 13*, 130–151.

Singleton, C., & Trotter, S. (2005). Visual stress in adults with and without dyslexia. *J Res Read, 28*, 365–378.

Stein, J. (2001). The magnocellular theory of developmental dyslexia. *Dyslexia, 7*, 12–36.

Stein, J., & Walsh, V. (1997). To see but not to read; the magnocellular Theory of dyslexia. *Trends in Neurosciences, 20*, 147–152.

Stromeyer, C. F., Gowdy, P. D., Chaparro, A., Kladakis, S., Willen, J. D., & Kronauer, R. E. (2000). Colour adaptation modifies the temporal properties of the long- and middle-wave cone signals in the human luminance mechanism. *The Journal of Physiology, 526*, 177–194.

Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language, 9*, 182–198.

Vandenberghe, R., Nobre, A. C., & Price, C. J. (2002). The response of left temporal cortex to sentences. *Journal of Cognitive Neuroscience, 14*, 550–560.

Vidyasagar, T. R. (2013). Reading into neuronal oscillations in the visual system: Implications for developmental dyslexia. *Frontiers in Human Neuroscience, 7*.

Wilkins, A. (2002). Coloured overlays and their effects on reading speed: A review. *Ophthalmic and Physiological Optics, 22*, 448–454.