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Spectral Overlays for Reading Difficulties: Oculomotor Function and Reading Efficiency Among Children and Adolescents With Visual Stress

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Abstract

This study analyzed the effects of spectral overlays on ocular motility during reading among a clinical group of children and adolescents experiencing visual–perceptual distortions of text. We reviewed the records of 323 eye-hospital patients diagnosed with visual stress and divided this participant sample into two age-based cohorts: children ($n = 184$; Mean [M] age = 10.1, standard deviation [SD] = 1.3 years) and adolescents ($n = 139$; M age = 14.6, SD = 1.5 years). We used a *Visagraph III Eye-Movement Recording System* to record ocular motor efficiency while reading with

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and without spectral overlays, and we examined the following parameters: (a) Fixations, (b) Regressions, (c) Span of Recognition, (d) Reading Rate, (e) Relative Efficiency, and (f) Comprehension. Our results showed that using one or some combination of 10 participant-selected spectral overlays immediately and significantly ($p < .001$) reduced the number of Fixations and Regressions per 100 words, while there were significant ($p < .001$) gains in positive factors such as Span of Recognition, Reading Rate, Relative Efficiency, and Comprehension. Our findings indicate that spectral filtering can be an effective tool for helping many young patients who experience visual–perceptual distortions while reading. Future expanded research employing eye-tracking technology is clearly needed.

Keywords
child motor development, eye-tracking analysis, ocular motor skills, perceptual disorders, reading difficulties, spectral overlays, visual measurement, visual perception, visual stress

Introduction

Reading is a challenging task, as it not only demands a complex cognitive network to process reading content, but it also requires a refined coordination of the eyes (and simultaneously compensating for head movements) in order to efficiently track lines of text. Thus, a growing number of researchers have investigated reading difficulties beyond those that can be explained by socioeconomic factors (e.g., poor education), neurocognitive anomalies (e.g., dyslexia), and optometric or ophthalmological deficits (e.g., refractive errors and visual acuity) (Gaertner et al., 2013; Nicolson & Fawcett, 2019; Stein, 2019; Vidyasagar, 2019). As will be detailed here, many studies have reported that the reading process can also be compromised by inadequate ocular motor skills or neural-based visual processing anomalies (such as those present in patients with Meares-Irlen syndrome or visual stress [VS]).

VS is characterized by visual discomfort when reading (e.g., sore or tired eyes, headaches, photophobia, excessive blinking or squinting) and visual–perceptual distortions of text (e.g., "halos" or "patterns" around words, or words appearing to "move," "vibrate," or "shimmer"). VS symptoms are typically accompanied by a clear and rapid deterioration in oral reading ability, usually occurring within 5–10 minutes (Evans & Allen, 2016; Evans, Allen, & Wilkins, 2017; Loew & Watson, 2013). Estimates of the incidence of VS in the general population have ranged from 5% (Evans & Allen, 2016) to 24% (Jeanes et al., 1997), while a number of studies have found significant symptoms of VS-related reading discomfort in 12–14% of unselected samples of school and university students

(Kriss & Evans, 2005; Loew, Marsh, & Watson, 2014; Loew et al., 2015). However, the levels of VS severity appear to lie on a continuum from mild to highly symptomatic (Evans & Allen, 2016; Evans & Joseph, 2002).

With respect to underlying biological factors, several studies have identified a range of biochemical anomalies in people with VS, including abnormal metabolism of essential fatty acids (crucial for retinal and visual-pathway functioning; Robinson, McGregor, Roberts, Dunstan, & Butt, 2001) and significant anomalies in urinary amino acids and blood lipids that may indicate immune system activation (e.g., lower cholesterol levels, including low density lipoprotein [LDL] cholesterol, and higher heptadecanoic acid levels; Sparkes, Robinson, Dunstan, & Roberts, 2003). There is also a strong genetic predisposition to VS, as 80% of VS-diagnosed children have one or both parents with similar symptoms (Robinson, Foreman, & Dear, 1996, 2000). A higher prevalence of certain variant alleles of the apolipoprotein-B100 gene (coding for a key cholesterol transporter molecule) has also been identified in people with VS symptoms (Loew & Watson, 2012).

It has been widely reported that VS symptoms can be alleviated by the use of spectral overlays (colored plastic sheets) placed over a page of text when reading. One variety of these translucent overlays is available from Irlen International™, and a set of these overlays contains a wide selection of spectral-filtering colors ranging from those favoring shorter wavelength transmissions (e.g., "Aqua," "Blue-Gray," and "Turquoise" overlays) to those that favor longer wavelength light (e.g., "Yellow," "Goldenrod," and "Peach" overlays). Many studies have reported positive reading effects through the use of spectral overlays, including improvements in letter or number recognition and in reading speed and accuracy (Allen, Evans, & Wilkins, 2012; Evans & Joseph, 2002; Kriss & Evans, 2005; Ludlow, Wilkins, & Heaton, 2006, 2008; Nichols, McLeod, Holder, & McLeod, 2009; Noble, Orton, Irlen, & Robinson, 2004; Singleton & Henderson, 2007; Wilkins, Lewis, Smith, Rowland, & Tweedie, 2001; Wright, Wilkins, & Zoukos, 2007). A recent study involving Brazilian elementary school children also found that those presenting with several symptoms of reading discomfort were three times more likely (odds ratio = 3.36) to experience increased reading speed with spectral filters compared with readers in a group of children with fewer symptoms (Garcia, Momensohn-Santos, & Vilhena, 2017). Longitudinal studies have produced analogous results, for example, Jeanes et al. (1997) and Wilkins et al. (2001) respectively found that 24% and 31% of unselected children who volunteered to select an overlay of their preference continued to read with it eight and 10 months later; thus, novelty or placebo effects were unlikely to have been primary motivational factors. Noble et al. (2004) found that reading with overlays helped VS-diagnosed children with school-documented delayed reading reach expected grade-level reading norms within three months, while a control group comprising similar children showed negligible gains.

While the use of spectral filters has remained controversial, with some researchers arguing that no benefits to reading by means of such tools have been validated through scientifically objective measures (Griffiths, Taylor, Henderson, & Barrett, 2016; Hyatt, Stephenson, & Carter, 2009; Ritchie, Della Sala, & McIntosh, 2011, 2012), recent studies employing highly objective measures (e.g., functional Magnetic Resonance Imaging) have detected hyper-excitability of the visual cortex in research participants with VS, epilepsy, or migraines and have produced evidence of marked reductions in excitation when participants read while using self-selected colored filters (Chouinard, Zhou, Hrybouski, Kim, & Cummine, 2012; Huang et al., 2011; Kim, Seo, Ha, & Kim, 2015; Wilkins, Huang, & Cao, 2007). As strong criticisms of spectral filter use persist, this study hypothesized that eye-tracking technology might provide a novel, parallel means of objectively testing the validity of reported benefits of spectral filters for people with VS by providing measurable physical evidence of any changes or absence of changes in ocular motor skills.

Currently, the two most widely accepted neurological explanations of VS (and spectral overlays as an assistive tool for VS) are the *Cortical Hyperexcitability* and the *Transient-on-Sustained Inhibition* (ToSI) theories. The former argues that visual distortions while reading are caused by hyper-excited or abnormal neuronal firing in the visual cortex due to inadequate sen-sorial excitation diffusion. Spectral overlays then might allow a greater diffusion or distribution of reading information to less excited areas (Allen, Gilchrist, & Hollis, 2008; Wilkins et al., 2001). This theory has been supported by the reported benefits of spectral filtering for other conditions associated with cortical hyperexcitability such as autism spectrum disorders (Ludlow, Taylor-Whiffen, & Wilkins, 2012; Ludlow & Wilkins, 2016; Whitaker, Jones, Wilkins, & Roberson, 2016), migraine headaches (Evans et al., 1999), photosensitive epilepsy (Wilkins et al., 1999), and stroke (Beasley & Davies, 2013).

Alternatively, the ToSI theory concerns the relationship between the sustained visual system (SVS) and the transient visual system (TVS), two parallel spatiotemporal divisions of the neuro-visual network that simultaneously process visual information transmitted via the parvocellular and magnocellular retino-geniculo-cortical pathways, respectively (Pammer & Wheatley, 2001; Stein & Walsh, 1997). The SVS primarily responds to low temporal and high spatial frequencies (important for color and fine spatial details), while the TVS is sensitive to high temporal and low spatial frequencies, and its high-velocity conduction of neural signals is believed to be crucial for inhibiting (masking) prior SVS-transmitted images formed from visual data received in immediately preceding saccades (hence the term ToSI). Accordingly, highly efficient magnocellular pathway processing is essential for optimal functioning of the TVS and is also crucial in controlling saccades, fixations, binocular coordination, and general ocular stability.

To date, it appears that only two studies have analyzed spectral overlay effects with an eye-tracking system. Solan, Ficarra, Brannan, and Rucker (1998) investigated the effects of filters on ocular motor skills (using Visagraph™ II equipment) among elementary school children with and without reading disabilities. Despite using only three spectral filters (Lee Filters™ clear, gray and blue), Solan et al. (1998) found that 75% of the reading-impaired participants demonstrated an increased reading rate and a decreased number of fixations and regressions when using the blue filter to the point that earlier statistical differences between the reading-impaired and control groups on these variables disappeared. More recently, Razuk et al. (2018) found that a group of 18 dyslexic children showed reduced eye-fixation durations when reading with a "green" versus a "yellow" filter ($p < .02$) and versus no filter ($p < .05$). For the age-matched control group without dyslexia, there were no differences in mean fixation durations between any filter conditions.

Although these prior studies shed light on improved ocular motor skills from the use of colored filters when reading, they did not use a wide variety of spectral overlays (with broad-ranging transmission specificities) and may not have obtained optimal or comprehensive results. Moreover, participants in both studies were children with *reading disabilities* who may or may not have had *VS* that is presumed to be the basis for needing spectral filters. Thus, this study used state-of-the-art eye-tracking technology (Visagraph™ III equipment) to observe the effects of VS child and adolescent participants' self-selected overlays (from a set of 10 colors) on their reading-related ocular motor skills.

Method

Participants

We performed this study at the NeuroVision Department of the *Hospital de Olhos de Minas Gerais*, which mainly attends to patients with vision-related learning problems. We reviewed records of all patients ($n = 883$) assessed from June 2007 to April 2015 in relation to ophthalmic variables (including visual acuity [far and near], high-order aberrations, phorias, stereopsis, color vision, contrast sensitivity, and visual field). All of these patients underwent assessments for the presence of VS symptoms (including patient responses to spectral overlays) and, for all patients, eye-movement data were recorded while reading. From this large data pool, we identified patients who met the following five criteria: (a) self-reported "visual distortions while reading" and "reduced distortions when viewing text through an overlay," (b) clinical ophthalmologist affirmation of their VS symptomatology, (c) good binocular visual acuity (better than 20/20 Snellen Chart) and normal color vision (Pseudoisochromatic Ishihara 25 Plates Test and Farnsworth D15 Dichotomous Test), (d) a score of at least 70% on a Comprehension Test, and (e) no extreme anomalies in their eye-tracking recordings (we applied the *Outlier Labeling Rule* [with a *g*-value of 2.2] and found that eye-tracking data from 22 of the 883 patients were extreme). It was crucial to apply these criteria in order to separate those patients who could be definitively categorized as having VS morbidity from those who may have other disorders that can affect reading ability, as a common flaw of many prior studies of overlay effects has been the use of cohorts with general reading disabilities, creating a participant sample bias, as spectral filters are presumed to mainly benefit people with VS (Evans & Allen, 2016).

The final "VS Group" consisted of 323 VS-diagnosed patients who met all of the above criteria. We then divided this sample into two age-related subgroups: children ($n = 184$; age range = 8–12; M age = 10.1, $SD = 1.3$ years; 67% male) and adolescents ($n = 139$; age range = 13–17; $M_{\text{age}} = 14.6$, $SD = 1.5$ years; 63% male), as age can affect the scale of any intervention-related changes in reading skills. The expected grade norms calculated for participants (according to the Visagraph III Test-Manual: Taylor Associates, 2006) indicated that mean group values closely corresponded to the reading performances of 5th-grade children and 10th-grade adolescents.

When first seen, all participants' parents or legal guardians consented (and participants assented) to participate in a future study. The study was conducted in accordance with the Declaration of Helsinki (2008).

Instruments

We assessed VS symptom levels with the Irlen Reading Perceptual Scale (IRPS; Irlen, 2003), a tool that challenges patients with various visually stressing images and tasks (e.g., counting how many lines or symbols are in an image). The IRPS is designed to increase visual discomfort in order to quickly identify VS symptoms. After assessing baseline visual discomfort levels with the IRPS, the 10 Irlen Overlays were individually presented to participants in the same order (Gray, Blue-Gray, Turquoise, Aqua, Green, Peach, Rose, Goldenrod, Yellow, and Purple) and were placed over a page of a text written in Dutch (meaningless to the patient). Participants were then asked to assess whether each overlay improved or worsened their visual comfort and the image quality, until they eventually selected an overlay (or two-overlay combination) that they felt gave the most reading comfort.

Participants were also given the option of choosing no overlay at all; however, among the initial 883 patients, only 14 (2%) did so. This small group did not take part in the comparisons of reading eye movements with and without an overlay and were not included in the VS group. Following each participant's selection of their preferred overlay(s), we presented them with 11 images illustrating possible visual distortions while reading in order to verify whether they felt such symptoms were minimized when viewed through their selected overlays.

As noted, participants' ocular motor skills were measured using a Visagraph III Eye-Movement Recording System (Taylor Associates, New York). This system uses lens-free goggles with inbuilt infrared sensors to record eye movements during reading. As these goggles are worn by the participant, the goggles automatically compensate for any small movements of the head or body. The following oculomotor and reading parameters were measured and analyzed: (a) Fixations: number of eye pauses (stationary periods) in a reading from left to right per 100 words, (b) Regressions: number of times eye movements are directed from right to left per 100 words, (c) Span of Recognition: number of words read divided by the number of fixations, (d) Reading Rate (with comprehension): number of words read in 1 minute without rereading, (e) Relative Efficiency: reading rate divided by fixations and regressions, and (f) Comprehension: percentage of correct answers in a questionnaire concerning the content of the text that was read (10 yes or no questions).

Procedure

We administered the Visagraph III eye-tracking examination after the participants self-selected their most preferred overlay(s). We adjusted the eye-movement recording system to each participant's interpupillary distance, taking into account any refractive corrections. All participants were provided with a text appropriate for their reading level and cognitive capacity in order to minimize abnormal reading eye movements and allow a continuous reading performance to be recorded. Participants read the texts aloud, first without an overlay (baseline) and then with their chosen overlay(s).

The order in which the two tests were given remained consistent for all participants, as there is prior broad research agreement that marked deteriorations in the reading skills of individuals with VS usually occur within a few minutes and would be expected to occur during the second reading test. Thus, a key premise underlying this aspect of the study design was that any results inferring improvements in eye-movement reading efficiency while using the overlays would (in theory) be manifested on the second, rather than the first, of the two reading tests. All texts were read from a viewing distance of 40 to 45 cm, and under standard office lighting (two-tube cool-white fluorescent lamp ceiling-fixtures; 20 W 60 cm-tubes; correlated color temperature: 5,000 K; 120 Hz flicker cycle).

The reading material consisted of a single paragraph of black text, printed on a white paper, in Times New Roman font size 18 (we used a larger font to highlight any reading-fluency problems that might be attributable to an inadequate Span of Recognition). The paragraph was 11.5 cm wide and made up of 10 lines (approximately 7 words in each); however, data from the first and last lines were excluded from the analysis. After each reading, participants answered

10 questions about the text, permitting us to evaluate whether reading comprehension was good.

Statistical analysis

We used IBM SPSS Statistics (version 21.0, Chicago, IL) for all data analyses. As Pearson bivariate correlations were above 0.97, the average values of eye-movement data for the right and left eyes were calculated in relation to Fixations, Regressions, and Span of Recognition.

To check for gender and age differences in the effects of spectral overlays interventions on the VS patients' eye movements and reading performance, we conducted a series of two-factor split-plot analyses of variance (ANOVAs), with F adjusted as per the Greenhouse–Geisser method. The between-group variable was gender group (girls vs. boys) or age-group (children vs. adolescents), and the within-group variable was the reading condition (without overlay vs. with overlay).

To establish the clinical significance of any group differences, we calculated Cohen's d to determine the effect size and interpreted results using Cohen's (1988) criteria of 0.2 for a small effect, 0.5 for a medium effect, and 0.8 for a large effect. Pearson bivariate correlations were used in all sample comparisons, effectively merging the ocular motor skills parameters with the two conditions ("with" and "without" spectral overlays). Accordingly, we considered a p value of less than .05 to be statistically significant.

Results

In this study, participants' preferred-overlay selections ranged across all 10 of the overlays presented (including 35 combinations), with the most frequently chosen colors being "Purple," "Gray," and "Turquoise." The results for each parameter measured by the Visagraph III (with and without spectral overlays) are shown in Table 1, and split-plot ANOVA analyses (*Group* × *Condition*) are illustrated in Figure 1.

With respect to any changes in the reading efficiency parameters when measured during the intervention condition (spectral overlays), there were statistically significant improvements across all six measures, with small-to-moderate effect sizes found in each of these analyses (Table 1). When using spectral overlays, the children's number of Fixations immediately decreased by 21% ($p < .001$, $d = 0.50$) and the adolescents' Fixations decreased by 13% ($p < .001$, $d = 0.27$). Likewise, Regressions were reduced by 26% ($p < .001$, $d = 0.45$) and 19% ($p < .001$, $d = 0.26$), respectively. Reading with overlays was significantly improved on the other parameters as well. Span of Recognition (the amount of information captured in each eye fixation) improved by 24% ($p < .001$, $d = 0.51$) and 18% ($p < .001$, $d = 0.40$) for the children and adolescents, respectively.

Table 1. Ocular Motor Skills, Without and With Spectral Overlays (Means), Intervention Differences (Δ), and Interaction Statistics (Groups or Conditions).

	Children ($n = 184$)							Adolescents ($n = 139$)							Interaction statistics (Group × Condition)	
	Without overlay		With overlay					Without overlay		With overlay						
Parameters	*Mean*	*SD*	*Mean*	*SD*	Δ (%)	*P*	*d*	*Mean*	*SD*	*Mean*	*SD*	Δ (%)	*p*	*d*	$F(1, 321)$	*p*
Fixations	163.6	75.3	129.6	61.1	–20.8	<.001	0.50	135.7	63.8	118.2	64.3	−12.9	<.001	0.27	11.4	.0008
Regressions	42.9	28.1	31.6	21.5	–26.3	<.001	0.45	31.5	22.2	25.6	22.6	−18.7	<.001	0.26	8.15	.0046
Span Recognition	0.75	0.33	0.93	0.38	24.0	<.001	0.51	0.89	0.36	1.05	0.43	18.0	<.001	0.40	0.46	.4975
Reading Rate	167.7	83.1	214.9	94.0	28.1	<.001	0.53	212.8	86.9	255.6	107.1	20.1	<.001	0.44	0.40	.5265
Relative Efficiency	1.21	1.26	1.93	1.57	59.5	<.001	0.51	1.81	1.39	2.67	2.01	47.5	<.001	0.50	1.18	.2777
Comprehension	87.2	10.8	92.3	8.7	5.8	<.001	0.52	85.8	10.5	90.7	9.7	5.7	<.001	0.48	.003	.9582

Note. *SD* = standard deviation; Δ = difference between conditions (*Without* and *With* overlays); *p* = statistical significance; *d* = effect size.

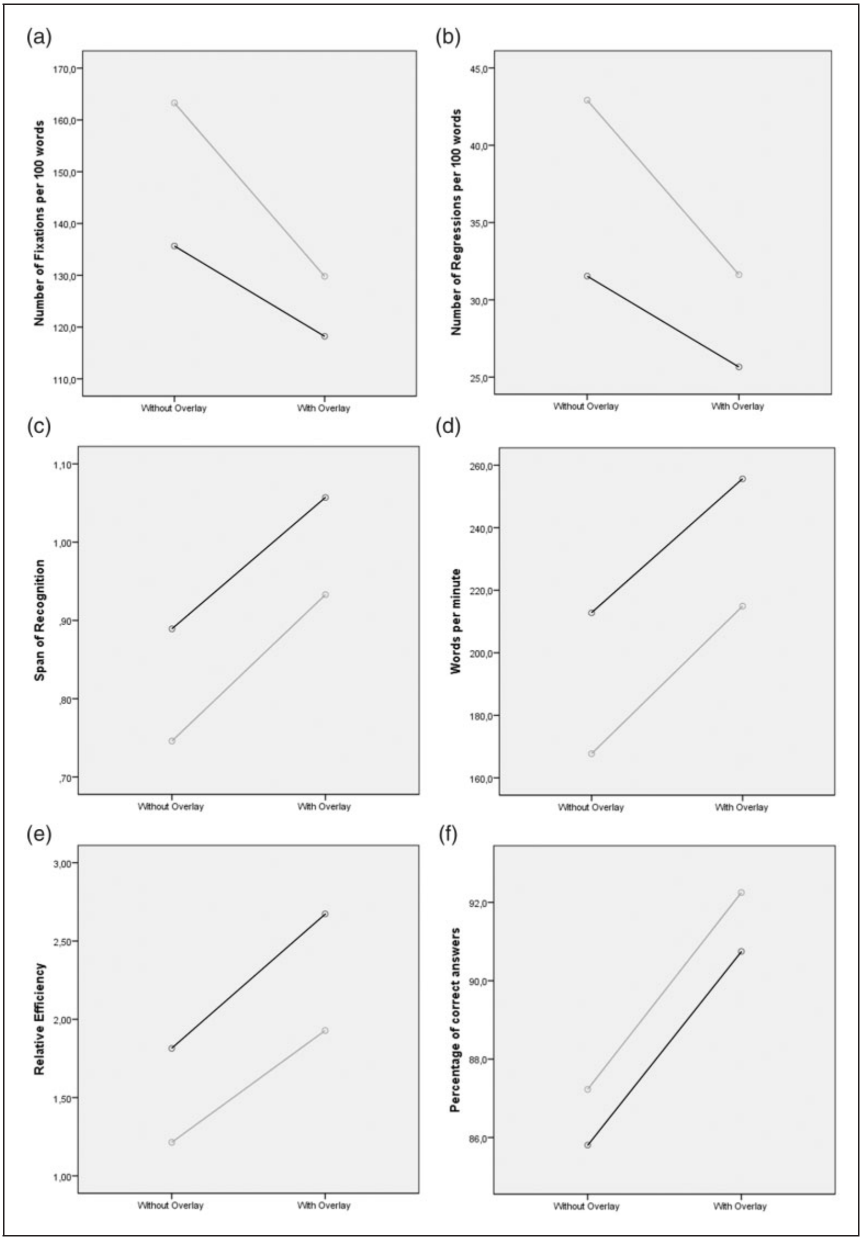

Figure 1. Split-plot analysis of the interaction effects of spectral overlays on Visagraph III Eye-Movement Recording System parameters. (a) Fixations, (b) Regressions, (c) Span of Recognition, (d) Reading rate, (e) Relative Efficiency and (f) Comprehension. Legend: gray line = children; black line = adolescents.

Reading Rate was 28% faster for the children ($p < .001$, $d = 0.53$) and 20% faster for the adolescents ($p < .001$, $d = 0.44$), with the two groups able to read 43 and 47 additional words per minute. Relative Efficiency improved by 60% among the children ($p < .001$, $d = 0.51$), and 48% among the adolescents ($p < .001$, $d = 0.50$). In addition, Text Comprehension also significantly improved when reading with spectral overlays in both age groups ($p < .001$, $d = 0.52$ and $p < .001$, $d = 0.48$), with the sample as a whole scoring 92% on a comprehension test following each participant's reading of a text in the overlay condition compared with 87% after reading an equivalent text without spectral overlays.

Split-plot analyses (see Table 1) revealed a statistically significant interaction between *Age Groups* and *Conditions* (without and with overlays) regarding Fixations, $F(1, 321) = 11.4$, $p = .0008$, and Regressions, $F(1, 321) = 8.15$, $p = .0046$. No significant interactions were observed in relation to the other parameters (Table 1). Post hoc analyses of these interactions showed that the reductions in the number of Fixations, and Regressions, were significantly more pronounced among children compared with adolescents (Figure 1). In other words, children's ocular motor skills appear to show greater immediate improvements using spectral overlays in comparison to adolescent readers.

We found significant gender-related eye-tracking differences (with post hoc analyses favoring girls better reading-related eye movements), with small effect sizes in relation to Fixations ($p = .013$, $d = 0.21$), Span Recognition ($p = .0096$, $d = 0.21$), Reading Rate ($p = .0023$, $d = 0.25$), and Relative Efficiency ($p = .012$, $d = 0.21$), but only a nonsignificant trend in Regressions ($p = .07$, $d = .15$) and no significant Comprehension differences. The gender sample did not differ in relation to age, and split-plot analyses revealed no significant interaction between gender and age.

As seen in Table 2, the number of Fixations were strongly positively correlated with Regressions ($r = .90$) and strongly negatively correlated with Span of Recognition, Reading Rate, and Relative Efficiency ($r = –.88$, –.80, and –.75, respectively). Regressions were also negatively correlated with Span of Recognition, Reading Rate, and Relative Efficiency ($r = –.77$, –.66, and –.64,

Table 2. Pearson Correlations Between Eye-Movement Parameters.

Parameters	2	3	4	5
1. Fixations	.90**	–.88**	–.80**	–.75**
2. Regressions		–.77**	–.66**	–.64**
3. Span of Recognition			.92**	.95**
4. Reading Rate				.95**
5. Relative Efficiency				1.0

Note. ** $p < .0001$.

respectively). It was also of note that increased Span of Recognition was very strongly and positively correlated with increases in Reading Rate and Relative Efficiency ($r = .92$, .95).

Discussion

The eye-tracking data recorded in this study showed immediate and significant improvements in six oculomotor and reading parameters when children and adolescents with VS read using self-selected spectral overlays compared with their baseline results. With overlays, there were statistically significant decreases in the number of Fixations and Regressions, whereas there were significant increases in Span of Recognition, Reading Rate, Relative Efficiency, and Comprehension. All of these eye-movement changes represent improvements for reading purposes. We observed more efficient eye movements from spectral filters with regard to the number of Fixations (per 100 words), as these were reduced by 21% for children and 13% for adolescents. Similarly, the use of spectral overlays decreased the proportion of regressive saccades by 26% among children and 19% among adolescents with VS in this study, reducing time and effort in the reading process.

The Span of Recognition (breadth of text in words or letters perceived during one fixation) averaged .75 of a word per fixation at baseline for the children, and this value jumped by 24% to almost full word recognition (.93) per fixation when children read using the spectral overlays intervention. A wider Span of Recognition should also assist the short-term memory for processing and manipulating larger amounts of information during each eye fixation. We obtained similar improvements with adolescents who were able to visualize in excess of one word (1.05) per fixation when using spectral overlays, an increase of 18% from their baseline levels. This implies that the spectral intervention increased both foveal and parafoveal visual information processing and this, in turn, would likely assist in predirecting the ensuing saccade to the next optimal fixation point and allow more fluent reading (Ashby, Yang, Evans, & Rayner, 2012), as, in fact, evidenced by reductions in Fixations and Regressions in both age groups.

With respect to Reading Rate, both children and adolescents read faster during the intervention condition (averaging 28% and 20% more words per minute, respectively). Such immediate and substantial improvements in reading rates also suggest that spectral overlays can promote more fluent reading for many young people with VS. The Relative Efficiency parameter provided a means of further evaluating reading performance by using a single, reliable value that integrates the three most important eye-movement variables: Fixations, Regressions, and Reading Rate. Moderate gains in Relative Efficiency (Cohen's $d = 0.51$) for the children and ($d = 0.50$) for the adolescents showed that both groups of patients with VS improved their reading performances. Our results also showed that Comprehension was markedly improved with the use of spectral overlays.

Comparatively, we found that the reductions in the number of Fixations and Regressions with the use of overlays were significantly greater in children compared with adolescents, although these differences might have been partly due to younger children starting from a lower reading efficiency baseline. In addition, our data seemed to confirm the higher incidence of reading disorders (and of neurodevelopmental problems generally) that have been found for males versus females (Quinn, 2018). Even with respect to reading-related eye movements, our post hoc analyses revealed that girls significantly outperformed boys on most measures that were responsive to the intervention (Fixations, Span Recognition, Reading Rate, and Relative Efficiency).

The high number of eye-movement regressions observed in the VS group (at baseline) may be indicative of a greater necessity in these individuals for corrective eye movements to recheck words (or phonemes) that were not sufficiently attended to initially (i.e., were "skipped over"). Alternatively, this eye-movement characteristic may reflect a need to adjust vergence (simultaneous pupil movements) to allow a clearer visualization or it may occur due to confused interpretation of prior content that then requires rereading. In individuals with VS, however, regressions usually trace to an inefficient tracking of the lines of text (Loew & Watson, 2013; Loew et al., 2014). In a sample of 27 children with reading difficulties, Solan et al. (1998) found that using spectral filters reduced the regression rate for their total group by 34%, a value similar to our finding of 26% reduction among child participants. Thus, our results, demonstrating that colored filters can significantly improve left-to-right eye-movement efficiency and enhance perceptual accuracy, concur with Solan et al.'s (1998) findings and are also consistent with positive reports of spectral overlay effects for readers with VS in studies using dependent measures other than eye tracking (Evans & Joseph, 2002; Garcia et al., 2017; Kriss & Evans, 2005; Ludlow et al., 2006, 2008; Nichols et al., 2009; Singleton & Henderson, 2007; Wilkins, Jeanes, Pumfrey, & Laskier, 1996; Wilkins et al., 2001; Wright et al., 2007).

Past research has shown that students with reading disorders demonstrate a higher number of Fixations while reading compared with other students (Okumura, Wakamiya, Suzuki, & Tamai, 2006; Solan et al., 1998), possibly due, at least in some instances, to the presence of visual distortions that necessitate increased comprehension effort. Neurobiologically, to generate clear and acute text visualization, the TVS and SVS must be highly synchronized so that the viewer can continually erase the image created from preceding eye fixations. This visual inhibition process is also referred to as *visual backward masking* (Solan et al., 1998; Williams, Breitmeyer, Lovegrove, & Gutierrez, 1991). A slight delay in the TVS may lead to delayed masking (inhibition) of the previous image, allowing it to outlast the normal duration of stimuli received from the SVS and creating an after-imaging effect (or "visual noise") that may then interfere with new detailed text perception. The superimposed older image inputs might generate a smeared or over-lapping image, explaining many of the visual distortions reported by patients with VS (e.g., "halos" surrounding words).

As it is already known that proficient, versus less capable, readers require fewer eye fixations (eye pauses) and regressions (backward eye movements) to read an identical passage of text, and prior research has shown that spectral filtering increases the efficiency of the magnocellular pathway (Ray, Fowler, & Stein, 2005; Stromeyer, Chaparro, Tolias, & Kronauer, 1997) and TVS–SVS synchronization (Croyle, 1998), eye-tracking technology for refined eye-movement analysis is a very logical next step for acquiring highly objective measures of reading efficiency within research to assess the reported benefits of spectral filters for VS, especially as ocular motor skills are only weakly influenced by voluntary control during reading (Chase, Ashourzadeh, Kelly, Monfette, & Kinsey, 2003; Greatrex & Drasdo, 1995; Stein, 2019).

Among the limitations of this study (and others) is its failure to fully control for placebo effects, as some participants might expect any overlays placed before them to be helpful. In the future, researchers might provide one overlay at random, in addition to a clear overlay, presented in counterbalanced order to all participants. This would allow testing for differences between self-chosen and randomly chosen overlays, as it would limit building expectations of benefits (placebo effect). Our own research design would have been improved by comparing reading-related eye-movement differences among participants with both self-chosen spectrally tinted overlay and a randomly assigned clear overlay. In partial response to this limitation, our use of four (of six) parameters that measured large involuntary micro eye movements meant that some of our dependent measures were less vulnerable to a placebo effect than dependent measures in other studies. Meanwhile, a number of separate studies, not using eye-tracking systems, have shown that self-chosen overlays yield greater performance gains in comparison to: (a) randomly selected color filters (Bouldoukian, Wilkins, & Evans, 2002; Wilkins & Lewis, 1999), (b) complementary colors (Jeanes et al., 1997), and (c) aesthetically preferred overlays (Ludlow et al., 2008). However, future research in this area should include an experimental condition involving reading with a clear spectral overlay. Our study had several clear and significant strengths in that our participant sample was very large, we excluded participants without professionally identified VS, and we required all participants to have 70% comprehension and good visual acuity. Yet, generalization of these findings may be limited by the fact that there may be VS severity differences between our VS participants, identified by ophthalmologists from among eye hospital inpatients, and ophthalmologist-identified individuals with VS from among an outpatient population. Further research might next replicate this study with a broader outpatient sample of VS participants.

An important demonstration within this study was that eye-movement recording systems are important tools in reading research. They provide objective data reflecting eye-movement reading activity that may either result from or cause reading problems, perhaps depending on the nature of different reading disorders. In what appears to be only the third eye-tracking study of the VS disorder and related overlay intervention strategies, we demonstrated that spectral filtering can be beneficial for some children and adolescents who are struggling with unexplained reading difficulties. This study showed that using spectral filters during reading significantly improved participants' ocular motor skills (e.g., fewer Fixations and Regressions) and reading rate, presumably alleviating baseline levels of print and background distortions among a clinical sample of participants with VS. We propose that such improvements may also free working memory to permit greater time and effort to be directed toward "the meaning of what is being read."

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Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical Statement

The Research Ethics Committee of the *Universidade Federal de Minas Gerais* approved all procedures in the study (approval no. 49765115.0.0000.5149), and the study was conducted in full accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki, 2008) for research involving human participants.

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