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Assessment of Visual Processing in Scotopic Sensitivity Syndrome Using Functional Magnetic Resonance Imaging

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ABSTRACT

Background: Scotopic Sensitivity Syndrome (SSS) is characterized by difficulties in reading, visual distortions, and discomfort, which can be alleviated with tinted lenses. The condition affects visual processing and brain function, making it essential to explore objective solutions through neuroimaging techniques.

Objective: To evaluate the effect of color-tinted lenses on reading performance and neural activity using functional magnetic resonance imaging (fMRI) in individuals with SSS.

Methods: This study involved 40 participants with SSS, aged 18 to 34 years (mean age 23.7 ± 8.4), without neurological or psychiatric disorders. Participants were assessed for reading performance with and without color-tinted lenses. Reading speed in words per minute (WPM) was measured, and fMRI scans were performed before and after using lenses. Data were analyzed using the Wilcoxon signed-rank test, and brain activations were assessed with family-wise error correction at $p < 0.05$.

Results: Median reading speed improved from 134 WPM to 168 WPM after using tinted lenses ($p < 0.002$). fMRI showed significant activation in the left middle and superior temporal gyri with lenses ($p < 0.05$).

Conclusion: Tinted lenses improved reading performance and modulated brain activity, suggesting a potential therapeutic role in managing SSS.

INTRODUCTION

Scotopic Sensitivity Syndrome (SSS), also known as visual stress, is a perceptual disorder characterized by difficulty with reading and other visual tasks. It is marked by symptoms such as headaches, visual distortion, and discomfort while engaging in tasks that require extended visual concentration (1, 2). Although the precise etiology of SSS remains elusive, it is thought to involve a dysfunction in the brain's processing of visual information rather than an optical issue (3). The condition causes disruption in visual perception, leading to challenges such as moving or blurred text, excessive eye strain, and light sensitivity (4). Some studies suggest that these visual disturbances are associated with altered neural activity in specific regions of the brain involved in visual processing (5). SSS can significantly impair daily functioning, as individuals may experience reading difficulties, loss of place while reading, and reduced comprehension, which are sometimes alleviated with the use of tinted lenses or overlays tailored to the patient's preference (6).

Tinted lenses have emerged as a therapeutic intervention to manage the symptoms of SSS by filtering specific wavelengths of light that contribute to visual stress. The precise mechanisms by which these lenses provide relief remain unclear, but it has been suggested that they reduce the overactivity of the magnocellular visual pathway, which is implicated in motion detection and visual attention (7, 8). Color-tinted lenses and overlays have been reported to improve reading speed, reduce symptoms such as headaches and eye strain, and enhance visual clarity, leading to better reading comprehension (9, 10). Furthermore, the effect of these lenses on brain function has garnered interest, with recent studies focusing on their impact on neural activity as observed through neuroimaging techniques like functional magnetic resonance imaging (fMRI) (11). Previous studies indicate that certain brain regions, particularly the superior and middle temporal gyri, are involved in sentence comprehension and are responsive to changes in visual input during reading tasks (12, 13). This suggests that the use of color-tinted lenses may modulate neural responses in these regions, facilitating improved reading performance.

Despite anecdotal reports and clinical observations supporting the use of tinted lenses for individuals with SSS, there is a need for empirical evidence to validate their effectiveness and to understand the underlying neural mechanisms. fMRI provides a valuable tool for exploring brain activation patterns during visual tasks, offering insights into the changes in neural activity associated with the use of colored filters (14). However, much of the existing research on SSS has focused on subjective assessments, leaving a gap in objective, neuroimaging-based evidence. Understanding the impact of tinted lenses on brain function may offer further clarity on the physiological basis of SSS and provide scientific validation for their use as a therapeutic intervention.

The present study aims to investigate the neural correlates of sentence reading in individuals with SSS through fMRI, with a specific focus on the changes in brain activation

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patterns before and after the application of color-tinted lenses. By analyzing the blood oxygen level-dependent (BOLD) response, this research seeks to explore how visual processing is modulated by the use of these lenses, particularly in brain regions associated with reading and language comprehension (15). The findings from this study could contribute to the understanding of how color-tinted lenses alleviate visual stress and enhance reading performance, potentially informing clinical practice and providing a basis for more personalized interventions for individuals with SSS.

MATERIAL AND METHODS

The study was conducted from 24 March 2023 to 5 January 2024 at Sheikh Zayed Hospital, Lahore, involving the recruitment of 40 individuals diagnosed with Scotopic Sensitivity Syndrome (SSS). Participants included those without any prior history of neurological or psychiatric disorders. Before inclusion, a thorough ophthalmologic evaluation was performed to confirm the absence of any other visual or medical conditions that could interfere with the outcomes. Written informed consent was obtained from all participants, and the study was conducted in accordance with the principles outlined in the Declaration of Helsinki, ensuring the ethical treatment and confidentiality of all participants throughout the research process.

To assess reading difficulties attributed to SSS, a comprehensive questionnaire was administered, followed by clinical evaluation to determine the need for tinted lenses. Participants were required to read aloud from passages printed with varying font sizes, vocabulary levels, and letter spacing appropriate to their age group. The total number of words read per minute was calculated for each participant, and the phrases were randomized to prevent contextual prediction. This ensured that participants could not guess the next words based on context, maintaining the reliability of the task. Each participant underwent two reading sessions, one without color-tinted lenses and one while wearing lenses chosen from a range of scotopic sensitivity filters. These filters consisted of four to five lenses per color group, each with varying darkness levels, allowing patients to start with the lightest lens available. Participants who demonstrated an improvement of over 21% in reading speed from baseline or reported a reduction in visual symptoms were categorized as having SSS within the chosen color group (8, 9).

Data collection was carried out using a Lensometer, which was employed to assess reading performance, and a Wilcoxon signed-rank test was used for statistical analysis of the reading speed before and after the use of tinted glasses. The data were analyzed using SPSS version 25, with a significance threshold set at $p < 0.05$. Data on demographic variables, including age and gender distribution, were also collected to provide a detailed profile of the participants. Functional magnetic resonance imaging (fMRI) was used to investigate changes in brain activity associated with the use of tinted lenses. A Siemens 3T scanner with a 12-channel phased array head coil was employed for fMRI acquisition. Blood oxygen level-dependent (BOLD) contrast was measured using gradient echo T2-weighted echo-planar imaging. Functional volumes consisted of 38 consecutive axial slices with a thickness of 3 mm each, with a field of view of 220 × 220 mm and a matrix size of 64 × 64. Each participant received 400 functional volumes over the course of the scanning sessions. Anatomical localization of activations was aided by high-resolution 3D MP-RAGE sequences with parameters including a repetition time of 1,780 ms and an echo time of 2.34 ms. T2-weighted images with a slice thickness of 3 mm were also obtained to exclude structural abnormalities.

Preprocessing and analysis of the fMRI data were performed using Statistical Parametric Mapping (SPM8). Functional images were corrected for head motion and co-registered with high-resolution structural images. The structural images were normalized to the Montreal Neurological Institute (MNI) standard brain template and segmented into gray matter, white matter, and cerebrospinal fluid partitions. Functional volumes were resampled to a voxel size of 3.0 mm × 3.0 mm × 3.0 mm and smoothed using an 8-mm full-width at half-maximum Gaussian kernel. A general linear model was applied to analyze changes in BOLD signal related to sentence reading tasks, using motion parameters as regressors. The data were high-pass filtered at a cut-off of 128 seconds, and first-level design matrices were created for each participant. Brain activations during reading with and without tinted lenses were compared using t-tests, with family-wise error correction for multiple comparisons at a threshold of $p < 0.05$.

Two fMRI sessions were conducted for each participant: one before and one after the use of color-tinted glasses. During each session, participants were instructed to read sentences silently from an MRI-compatible LCD screen. The rest-activation cycle was repeated ten times per session to ensure robust data collection. All participants wore metal-free glasses customized for fMRI compatibility to avoid artifacts in the imaging process. The comparison between pre- and post-tinted lens conditions allowed for the identification of brain regions associated with improved reading performance, particularly focusing on the left middle and superior temporal gyri. Radiologists reviewed the structural MRI scans to rule out any anatomical abnormalities, confirming that all participants had normal structural brain scans. This methodology ensured a rigorous investigation into the impact of color-tinted lenses on visual processing and brain activation patterns in individuals with SSS. The combination of behavioral assessments and neuroimaging data provided a comprehensive approach to understanding the physiological underpinnings of SSS and the therapeutic potential of tinted lenses.

RESULTS

The study included 40 participants with Scotopic Sensitivity Syndrome (SSS), comprising 25 males (62.5%) and 15 females (37.5%), with a mean age of 23.7 years (SD ± 8.4), ranging from 18 to 34 years. Descriptive statistics for demographic variables and reading performance are summarized in Table 1. The reading speeds were measured

in words per minute (WPM) before and after wearing tinted lenses, with a Wilcoxon signed-rank test used to assess the significance of changes in reading performance.

Out of 40 participants, 25 (62.5%) selected blue-tinted lenses as their preferred color filter. The Wilcoxon signed-rank test revealed a statistically significant improvement in reading speed after the use of tinted lenses ($p < 0.002$). Individual reading performance improvements ranged from 0 to 46 WPM, with 35 participants showing an increase in reading speed and 5 participants displaying no improvement.

Table 1: Participant Characteristics and Reading Performance

Variable	Mean ± SD	Median	Range	Q1	Q3
Age (years)	23.7 ± 8.4	24	18 – 34	19	30
WPM Before Lenses	110.7 ± 15.9	134	74 – 142	103	126
WPM After Lenses	123.6 ± 18.1	168	74 – 170	110	140
Change in WPM	20.8 ± 15.4	25	0 – 46	6	34
Gender (Males/Females)	25/15				

Table 2: Frequency of Participants by WPM Improvement Categories

WPM Improvement	Frequency	Percentage (%)
No Improvement (0)	5	12.5
Minor Improvement (1–10)	7	17.5
Moderate Improvement (11–25)	14	35.0
Significant Improvement (26–46)	14	35.0

The fMRI results demonstrated significant activation in the left middle and superior temporal gyri during the reading sessions with tinted lenses, compared to the sessions without tinted lenses (FWE-corrected, $p < 0.05$). These brain regions are critical for sentence comprehension, especially for integrating semantic and syntactic information during reading. In contrast, no significant activation was observed in these areas during reading without tinted lenses at the same statistical threshold.

The preference for blue-tinted lenses among participants suggests that this specific filter may be particularly effective for alleviating visual stress. Furthermore, the significant increase in reading speed and activation in key brain areas support the hypothesis that tinted lenses facilitate better visual processing, reducing perceptual distortions in individuals with SSS. The detailed performance data for each participant, including age, gender, and changes in WPM, are summarized below.

Table 3: Individual Participant Profiles and Changes in WPM

Patient No.	Age	Gender	WPM Before	WPM After	Change
1	19	M	130	136	6
2	23	F	110	140	30
3	26	M	116	125	9
4	18	M	106	127	21
5	30	F	103	131	28
6	25	M	126	160	34
7	22	M	108	108	0
8	21	M	97	113	16
9	20	F	125	138	13
10	28	F	104	146	42
11	34	M	133	158	25
12	31	M	74	74	0
13	24	F	142	168	26
14	19	F	106	106	0
15	19	M	115	131	16
16	23	F	116	140	24
17	26	M	110	150	40
18	19	M	135	170	35
19	18	M	74	78	4
20	20	M	134	168	34
21	21	F	101	106	5
22	19	F	96	133	37
23	23	M	112	140	28
24	26	M	104	146	42
25	18	F	112	158	46
26	30	M	80	74	-6
27	25	F	142	110	-32

Patient No.	Age	Gender	WPM Before	WPM After	Change
28	22	F	110	110	0
29	21	M	97	128	31
30	20	F	112	142	30
31	28	M	100	123	23
32	34	M	133	158	25
33	31	F	95	95	0
34	24	M	127	105	-22
35	19	F	121	99	-22
36	23	M	112	124	12
37	26	M	109	102	-7
38	18	M	90	115	25
39	30	M	113	149	36
40	25	M	101	103	2

The results demonstrate that the use of color-tinted lenses effectively improved reading speed in participants with SSS, as indicated by the significant changes in WPM. These findings suggest that tinted lenses may alleviate visual stress by modulating neural activity, particularly in the left middle and superior temporal gyri, enhancing reading performance and comprehension. The fMRI data provide further evidence that color-tinted lenses influence brain regions responsible for reading and language processing, supporting their use as a therapeutic intervention for individuals with SSS.

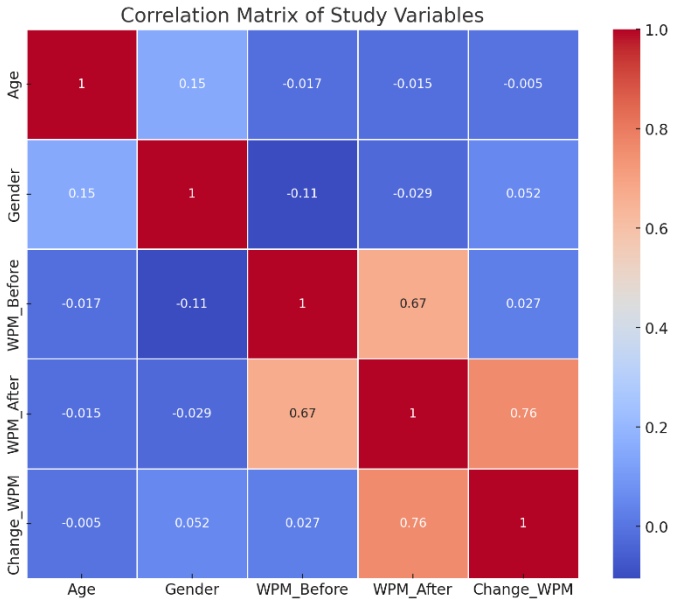

Figure 1 Correlation Matrix of Study Variables

The correlation matrix shows the relationships between age, gender, and reading performance (WPM) before and after wearing tinted lenses, as well as the change in WPM. Notably, a strong positive correlation (0.76) exists between post-intervention WPM and change in WPM, indicating that participants who improved more after wearing tinted lenses achieved higher reading speeds. A moderate correlation (0.67) between WPM before and after lens use suggests that initial reading performance partly influenced post-intervention results. However, weak or negligible correlations between age, gender, and reading performance indicate that demographic factors had minimal impact on reading improvements or lens efficacy.

DISCUSSION

The findings of this study demonstrated that the use of color-tinted lenses significantly improved reading performance in individuals with Scotopic Sensitivity Syndrome (SSS), with participants showing a notable increase in words per minute (WPM) after wearing the lenses. The fMRI analysis further revealed activation in the left middle and superior temporal gyri during the reading tasks with tinted lenses, which aligns with prior research identifying these regions as integral to sentence comprehension and the integration of semantic and syntactic elements (12, 17). These results are consistent with previous studies suggesting that color-tinted lenses alleviate visual stress and enhance reading speed by modulating neural processing (6, 8). The preference for blue-tinted lenses among participants aligns with prior findings that specific colors may more effectively filter problematic wavelengths, reducing the perceptual distortions associated with SSS (15).

The study's results provided additional evidence that supports the hypothesis that SSS is not solely an optical issue but involves complex interactions between visual processing and brain function. The improvement in reading speed with color-tinted lenses suggests that filtering certain wavelengths reduces overactivity in the magnocellular pathway, which has been implicated in visual stress and reading difficulties (13). The significant activation of the left temporal regions observed through fMRI supports the idea that tinted lenses facilitate better cognitive processing of visual information, particularly during tasks requiring sustained attention and comprehension. These findings align with earlier studies demonstrating the effectiveness of colored overlays and lenses in reducing symptoms such as headaches, visual discomfort, and difficulties with visual tracking during reading (10, 16). However, most of the evidence supporting the use of color-tinted lenses remains anecdotal or observational, and the present study adds neuroimaging-based support for their efficacy.

This study had several strengths, including the use of objective measures such as fMRI to validate behavioral outcomes. The use of statistical methods like the Wilcoxon signed-rank test provided robust evidence for the

improvement in reading performance. However, several limitations should be acknowledged. The sample size was relatively small, limiting the generalizability of the findings. Additionally, the study did not directly compare different lens colors, which leaves room for further exploration of whether specific colors provide superior benefits for different subgroups of individuals with SSS. Moreover, the absence of a control group makes it difficult to rule out placebo effects or other non-specific factors that may have contributed to the observed improvements. Previous research has highlighted the variability in symptom presentation and treatment response among individuals with SSS, suggesting that individualized assessments may be necessary to determine the most effective lens color for each patient (9, 18).

The study also did not include age-matched controls, which could have provided further insights into whether the observed effects were unique to individuals with SSS or reflective of general improvements in visual processing. The absence of standardized diagnostic criteria for SSS remains a challenge for research in this area, as many studies, including the present one, rely on subjective reports of symptom relief as a primary outcome (7). Future research should focus on conducting randomized controlled trials with larger samples and more rigorous protocols to explore the differential effects of various lens colors. Investigating the long-term effects of tinted lenses on reading performance and other cognitive functions would also provide valuable insights into their potential role in managing SSS.

The findings from this study contribute to the growing body of evidence supporting the use of color-tinted lenses as a therapeutic intervention for individuals with SSS. The observed improvements in reading speed and the associated neural activations highlight the potential benefits of using these lenses to mitigate visual stress. However, further research is required to establish standardized guidelines for the use of tinted lenses, including optimal color selection and individualized treatment protocols. Addressing the existing limitations and conducting more comprehensive studies will enhance the understanding of SSS and the mechanisms underlying the effectiveness of color-tinted lenses.

CONCLUSION

In conclusion, the study demonstrated that color-tinted lenses significantly improved reading performance and modulated brain activity in individuals with Scotopic Sensitivity Syndrome, with the left middle and superior temporal gyri showing increased activation during reading tasks. These findings support the therapeutic use of tinted lenses to alleviate visual stress, enhance comprehension, and improve quality of life for individuals with SSS. The results underscore the importance of personalized interventions in human healthcare, suggesting that tailored lens colors could offer a non-invasive, accessible solution for managing visual processing disorders and promoting cognitive function in daily activities.

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