Use of Visual Search in the Assessment of Pattern-Related Visual Stress (PRVS) and Its Alleviation by Colored Filters

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PURPOSE. Visual search measures have been used to evaluate the effects of pattern-related visual stress (PRVS), and its alleviation by colored filters, but tasks and results have varied between studies. Performance on a high-difficulty search task was measured in individuals having low- and high-PRVS susceptibility.

METHODS. Two PRVS groups (low and high) were formed on the basis of participants' responses to a visual symptoms questionnaire and perceptions of a high-contrast grating pattern. Each participant searched for multiple instances of a single-digit number (target) within an array of similar numbers (distractors). Performance was measured by response time and error count. A three-factor, mixed-factorial ANOVA design was used to investigate the effects of PRVS group, a high-contrast background PATTERN, an overlay of an individually-selected COLOR.

RESULTS. Individuals classified with high visual stress were found to experience significantly greater improvement in reading performance ($F_{(1,26)} = 24.579$, $P < 0.001$) and reduction in the number of errors ($F_{(1,26)} = 9.502$, $P = 0.005$) when performing the Wilkins Rate of Reading Test with a colored overlay than those with low visual stress. Error count was significantly higher in the high-PRVS group, when subjects were performing a visual search task, in the absence of either PATTERN or COLOR, but response time was not significantly different. Neither response time nor error count was significantly affected by background PATTERN and/or colored overlay.

CONCLUSIONS. Results of this and previous studies confirm that visual search measures may be helpful in the assessment of PRVS, but several important methodological issues may limit their application in this context. (*Invest Ophthalmol Vis Sci.* 2008;49:4210–4218) DOI:10.1167/iovs.07-1587

The inability to see comfortably without distortion and discomfort has been referred to as visual stress.[1,2] Wilkins[2] refers to a condition that is caused or at least exacerbated by characteristics of the visual stimulus and is therefore sensory in origin, as opposed to visual stress of motor origin caused by factors such as anomalies of eye movement control, accommodation, and/or binocular vergence.[3] The motor form of visual stress will not be considered in the present article.

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. The condition appears to be particularly prevalent in individuals who have migraine,[4] photosensitive epilepsy,[5,6] or dyslexia,[7,8] as well as in those who deliver high scores on the neuroticism scale in personality analysis.[9]

Previous research has generally identified individuals who have pattern-related visual stress (PRVS) either indirectly, through questionnaires and interviews asking people to report symptoms of visual discomfort and disturbance that they experience from day to day,[10–12] or directly, by asking them to report the occurrence of perceptual distortions when they view a pattern likely to evoke a visual stress response.[13] The latter approach is the basis of the pattern glare test as described by Wilkins and Evans.[14] These indirect and direct forms of symptom-based assessment have also been described, respectively, as measures of *trait* and *state*.[15] Hollis and Allen[16] have shown that direct assessment of the visual stress *state* using a patterned stimulus is the more meaningful for determining whether an individual is experiencing PRVS that may be alleviated by a colored filter. They suggested that, while measures of *trait* based on reports of preexisting symptoms provide a useful indication that an individual may warrant further investigation, they are not strong predictors of the potential benefit of a colored overlay for a particular individual in terms of their performance on a visual task such as reading.

Wilkins[2] (see also Conlon et al.[17] and Wilkins et al.[18]) has described the stimulus characteristics most likely to evoke sensory visual stress. When aspects of the visual scene are of high contrast and in a striped configuration, with each stripe subtending 10 minutes of arc at the eye (spatial frequency of the pattern approximately 3 cyc/deg), and are of an equal width and spacing (duty cycle of approximately 50%), visual stress is likely to be evoked in those who are susceptible. Consequently, reading material also has the potential to elicit visual stress, given its spatial characteristics.[19] The occurrence of visual stress specifically associated with reading has been described by Meares,[20] Irlen,[10] and Wilkins.[21] The susceptibility of some individuals to reading-related visual stress has been called *Irlen syndrome*,[22] *Meares-Irlen syndrome*,[23,24] and (incorrectly) *scotopic sensitivity syndrome*.[10] In the present study, we adopted the general term PRVS to describe any form of sensory visual stress associated with viewing patterned stimuli. Wilkins[2] (see also two other studies by Wilkins et al.[15,25]) has proposed that the underlying anomaly in pattern-related visual stress is hyperexcitability of the visual cortex, possibly as a result of impaired gain control mechanisms, and that the effects of this can be alleviated in a variety of ways including modifying the design and layout of printed text and, notably, through the use of color.

Much research on the problem of visual stress has concentrated, not on the perceptual origins, characteristics, and ef-

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fects of the phenomenon, but on the fact that its symptoms of visual discomfort and distortion can often be alleviated by using colored filters, particularly if the choice of color is precisely matched to the individual.[26,27] Individualized colored filters have been found to reduce the symptoms of visual stress in some cases of migraine[28–30] and epilepsy,[31] and they have also been found to improve performance in various tasks, notably reading.[13,32,33] For example, impaired readers may show an increase of 25% or more in reading speed when they read a text with a colored overlay of their choice.[11,34,35] These changes in comfort and performance appear robust and are not considered to be mere placebo[31,36,37] or due to a reduction in contrast.[38] Overlays have been shown to benefit sentence comprehension, reading accuracy, and reading speed.[39–41] Conflicting views have been expressed by Menacker et al.[42] and Iovino et al.[43] who found no significant improvement in reading with the use of colored filters. However, the lack of improvement found in the latter two studies could be explained by the limited range of color used, as it has since been shown that a sufficient choice of color is necessary to obtain effects on reading speed.[44]

The close association that appears to exist between occurrence of pattern-related visual stress and its alleviation (as shown by improved reading performance) by color, has resulted in the adoption of improvement in reading performance with color in its own right as a diagnostic criterion for PRVS or Meares-Irlen syndrome.[7] The most popular approach to this has used the Wilkins Rate of Reading Test (WRRT; Wilkins et al.[34]) in which reading rate (in words per minute) is measured by using passages of text comprising the same 15 common words repeated in random sequence over a series of closely spaced lines. The intent of this task design is to provide a striped pattern of text likely to provoke PRVS and also to provide a measure of reading speed that relies on visual and oculomotor factors and minimizes the influence of the syntactic and semantic aspects of reading.

Although most studies of visual performance during visual stress have concentrated on rate of reading, there is also evidence that visual search performance may be impaired in some individuals with migraine and symptoms of visual stress,[45–47] as well as in individuals who are slow readers.[48,49] Conlon and Humphreys[47] divided a sample of individuals into low- and high-discomfort groups, according to their results on the Visual Discomfort Scale[12] and administered two different visual search tasks; *parallel search* involving identification of a vertical line target in a set of tilted line distractors and *serial search* involving identification of a target circle with a gap in a particular orientation in a set of distractor circles having gaps in a variety of different orientations. Here, use of the terms parallel and serial follows the widely accepted assumption that search for targets with high visual salience (that is, targets that are easily discriminated from their distractors) is performed using parallel neural processing, whereas search for low-salience targets requires focused attention to determine whether each item is a target or a distractor, and therefore it involves serial processing of search items.[50,51] Conlon and Humphreys[47] found that the high-discomfort group was significantly slower than the low-discomfort group on serial search in every set-size condition (4, 8, or 16 distractors) and also on parallel search in which there were many distractors. Performance of the two groups on parallel search was no different when there were few distractors. Conlon and Humphreys[47] concluded that theirs was the first study to show less efficient search performance in high visual discomfort without the presence of background pattern, implying that a measure of visual search performance might prove useful as a quantitative indicator of susceptibility to visual discomfort or stress.

More recently, Singleton and Henderson[52] have demonstrated that performance on a visual search task can predict visual stress susceptibility in children of primary and secondary school ages, and they have suggested that such a task could be used effectively to screen for visual stress in children, including those with dyslexia.[53] Singleton and Henderson[52] required their subjects to locate a random three-letter target word in a matrix of three-letter distractor words in one of two configurations: visually nonstressful (10-point Arial normal font surrounded by a gray background) or stressful (10-point Arial bold font surrounded by a background of alternating horizontal black and white stripes). Singleton and Henderson,[52] in contrast to Conlon and Humphreys,[47] found no difference in mean visual search response time between groups of subjects with low and high visual stress (VS) in the nonpatterned (nonstressful) task configuration. They did, however, find that introduction of the patterned (stressful) background produced a significant difference in response times between low- and high-VS groups, with the high-stress group taking longer to respond, supporting a conclusion that measurement of visual search performance provided a promising diagnostic method for identifying susceptibility to visual stress.

Singleton and Henderson[52] also explored the effects of using a colored overlay on the rate of reading (WRRT), finding a significant increase in the reading rate of the high-VS group when participants used an individually selected colored overlay, supporting the principle observed previously that improvement in reading rate with colored overlay provides an alternative criterion for identifying those with high visual stress susceptibility. They did not, however, investigate the effect of a colored overlay on visual search performance, but visual search has been included in some other studies concerned with the effects of colored overlays on visual performance. Tyrrell et al.,[54] for example, investigated children of normal and below average reading ability using a visual search task in which participants had to locate occurrences of a letter "x" within a passage of text. All participants were permitted to choose an overlay, either colored or clear, based on their subjective impressions of the effects of various overlays on their perception of a passage of text. Visual search performance was measured with and without the chosen overlays and showed that those who chose a colored overlay found a significantly higher number of targets in the search task with the overlay than without, whereas those who chose a clear overlay achieved the same search performance with and without the overlay. The principal purpose of Tyrrell et al. was to investigate the effect of colored filters on children's reading skills, and participants were therefore selected according to their impaired reading abilities rather than their susceptibility to visual stress. The study therefore does not provide any direct evidence of the association between visual stress and visual search ability. Similarly, a recent study by Wright et al.[55] of patients with multiple sclerosis, has shown that use of an individualized colored overlay reduces symptoms of visual stress and improves rate of reading and visual search performance. In this study, the search task was a matrix (15 rows $\times$ 7 columns) of ellipses with random orientation of the major axes. Within the matrix there were 15 circles, and participants in the task were required to locate the circles. Wright et al.[55] and Tyrrell et al.[54] both used a task involving multiple targets (or, more precisely, multiple instances of the same target). This is of interest because, as we shall see, they resemble the task used in the present study, which is distinctly different from the single-target task structure used by Conlon et al.[45–47] and Singleton and Henderson.[52,53]

Singleton and Henderson[52] found that visual search performance in high-VS participants was impaired only when a high-contrast pattern surrounded the lines of the word-search task, however, Conlon and Humphreys,[47] particularly in their *serial search* experiment, found impairment in the search performance of high-VS participants without any additional interference pattern. This finding implies that search task difficulty may be a critical factor in the performance difference between low- and high-VS groups, rather than the presence of a stressful pattern per se. Discriminating the single target from its distractors is relatively easy in the word search task[52,53] because recognition of simple words is highly automatic,[56–58] to such an extent that very often the target word will effectively pop out in the manner of a parallel processing task, with little need for systematic serial search through many distractors. Hence, the children participating in Singleton and Henderson's studies[52,53] were able to locate target words quickly in the presence of more than 100 distractor words. In contrast, search for a specific target gap orientation when the target and its distractors are of similar form[47] is more difficult and more likely to require systematic serial search to identify the target correctly, even with a much smaller number of distractors.

In this study, we investigated visual search performance by using a task that may be considered to present a higher level of difficulty than those of both Singleton and Henderson[52,53] and Conlon and Humphreys.[47] The task involved a search for *multiple instances of a single target* (MIST). Participants were presented with a rectangular array of single-digit numbers (0–9), within which any digit can occur more than once, and the search task was to identify how many instances of a particular digit occurred in each presentation of the array. Such a task structure is taxing in a variety of ways: participants must undertake an exhaustive serial search of the number array, attending to every item, because any item might be a target. In addition, they must count how many instances of the target they have seen. Accurate target counting requires not only effective use of short-term and working memory but also adoption of a strategic approach to scanning the number array so that no target is either missed or counted more than once. Thus, the MIST task imposes attentional/memory and oculomotor demands that are generally greater than those required in single-target search (STS). Furthermore, use of a multiple-instance (or multiple-target) structure allows search performance to be evaluated in terms of both response times and error rates, whereas single-target searches are typically evaluated only in terms of response times, with errors either not permitted, ignored due to their low frequency of occurrence,[47] or considered only insofar as they enable adjustment for a tradeoff of accuracy against speed (see Singleton and Henderson[52,53]).

We were interested in knowing whether individuals with susceptibility to low and high visual stress achieve different response times and/or error rates with the MIST search task under various test conditions similar to those used in previous studies.[45–47,52,53] Assuming that visual stress impairs one or more of the processing abilities required in visual search, the increased difficulty of the MIST task, relative to the STS configurations of earlier studies, naturally led to a hypothesis that search performance in high visual stress would be poorer in the present study than in those reported previously.

Thus, the purposes of the present study were to investigate the following questions: (1) Does performance on a multiple-instance visual search task discriminate between low- and high-PRVS subject groups? (2) Does addition of a high-contrast background pattern affect visual search performance, and does this differ in low-PRVS and high-PRVS groups? (3) Does use of an individualized colored filter affect visual search performance, and does this differ in low- and high-PRVS groups?

Methods

Selection of Participants

Twenty-eight participants (12 men and 16 women; age range 18–65 years; mean, 38.0 ± 11.3 [SD]) were recruited from an open university student population. Informed consent was obtained from every participant after a verbal and a written explanation of the procedures was given. The study protocol complied with the tenets of the Declaration of Helsinki.

All participants had normal or corrected-to-normal vision; could read N5 at 0.4 m and had distance visual acuity of at least 6/5 (−0.1 logMAR). None of the participants had ever been classified as having dyslexia or as having a reading disability. None had used colored overlays or taken an assessment of this nature, and none had ever been treated for binocular vision anomalies. Other optometric data were not obtained because previous studies have suggested that subtle binocular and accommodative anomalies are not major etiological factors in visual stress.[23,24,59]

Two subjective measures of visual stress susceptibility were obtained from each participant. First, a questionnaire was used to identify symptoms that participants had noticed before the testing session. Twenty questions were included, based on those used by the Irlen Institute[10] and detailed in a previous publication.[16] Each question received a score of 1 for a positive response and 0 for a negative, giving a total possible score of 20 for each participant. In accordance with Irlen[10] scores of 4 or more were taken to indicate that a person may be susceptible to visual stress and would be likely to experience symptoms. The second measure evaluated participants' direct subjective responses on viewing a high-contrast pattern.[2] The pattern was a horizontal grating with a square-wave luminance profile and a Michelson contrast of 0.8. It was circular in outline and presented an overall diameter of 28° and spatial frequency of 3 cyc/deg when viewed at a distance of 0.4 m. Hollis et al.[9] have used this technique to identify whether people are likely to have pattern glare sensitivity. Participants viewed the grating and answered questions to identify the number of perceptual distortions they experienced, (for example: "Looking at the pattern, do you see any of the following: blurring, bending of the lines, shadowy shapes among the lines?") (see the Appendix for the remaining distortions). A score of 3 or more indicates that a person may have a susceptibility to pattern glare and experience symptoms.[29]

Each participant was classified as exhibiting either low or high PRVS based on responses to the visual symptoms questionnaire and pattern test. Scores above threshold were required on both measures; >4 for the visual symptoms questionnaire, >3 for pattern. Groups were formed from the first 14 participants who conformed to the classification criteria for each category. Those assigned to the low-VS group gave scores ranging from 0 to 4 (mean, 1.64 ± 1.34 [SD]) for the visual symptoms questionnaire, and from 0 to 3 (mean, 0.86 ± 1.03) for pattern glare evaluation. Those assigned to the high-VS group had scores ranging from 7 to 11 (mean, 9.07 ± 1.69) for the visual symptoms questionnaire, and from 4 to 7 (mean, 4.93 ± 1.00) for pattern glare evaluation. It is notable that low- and high-stress groups were well separated by both visual symptom scores ($t_{(26)} = 12.92$, $P < 0.001$) and pattern glare evaluation ($t_{(26)} = 10.64$, $P < 0.001$), and scores on the two measures were highly correlated (Spearman R = 0.78, $t = 6.34$, $P < 0.001$). The consequence of this is that the low- and high-PRVS classifications given by the two measures are in perfect agreement (Fig. 1).

Apparatus and Materials

Wilkins Rate of Reading Test. The WRRT, developed by Wilkins et al.,[34] presents of a set of 15 easily recognizable words repeated in random, meaningless sequences and laid out in paragraphs of typically 150 words arranged in 10 lines to resemble conventional printed text. A version of the test suitable for adult readers was used in which words were presented in 9-point Times font, with 4-point

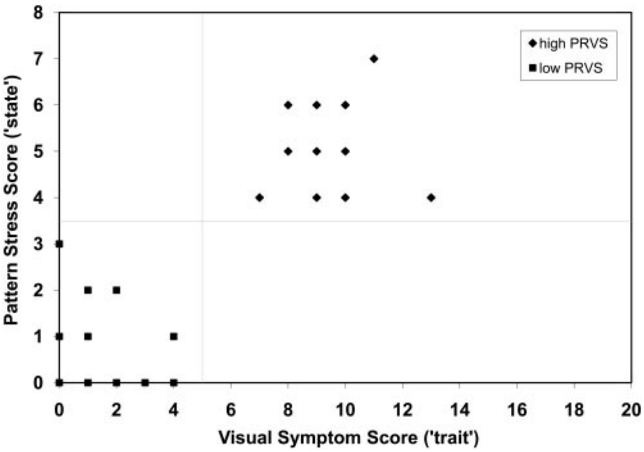

Figure 1. Classification of participants into high- or low PRVS groups based on their responses to the visual symptoms questionnaire (trait) and pattern glare test (state).

horizontal spacing between words and single line spacing. Participants are required to read the words aloud for a period of 1 minute as though they were reading a conventional passage of text. The test is scored by noting errors on a score sheet (an enlarged version of the test text) and by measuring the number of words read per minute.

Intuitive Colored Overlays. Colored overlay assessment was performed with Intuitive Overlays (IOO Sales Ltd., London, UK). The transparent plastic overlay sheets are A5 in size and are available in nine colors, the spectral properties of which have been chosen so as to sample colors systematically from the CIE 1976 UCS diagram.[21,36,60] A pair of identical overlays is provided for each of the nine colors, with the intention that each color be either used alone or combined with the same or a neighboring color to create 27 possible shades. In the present study, all overlays were used singly. Each participant's optimal overlay was chosen using the method outlined in the intuitive overlays manual. For use with the rate-of-reading test, a single overlay sheet was laid over, and in contact with, the printed passage of text. For use with the visual search task, a single overlay sheet was placed in direct contact with the LED flat screen (matt side in contact with the screen) so that any potential blur was minimized. There was approximately a 10% loss of contrast.

Visual Search Task. The task involved searching a matrix (grid) of numbers to determine how many instances of a particular number occurred in each presentation. Seventy-two number search grids were generated in two sets (56 experimental grids and 16 practice grids). Each grid comprised a set of random single-digit numbers in a 10-column × 4-row configuration in New York 10-point font (3 mm high). The task instructions appeared in 12-point New York font above the grid, and remained on the screen for each presentation. The task background was either plain white (pattern absent) or consisted of rows of uppercase random letters presented in New York 12-point font, 4 mm high (pattern present). The number-grid measured 2.5 × 2 cm within a background pattern measuring 12.5 × 7.5 cm. The appearance of the search grid with pattern present is shown in Figure 2. The search task was presented on a computer (Macintosh 540c; Apple, Cupertino, CA) with an LCD display measuring 0.190 × 0.145 m. The controlling program for the experiments was written in commercial software (Superlab 1.68; Cedrus Corp., San Pedro, CA). At a testing distance of 0.6 m, the spatial frequency for the lines of text was approximately 2 cyc/deg with a duty cycle of 43%. The background pattern subtended approximately 12°.

Standardized instructions were given on how to perform the search task. At the top of each grid, a single sentence instructed the participant to search for a particular number (e.g., How many 3's?). Each grid required a different response from 1 to 9, and the responses were balanced for the two sets of grids. Participants were asked to keep their fingers on the keyboard during grid presentations, to count the number of targets as instructed on the screen and indicate the answer as quickly and as accurately as possible, by pressing a computer key. Each participant received 8 practice trails, followed by four blocks of 14 trials. Half the trials were conducted with their chosen colored overlay placed flat against the screen, the other half of the trials were conducted with a clear overlay placed flat against the screen. The presentation order of the blocks and the trials was randomized. Each stimulus grid was preceded by a fixation cross that appeared in the center of the screen for 500 ms, followed by the number-search grid and background, which remained on the screen until the participant made a response. The room was illuminated with main voltage (50 Hz) fluorescent lighting (daylight CCT [correlated color temperature], 6500 K) providing an illuminance of 300 lux on the horizontal working plane and 200 lux on the task display. The display was positioned so as to prevent reflections of room luminaires from being visible to participants in the experiment.

Experimental Design

Each participant was classified as having low or high PRVS, based on responses to the visual symptoms questionnaire and pattern test.

A three-factor, mixed-factorial design was used, having 1 between-groups and 2 within-subject factors. The between-groups factor had two levels: low- and high-PRVS. The within-subject factors, each with two levels, were color (overlay absent/present) as described in the previous section, and pattern (absent/present), to be described in the following section. Dependent variables were search response time (in milliseconds) and number of errors.

Results

All statistical analysis was performed using commercial software (SPSS ver. 14; SPSS Sciences, Chicago, IL).

Figure 2. Example of Search Screen presentations (*top*) without and (*bottom*) with pattern background.

Rate of Reading: WRRT

The WRRT was used to evaluate participants in the low- and high-PRVS groups who performed the test under two viewing conditions: natural viewing (overlay absent) and with a transparent colored overlay sheet placed in front of the text (overlay present). Data were obtained for both reading rate (words per minute) and number of errors. The latter were transformed to improve normality by $x' = \sqrt{(x + 0.5)}$, where x is a observed error count, and x' is its transformed value.[61] Both measures were analyzed using two-factor (between-within) ANOVA. The between-groups factor comprised two levels: low- and high-PRVS, as did the within-subjects factor: overlay present/absent. Neither reading rate ($F_{(1,26)} = 1.490$, $P = 0.233$) nor number of errors ($F_{(1,26)} = 1.353$, $P = 0.255$) was significantly different between groups, but there was a significant interaction between the factors, in that the increase in average reading rate with color was significantly greater in the high-PRVS group (low-PRVS mean change −3.07 wpm, high-PRVS mean change 20.64 wpm: $F_{(1,26)} = 24.579$, $P < 0.001$).

Thus, the individuals classified with high visual stress according to the study criteria were found to experience significantly greater improvement in reading performance when using a colored overlay than those with low visual stress (Fig. 3).

This result is in keeping with findings in previous work.[24,34,35,54]

Visual Search

Data were analyzed using 2 × 2 × 2 between-within ANOVA in keeping with the experimental design. Search response times (in milliseconds) and error counts were analyzed separately. Note that, in principle, a single combined measure may be derived by adjusting response time values according to the number of errors. However, our data show no systematic relationship between response times and error counts that would justify such an approach ($R^2 < 0.002$ in each group).

Two actions were taken before analysis: (1) Response times less than 2000 ms and more than 10,000 ms were classed as outliers and excluded from the response time analysis. Values in this range accounted for <2% of the data. (2) Error counts were subjected to a square-root transformation to improve normality, as described previously.

Mean visual search response times and error counts obtained under each condition are given in Table 1.

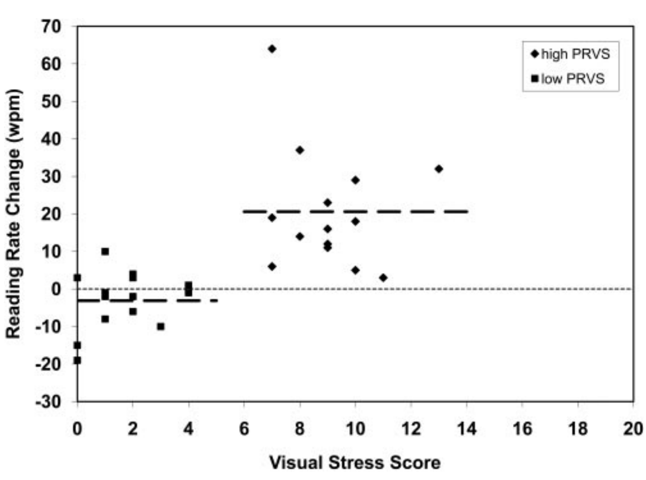

Figure 3. Improvement in rate of reading performance (words per minute) when using a specific colored overlay for participants with high or low PRVS on the WRRT.

Table 1. Search Response Time and Number of Errors in the High- and Low-PRVS Groups When Performing the Visual Search Tasks

	Colored Overlay	Clear
Mean reponse time (ms)		
High PRVS susceptibility		
Pattern	6145 (1714)	6269 (1684)
No pattern	6017 (834)	5738 (731)
Low PRVS susceptibility		
Pattern	5764 (651)	5738 (718)
No pattern	6307 (654)	6067 (596)
Mean errors (n)		
High PRVS susceptibility		
Pattern	5.2 (2.0)	5.3 (2.1)
No pattern	3.9 (2.0)	5.0 (2.1)
Low PRVS susceptibility		
Pattern	1.2 (1.7)	0.7 (1.2)
No pattern	1.3 (1.1)	1.4 (1.5)

Data are expressed as the mean (SD) of results of tasks performed with and without the background pattern and with and without the use of overlays

Between-Groups Analysis: Main Effects and Interactions. We note first that only the error counts are effective at discriminating between the groups because, over all conditions, those with high-PRVS make significantly more errors (low-PRVS mean errors, 1.4; high-PRVS mean errors, 5.1: $F_{(1,26)} = 83.943$, $P < 0.001$), but they do not respond significantly more slowly (low-PRVS mean, 5969 ms; high-PRVS mean, 6042 ms: $F_{(1,26)} = 0.062$, $P = 0.806$).

It is also striking that this marked distinction between search response times and error counts persisted under subconditions. For example, when search performance in the baseline condition (that is, absence of both background pattern and colored overlay) is examined by 1-way ANOVA, we find that response times do not separate the groups (low-PRVS mean, 6067 ms; high-PRVS mean, 5738 ms: $F_{(1,26)} = 1.703$, $P = 0.203$), but error counts do (low-PRVS mean errors, 0.87; high-PRVS mean errors, 4.77: $F_{(1,26)} = 25.729$, $P < 0.001$). Similarly, one-way between-group comparisons in the presence of background pattern reveal no difference in response times (low-PRVS mean, 5738 ms; high-PRVS mean, 6269 ms: $F_{(1,26)} = 1.175$, $P = 0.288$), but a highly significant difference in error counts (low-PRVS mean errors, 0.24; high-PRVS mean errors, 5.09: $F_{(1,26)} = 60.395$, $P < 0.001$), and a similar one-way analysis of search data taken in the presence of a colored overlay demonstrates the same outcomes for response times (low-PRVS mean, 6307 ms; high-PRVS mean, 6067 ms: $F_{(1,26)} = 2.805$, $P = 0.118$) and error counts (low-PRVS mean errors, 0.88; high-PRVS mean errors, 3.49: $F_{(1,26)} = 13.239$, $P = 0.001$). Figure 4 summarizes the overall between-group main effects for search response time and error data.

Second, most interactions between the *group* factor and the others (*pattern* and *color*) are not significant (response time: *group* × *pattern*, $F_{(1,26)} = 2.442$, $P = 0.130$; *group* × *color*, $F_{(1,26)} = 0.181$, $P = 0.673$; *group* × *pattern* × *color*, $F_{(1,26)} = 0.443$, $P = 0.511$ and error count: *group* × *color*, $F_{(1,26)} = 1.315$, $P = 0.262$; *group* × *pattern* × *color*, $F_{(1,26)} = 0.038$, $P = 0.847$). The only exception is the case of *group* × *pattern* interaction for error counts ($F_{(1,26)} = 6.050$, $P = 0.021$). Inspection of the mean error counts for this interaction indicates that introduction of the pattern results in the number of errors decreasing in the low-PRVS group, but increasing in the high-PRVS group; thus the interaction is significant. However, one-way analysis of the pattern effect within each level of the *group* factor reveals that the number of errors with and without pattern is not significantly different in either group (low-

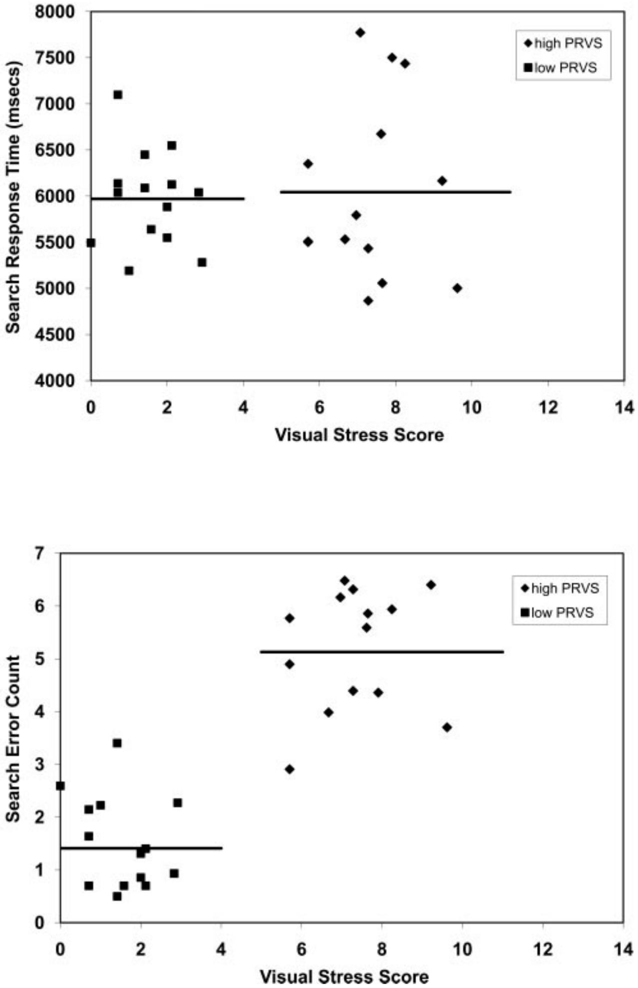

FIGURE 4. (*Top*) Visual search response time and (*bottom*) error count for participants with high or low PRVS.

PRVS: $F_{(1,13)} = 3.549$, $P = 0.082$, high-PRVS: $F_{(1,13)} = 0.146$, $P = 0.708$).

Within-Subject Analysis: Main Effects and Interactions. Neither of the within-subject factors (*pattern* and *color*) exhibited a significant main effect for either response time or error count (response time: *pattern*, $F_{(1,26)} = 0.047$, $P = 0.829$; *color*, $F_{(1,26)} = 2.655$, $P = 0.115$, and error count: *pattern*, $F_{(1,26)} = 0.002$, $P = 0.965$; *color*, $F_{(1,26)} = 0.109$, $P = 0.743$), nor is there any significance in the interaction of error counts for *pattern* × *color* ($F_{(1,26)} = 2.337$, $P = 0.138$). There is, however, a significant interaction between response times for *pattern* and *color* ($F_{(1,26)} = 4.673$, $P = 0.040$), because introduction of a colored overlay increased the overall average response time (impaired search performance) when the background pattern was absent, but decreased it (improved performance) when pattern was present (Fig. 5).

Further investigation of the effects of *color* within the two levels of *pattern* reveals that the increase in mean response time with color in the absence of pattern is significant (color absent, 5903 ms; color present, 6163 ms: $F_{(1,27)} = 6.875$, $P = 0.014$), but the decrease with color in the presence of pattern is not significant (color absent, 6004 ms; color present, 5955 ms: $F_{(1,27)} = 0.283$, $P = 0.599$). Since there was no significant three-way interaction between *group* × *pattern* × *color*, further investigation of pattern–color interactions within each group did not change this result. In each group and overall, use of the colored overlay impaired search performance (increased response time) in the absence of pattern, but did not affect (improve or impair) it significantly when pattern was present.

DISCUSSION

Rate-of-Reading and Colored Overlays

Before discussing the visual search results that relate to the principal goals of this study, we note that results relating to the classification of participants into low- and high-PRVS groups and the performance of these two groups on the rate-of-reading test (WRRT), with and without colored overlays, are in broad agreement with many previous studies.[24,34,35,54,62]

We found that introduction of an individualized colored overlay improved reading rate significantly in the high-PRVS group but not in the low-PRVS group (Fig. 3), providing further validation of the idea that rate-of-reading improvement with overlay may serve as a "proxy" diagnostic test for the existence of visual stress.[7] Note, as has also been observed by others,[11,36,37] that it is the change in the rate-of-reading with color that discriminates between people with different stress levels and not the initial reading rate.

Visual Search in Low- and High-PRVS

The primary purpose of this study was to explore whether visual search measures may be used to discriminate between low- and high-PRVS groups. Our finding that search performance on the multiple-instance (MIST) number-search task was impaired in high-PRVS (Fig. 4) is in general agreement with previous studies that have used single-target serial search[47] and single word search in the presence of a visually stressful pattern.[52] These results, taken together, confirm that a measure of visual search performance, under suitable task conditions, is able to identify individuals with high-PRVS susceptibility, and therefore visual search has potential as a tool for visual stress diagnosis and/or for characterizing the visual stress condition.

The main difference in results between this and previous studies[47,52] is our finding that low- and high-PRVS groups did not differ in response times but that error counts were significantly higher in the high-PRVS group. This outcome reflects a fundamental difference between single-target search (STS) tasks and those with multiple targets or multiple instances of the same target. Tasks requiring location of a single target[52] present no dilemma for the participant; the target is known to be present and the participant only needs to keep searching

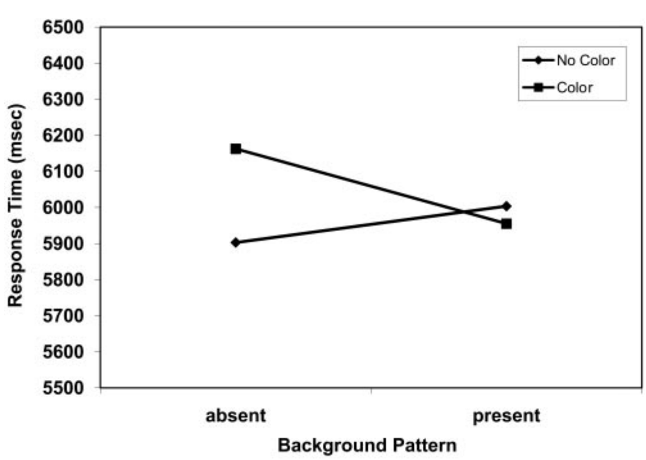

FIGURE 5. Effect of presence of background pattern on visual search response time, with and without colored overlay.

until it is found, however long this may take. Thus, the natural measure of performance is response time and, although some misidentification errors will occur due to lapses of attention or "finger-errors," the error rate generally should be very low. Single-target search involving repeated stimulus presentations (trials) in each of which the target may be either present or absent[47] is likely to result in more errors than the target-location task since two types of error, false-positive and -negative, are possible in every trial. However, if there is no limit on stimulus presentation time, as is required for response-time measurement, and if participants are instructed that they should endeavor to respond without error[47] then the overall error rate will generally be low, and search performance will again be represented by response time. On the other hand, a multiple-instance or multiple-target task, which presents an unknown number of target occurrences, invites a different sort of search strategy. The dilemma for the participant now is whether to search exhaustively until he or she is certain that all targets have been identified. Alternatively, the participant may allow what seems to be a reasonable time to do the search, at the expense of making more errors. In the present study, where participants were asked to count the targets and give their responses "as quickly and accurately as possible," it is likely that most were willing to admit errors to limit their response times. Thus, it is not surprising to find that performance differences between groups are represented by number of errors rather than response times.

Visual Search with Background Pattern

Introduction of a high-contrast background pattern, which may be expected to increase visual stress susceptibility in some participants, was generally found to make no significant difference in either response times or number of errors (Table 1). The only result involving pattern to reach statistical significance (at the 5%, but not at the 1% level) is the interaction of the number of search errors between visual stress groups and the presence or absence of background pattern. Further analysis of this interaction showed that the overall magnitude of this marginally significant effect arose from an insignificant *decrease* in errors with pattern in low-PRVS participants combined with an insignificant *increase* in errors with pattern in high-PRVS participants. Of these two effects, the improvement in search performance in the low-PRVS group was closer to significance ($P = 0.082$) than was the decline in performance in the high-PRVS group ($P = 0.708$).

Therefore, contrary to the findings of Singleton and Henderson,[52] we obtained no evidence that visual search performance in high-PRVS individuals was impaired by introduction of a high-contrast patterned background. A possible explanation is that the stimulus used by Singleton and Henderson[52] was more effective at invoking a pattern–glare response. Both studies used a pattern that surrounded the visual search task peripherally but remained spatially distinct from it. In Singleton and Henderson,[52] however, this pattern was composed of dark, solid stripes that surrounded the search material closely, whereas the present study used a pattern composed of text having a wider margin between it and the search material. The possibility that these differences may have been enough to render one pattern more effective than the other for provoking pattern glare in susceptible observers suggests that further studies on the psychophysical relationship between PRVS response and stimulus configuration may be warranted.

Visual Search with Colored Overlay

Introduction of a colored overlay has been found to improve the rate-of-reading of high-PRVS individuals in the present study and in others discussed previously, and some studies have also reported an improvement in visual search performance.[54,55] However, we found no evidence *overall* of any difference in visual search performance with colored overlays, nor was there any significant difference in effect between low- and high-PRVS groups (Table 1). The only effect involving color to reach statistical significance in our study related to an interaction between the response times for pattern and color. As indicated in Figure 5, this can be attributed to a significant *decline* in search performance ($P = 0.014$) when color was introduced in the absence of pattern. A similar finding is apparent in the study by Wright et al.[55] who report one result showing that a group of subjects performed a multiple-instance search task significantly more slowly and failed to identify a larger number of targets, with a colored overlay than without, although this may be a short-lived effect under which performance returns to normal levels after subjects have adapted to the use of the filter.

The striking result in the present study, however, is that use of the colored overlay did not improve the visual search performance of the high-PRVS group, either in terms of response times or error counts. This implies that any reduction in visual stress as a result of using color is insufficient to bring about an improvement in search performance on the multiple-instance task. Although this finding is at odds with the reports of Tyrrell et al.[54] and Wright et al.,[55] it is difficult to reconcile the disparate results due to marked differences in study methodologies and especially the fact that the earlier studies were conducted on subjects selected for their specific stress-related conditions (poor reading ability and multiple sclerosis, respectively) rather than based on the occurrence of pattern-related visual stress in its own right.

On the other hand, there are clear similarities between the participants in our study and those studied by other researchers, in that those with high stress susceptibility in all studies show an improvement in reading rate with colored overlay. Thus, the implication of our result is that individualized colored overlays, even if they bring about a reduction in visual discomfort and/or an improvement in reading rate, will not necessarily alleviate other forms of visual performance deficit, and that use of color should not therefore be regarded as a general-purpose solution to the problem of pattern-related visual stress. We therefore consider that further research should give priority to investigating the characteristics and visual performance implications of PRVS, rather than concentrating primarily on its possible alleviation with color.

Conclusion

We have presented results showing that a measure of the number of errors on a multiple-instance visual search task can discriminate between groups of individuals with low and high susceptibility to PRVS. We found no significant difference in the search performance of either group when a high-contrast, visually stressful pattern surrounded the search task, nor did we find any change in search performance, with or without this pattern, when participants performed the task using an individualized colored overlay. Because this finding means that a significant search performance deficit persisted in high-PRVS participants when colored overlays were used, it suggests that use of color should not therefore be regarded as a general-purpose solution to the problem of pattern-related visual stress.

Overall, our results indicate that measurement of visual search performance may be helpful in the assessment of PRVS, but several important methodologic differences may limit the application of visual search methods in this context. We propose that further studies relating visual search to visual stress should pursue an approach aimed at elucidating the nature of the relationship between search performance and task design in those with and without PRVS.

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Appendix

Looking into the center of the grid that is in front of you, do you experience any of the following? Please answer each question yes or no.

Pain or discomfort
Shadowy shapes among the lines
Shimmering of the lines
Flickering
Red
Blue
Green
Yellow
Blur
Bending of any lines
Nausea/dizziness
Unease