Exploring a Short-Wavelength Sensitive Cone Mechanism to
Brightness and Discomfort Glare

David Glabe
Pacific University, dkglabe@gmail.com

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Exploring a Short-Wavelength Sensitive Cone Mechanism to Brightness and Discomfort Glare

Abstract
Yellow lenses have long been reported to alter visual perception, including subjective impressions of brightness and discomfort glare. To date, no consensus has been reached regarding the physiological mechanism behind this altered perception, although recent research suggests a possible short-wavelength sensitive cone (S-cone) mechanism. An experiment was conducted to test the hypothesis that S-cones are responsible for the perceived increase in brightness and decrease in discomfort glare perception when viewing through yellow lenses. Thirty participants were asked to use neutral density filters to match perception of brightness and discomfort glare through colored filters and with no filters in low and high lighting conditions. Colored filters were selected to test the influence of S-cones versus M- and L-cone stimulation. Results show that, in a high-luminance outdoor setting, findings were consistent with decreased S-cone stimulation resulting in an increased perception of brightness. This was not found in lower luminance settings, or with the perception of discomfort glare at either luminance level. It is suggested that S-cone involvement in brightness perception through yellow lenses may be luminance-dependent and occur in opponent fashion, as has been postulated elsewhere in the literature.

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Degree Name
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Committee Chair
James E. Sheedy, OD, PhD

Second Advisor
John R. Hayes, PhD

Third Advisor
Karl Citek, OD, PhD / James Kundart, OD, MEd

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EXPLORING A SHORT-WAVELENGTH SENSITIVE CONE MECHANISM TO BRIGHTNESS AND DISCOMFORT GLARE

by

David K. Glabe

A thesis submitted to the faculty of
Pacific University of Oregon
in partial fulfillment of the requirements for the degree of

Master of Science

College of Optometry
Pacific University of Oregon
April 2010
PACIFIC UNIVERSITY
GRADUATE COMMITTEE APPROVAL

of a thesis submitted by
David K. Glabe

This thesis has been read by each member of the following graduate committee and by majority
vote has been found to be satisfactory.

5/11/11
Date
James E. Sheedy, OD, PhD, Chair

5/11/11
Date
John R. Hayes, PhD

May 5, 2011
Date
Karl Citek, OD, PhD

05/10/2011
Date
James Kundart, OD, MEd
ABSTRACT

EXPLORING A SHORT-WAVELENGTH SENSITIVE CONE MECHANISM TO BRIGHTNESS AND DISCOMFORT GLARE

David K. Glabe
College of Optometry
Master of Science

Yellow lenses have long been reported to alter visual perception, including subjective impressions of brightness and discomfort glare. To date, no consensus has been reached regarding the physiological mechanism behind this altered perception, although recent research suggests a possible short-wavelength sensitive cone (S-cone) mechanism. An experiment was conducted to test the hypothesis that S-cones are responsible for the perceived increase in brightness and decrease in discomfort glare perception when viewing through yellow lenses. Thirty participants were asked to use neutral density filters to match perception of brightness and discomfort glare through colored filters and with no filters in low and high lighting conditions. Colored filters were selected to test the influence of S-cones versus M- and L-cone stimulation. Results show that, in a high-luminance outdoor setting, findings were consistent with decreased S-cone stimulation resulting in an increased perception of brightness. This was not found in lower luminance settings, or with the perception of discomfort glare at either luminance level. It is suggested that S-cone involvement in brightness perception through yellow lenses may be luminance-dependent and occur in opponent fashion, as has been postulated elsewhere in the literature.
Dedication

To my beautiful family, without whose tireless support and endless encouragement I could never have accomplished this and so many other things.
Acknowledgements

I would not be where I am today without the influence of my family and all they have done to motivate, encourage, and support me in my educational pursuits. To my wife, our two beautiful children, and my parents, I extend the foremost recognition. They have reminded me time and again that a profession is merely the means to an end of spending more quality time with the real future of the world – our children.

I acknowledge Dr. James Sheedy’s generous support and inspiration in this project. He has not only served as my faculty advisor, but has helped me to truly appreciate the academic side of the vision sciences. Even more, his sense of curiosity and wonder (the best qualities possessed by any good scientist) have been contagious. He has encouraged me to pursue my dreams. For this, and so many other things, I thank him with deepest sincerity.

I offer gratitude to Dr. Heidi Vollmer-Snarr, Dr. John R. Hayes, and Dr. James Kundart, all of whom have facilitated my pursuit of research in the vision sciences. Their advice and, more importantly, their friendship, have helped me be a better professional and person.

Finally, it is true that we stand on the shoulders of giants when we seek to further human knowledge and understanding in any arena. I recognize those intellectual giants who laid the foundations for the work described herein.
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Chapter 1 – Background on Perceptual Effects of Yellow Lenses

Introduction

For decades, scientists have been intrigued by the way yellow-tinted lenses appear to alter visual perception. Yellow lenses have been reported to make objects appear brighter (Wolffsohn, et al. 2000) (Kelly 1990) (Luque, et al. 2006), reduce glare (Kooi and de Vries 2002), increase contrast of a scene (Wolffsohn, et al. 2000) (Rabin and Wiley 1996) (Yap 1984), and even enhance visual performance (Ray, Fowler and Stein 2005). For one or more of these reasons, several groups have reported a subjective preference for yellow-tinted lenses, including aviators, skiers, shooters, and those with reduced vision secondary to disease (Wolffsohn, et al. 2000), and a substantial market has been developed for yellow-tinted ski goggles, shooting goggles, sport and driving sun lenses, and computer glasses. In addition, with the recent development of yellow intraocular lenses for implantation following cataract removal, the subjective effects of viewing through yellow lenses have gained even greater attention (Augustin 2008) (Wohlfart 2007), giving new importance to studies addressing the perceptual effects of yellow lenses. Of particular interest among such studies are attempts to identify the physiological mechanisms that govern the effects of yellow lenses on brightness and glare perception (Kooi and Alferdinck 2004).

Yellow lenses and brightness perception

Numerous studies have explored the effect of yellow lenses on perceived brightness, and the majority has shown an increase in brightness in at least some circumstances when viewing through yellow lenses. In an earlier work, Kelly (1990) showed in a heterochromatic flicker photometry brightness matching experiment using Norton Visitor Wraparound glasses (cutoff ~500nm) that yellow lenses resulted in up to a 40% increase in perceived brightness over luminance-matched neutral lenses. Interestingly, Kelly notes that the effect is present only at moderate luminance levels in her experiment, and absent at low and high luminance. This latter finding is disputed by Rabin and Wiley (1996) who, using a target simulating the effect of viewing through a spectrally broad yellow filter, found the greatest effect on contrast (33% enhancement) at high luminance levels with a 14% enhancement at low levels, indicating that at least some of the brightness enhancing effect of yellow filters increases with luminance. Similarly, Septon (1968) found brightness enhancement by yellow lenses to be increased at higher luminance levels, but noted a reversed effect altogether at low luminance. Perez et al
(2003) confirmed that yellow filters enhance brightness perception under mesopic viewing conditions, utilizing the Essilor X-482 cutoff filter and a differential light sensitivity measure with an automated campimeter. And more recently, an investigation by Luque et al (2006) showed that yellow filters may cause an increase in perceived brightness when compared to the naked eye and luminance-matched neutral density filters. Luque et al employed a CRT display to allow haploscopic matching of both chromatic and achromatic stimuli presented on different colored backgrounds. These authors found the greatest effect of yellow filters on brightness enhancement when the target surround was blue, suggesting that the chromaticity of a surround influences brightness perception. A study by Wolffsohn et al (2000) offers some explanation for the varying literature results regarding brightness perception with yellow lenses, showing that the spectral profile of yellow filters used may significantly influence the effect. In particular, these authors note a subjective increase in brightness perception through yellow lenses for 450nm cutoff filters but not for 511nm or 527nm cutoff filters.

Given the findings of these many experiments, the literature clearly shows that yellow filters may induce an increase in brightness perception under certain conditions; and although a number of potential physiological mechanisms have been proposed, there is no apparent consensus regarding an explanation of the effect. For example, Kinney et al (1983) qualitatively suggest a mechanism through reduction of the opponent component of the chromatic channel. Kelly’s experimental results (1990), on the other hand, implicate rod contribution to the luminance channel as the primary mechanism for the brightness effect, apparently ruling out cone contributions by noting that the effect increases with larger target size and is limited to the 1-log unit range from 7 to 76 Cd/m². Kelly’s experimental findings state that brightness enhancement by yellow filters commences at the chromatic threshold, and disappears at luminance levels corresponding to rod saturation. In direct contrast to Kelly, Rabin and Wiley (1996) conclude that the brightness increase effect is a photopic phenomenon, based both on luminance levels associated with the effect and the independence of target size on brightness enhancement in their experiment. Luque et al (2006) also seem to rule out a rod mechanism with their findings and (somewhat similar to Kinney) propose a role of the blue-yellow opponent input to the chromatic channel. Although Luque et al do not explicitly suggest an S-cone role, the S-cone component of the blue-yellow channel may be inferred. In an important recent publication, Ripamonti et al (2009) lend credence to this possibility by showing, along with earlier studies, that S-cones may contribute to luminance channels in an inverted and delayed fashion and that S-cone contribution to luminance is directly dependent upon M- and L-cone adaptation levels through an apparent gating mechanism.

Yet other possible mechanisms have been proposed. Wright (1949), in an early application, suggested that the brightness effect may be explained through a psychological association with the color of the sun. More recently, Chung and Pease (1999) provide evidence for a pupil size
contribution to explain at least part of the brightness-enhancing effect of yellow filters. Indeed, given the variety of hypotheses proposed, it is apparent that further exploration is necessary to more definitively identify the mechanism behind yellow-lens-induced enhancement of brightness perception.

Yellow lenses and discomfort glare perception

In addition to findings regarding yellow lenses and brightness perception, multiple studies have shown or implicated that yellow filters may decrease perception of discomfort glare. Kooi and de Vries (2002) report that yellow filters may subjectively reduce discomfort glare to a level corresponding to that of a 2.3x dimmer white light, as cited in a later study by Kooi (Kooi and Alferdinck 2004). Data from several studies exploring spectral responses to discomfort glare seem to support the idea that yellow filters may reduce glare sensation. For example, Sivak et al. (2005) discovered that the radiant power of different types of car headlamps, when weighted by the S-cone spectral sensitivity function, was a strong predictor of discomfort glare. Similar findings were obtained in two previous studies by Bullough et al. (2002) (2003), who also suggest that the S-cones may be strong contributors to discomfort glare perception based on the apparent contribution of short wavelengths to sensations of discomfort glare.

As with brightness perception through yellow lenses, multiple physiological mechanisms have been proposed to explain discomfort glare responses. The most popular of these proposed mechanisms for many years was pupillary response, which has been shown to be most active in the blue wavelengths of the visible spectrum, consistent with – but potentially independent of – a rod or S-cone mechanism (Fry and King 1975) (Fugate and Fry 1956) (Berman, et al. 1996). Recently, Kooi and Alferdinck (2004) designed an experiment to compare rod photoreceptors, melanopsin-containing photosensitive ganglion cells, and the S-cones to determine which neural elements were responsible for the sensation of discomfort glare on a physiological level. These authors conclude that S-cones are the most likely candidates responsible for the effect; however, as with yellow lens-induced brightness perception, the mechanism behind discomfort glare reduction through yellow lenses remains a subject of some controversy.

Purpose of this study

Taken together, the literature suggests that, among other possible effects, yellow filters both increase brightness perception and decrease the sensation of discomfort glare. On an intuitive level, this conclusion is quite surprising, since an increase in brightness perception might be
expected to simultaneously increase the sensation of glare. However, it may be possible to explain these experimental findings. One hypothesis is that the S-cones may cause a decrease in brightness perception through an inhibitory post-receptoral processing opponent channel interaction with the M and L-cones. Assuming this, a yellow filter that selectively inhibits stimulation of the S-cones would result in a decrease in the inhibitory component of the opponent channel signaling brightness perception, ultimately leading to an increase in the perceived brightness of a scene. It is then plausible that S-cone involvement in the perception of discomfort glare occurs through a separate channel. One thought holds that S-cones, often considered the most primitive cone type from an evolutionary perspective, saturate more quickly than M-cones and L-cones (Sheedy 2009). This saturation may be perceived as discomfort glare; therefore, a yellow lens that selectively inhibits S-cone stimulation would result in a decidedly reduced perception of discomfort glare.

In accordance with the model described, this study was based on the hypothesis that decreased S-cone stimulation (resulting from selective blocking of shorter wavelengths by yellow lens wear) increases perception of brightness and decreases the sensation of discomfort glare. The primary objective of this study was to determine through a forced-choice comparison with colored filters and a series of neutral density filters whether or not S-cones are indeed responsible for the perception of increased brightness and decreased discomfort glare reported with yellow lens wear, as well as provide data to aid in discriminating between disparate hypotheses in the literature regarding the mechanism behind these effects.

Chapter 2: Experimental

Materials and Methods

Filters

A series of four yellow filters, one blue colored filter, and 5 neutral density (grey) filters were used in this experiment. All filters were manufactured by Schott and obtained through S.I. Howard Glass Company, Inc. in Worcester, MA, USA. The filters were glass, 5 cm square in size, with thicknesses of 3 mm for the yellow and lightest neutral density filters, and 1 mm for the blue and remaining four neutral density filters. Table 1 lists the filters used in this experiment by manufacturer identification code. The spectral characteristics of these filters are
shown in Figures 1 and 2, and photopic transmittance for the colored filters is displayed in Figure 3.

<table>
<thead>
<tr>
<th>Colored Filter Codes</th>
<th>Neutral Density Filter Codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>GG420 (light yellow)</td>
<td>Clear Glass Blank</td>
</tr>
<tr>
<td>GG435 (light yellow)</td>
<td>NG3</td>
</tr>
<tr>
<td>GG455 (medium yellow)</td>
<td>NG4</td>
</tr>
<tr>
<td>GG475 (medium yellow)</td>
<td>NG5</td>
</tr>
<tr>
<td>BG39 (blue)</td>
<td>NG11</td>
</tr>
</tbody>
</table>

Table 1. List of filters by Schott code.

![Spectral Profiles of Colored Filters](image)

Figure 1. Spectral transmittance profiles of colored filters.
Figure 2. Spectral transmittance profiles of neutral density filters.

Particular attention was paid to the selection of colored filters for this study. In accordance with the S-cone hypothesis for brightness and discomfort glare perception, filters were chosen based on a calculated ratio of their relative S-cone stimulation versus M-cone + L-cone stimulation, or S/(M+L) ratio. This ratio was chosen based on work by several authors (Ripamonti, et al. 2009) (Stockman, Macleod and Priest 1987) (Stockman, Macleod and Priest 1991) suggesting that S-cones may have a small but inhibitory input to the luminance channel under certain adaptation conditions, consistent with our hypothesis that decreased S-cone stimulation could enhance brightness perception. S/(M+L) values were calculated by summing the products of the transmittance values of a given colored filter across the visible spectrum and the corresponding S-, M-, and L-cone spectral sensitivities derived from Smith’s and Pokorny’s estimates (Smith and Pokorny 1975) (Wyszecki and Stiles 1982) (see Figure 5), then dividing the summed S-cone value by the summed M- and L-cone values (see Equation 1). A linear, rather than logarithmic, transformation of the Smith and Pokorny fundamentals was used to avoid negative numbers in the S/(M+L) calculation; for graphical purposes, the logarithms of the S/(M+L) ratios are used elsewhere in this report.
An attempt was made to utilize filters that covered a linear decrease in $S/(M+L)$ values ranging from larger than the naked eye ratio (blue filter) to much less than that amount (yellow filters). Calculated relative $S/(M+L)$ values for each colored filter and the naked eye, along with corresponding transmittance values, are shown in Figure 4.

\[
\int_{400}^{700} \frac{(T_\lambda \times S_\lambda)}{(T_\lambda \times M_\lambda + T_\lambda \times L_\lambda)} d\lambda
\]


Figure 3. Measured transmittance values for colored filters.
Figure 4. $S/(M+L)$ Ratio by Schott filter type.

Figure 5. Cone fundamentals derived from Smith and Pokorny (1975). Logarithmic scale used to better display S-cone sensitivity.
Photometers

In addition to S/(M+L) values, the photopic transmittance of each colored filter and combinations of that filter with neutral density filters was measured with a Photo Research SpectraScan PR670 Spectrophotometer (Photo Research, Inc. 9731 Topanga Canyon Place, Chatsworth, CA 91311, USA). Measured values were used in data analysis.

A separate, more portable Hagner Universal Model S2 photometer (Universal Photometer, 9 Seminole Ave. Corte Madera, CA 94925) was used to measure environmental luminance and illuminance in the outdoor testing conditions.

Lights

Two General Electric 15W helical Hg T3 lights (6500K color temperature, 82 CRI, 738 mean lumens), obtained through a local department store, were used to provide a source of glare during indoor testing conditions. The lights were mounted on two thin metal poles via a clamp system attached to the bulb housing.

Subjects and Recruitment

Thirty subjects, aged 18 to 40, were recruited for this study. Inclusion criteria consisted of age (between 18 and 40 years) and visual acuity (at least 20/25 distance acuity in the eye to be tested). Exclusion criteria included any significant ocular or manual pathology or disability, or the presence of any clinically significant cataract. Age and cataract restrictions were incorporated for the purpose of eliminating any effect of crystalline lens brunescence on visual perception through the colored filters utilized.

All but two subjects were recruited from Pacific University College of Optometry. Optometry student subjects were offered a small amount of extra credit in one professional course for their participation. Alternatively, subjects could elect to be paid at the rate of $10/hr for the study.

Experimental Procedure

Four unique test conditions were employed in the experiment: Brightness Perception Indoors, Brightness Perception Outdoors, Glare Perception Indoors, and Glare Perception Outdoors. Testing was performed from August 2009 to January 2010 during daylight hours only. Individual sessions generally lasted between 60 and 90 minutes total duration.

Indoor testing was performed with the intent of better simulating lower indoor luminance levels and providing a controlled viewing environment with regard to both luminance and
chromaticity. For this condition, subjects were seated 1.5 m from a bright white fabric screen, viewing in primary gaze at a small black dot centered on the screen. Two lights located 60 cm in front of the screen and 19 cm on either side of the fixation dot were used to illuminate the screen as well as provide a source of glare during glare testing. With both lights on, the sheet had a central luminance of approximately 50 Cd/m². The luminance at the center of each bulb was approximately 20,000 Cd/m², as measured by a Hagner Universal photometer. Figure 5 shows the setup of the Indoor testing conditions.

Outdoor testing was performed with the intent of simulating a relatively normal viewing environment for yellow lenses. This condition involved the subject standing in front of a large floor-to-ceiling window pane located on the north side of Taylor Meade Auditorium on Pacific University campus. The subject viewed an outdoor scene through the window consisting of both deciduous and evergreen trees, green lawns, red brick buildings, and cement walkways. A portion of the sky was visible. In order to control for varying luminance in the environment, photometric measures of the luminance of three areas (grass, sky, and the cement walkway) were taken at the beginning of each outdoor trial. The scene viewed through this window on a January day is shown in Figure 6.
Testing was performed in a semi-random sequence, with subjects being randomized to indoor or outdoor conditions first, and brightness or glare testing first.

The testing sequence was performed in the following manner:

For each condition, the subject had one eye occluded with an opaque patch. In a forced-choice fashion, the subject alternately viewed the scene in front of him with the non-occluded eye through a colored filter and with no filter, and stated (for brightness testing) whether the scene appeared brighter or dimmer with the filter in place, or (for glare testing) whether the subjective sensation of discomfort glare was increased or reduced with the filter in place. If the scene appeared brighter or glare increased with the filter, one or more neutral density filters
were placed in contact with the colored filter in order to decrease the overall transmittance. The subject was then asked to compare the brightness or discomfort glare of the scene with and without the new filter combination. To reduce the number of presentations needed, neutral density filters were added in a pre-determined manner, as shown in Table 2. This process was repeated until the subject reported the opposite response (i.e. “dimmer” if “brighter” was the first response given).

Table 2. Order of presentation of neutral density filters. The number to the left indicates the order in which the filter was presented based on subject responses.

If the subject initially reported that the scene was dimmer or glare was reduced with the colored filter as compared to the naked eye, he was asked to alternately compare brightness or glare of the scene viewed with the colored filter versus a neutral density filter. Higher density ND filters were added in a stepwise fashion until the subject reported the opposite response.

Once an “opposite response” was reached for a particular colored filter trial, the testing was repeated from the last filter condition where the same response as the initial response was given in order to verify the first endpoint. This was repeated for each of the five colored lenses for each of the four testing conditions (Brightness Outdoors, Glare Outdoors, Brightness Indoors, Glare Indoors).

**Analysis and Results**

For each subject, the ultimate data point used for analysis was the average of the transmittances of the filter combinations that bordered a response change. Since two trials
were given for each colored lens, an average was taken of the two transmittance values of each trial for a given lens and condition. This second average was then used to generate a theoretical “enhancement factor” that describes the overall effect of the lens on a particular individual’s perception of brightness or glare.

Enhancement Factor

In order to quantify the effects of the colored filters on perception of brightness and discomfort glare, a variable aptly termed the “enhancement factor” ($W_{CF}$), was calculated based on the following formulas:

$$W_{CF} = \frac{W_{NL}}{t_{CF} \times t_{ND}}$$

(Colored lens perceived as brighter than or more glaring than the naked eye)

Equation 2. Enhancement Factor calculation 1.

$$W_{CF} = \frac{W_{NL} \times t_{ND}}{t_{CF}}$$

(Colored lens perceived as dimmer than or less glaring than the naked eye)

Equation 3. Enhancement Factor Calculation

Where $W_{CF}$ indicates the apparent brightness (or glare) of the scene viewed through a colored filter, $W_{NL}$ is the brightness of the scene with no lens in place (equal to 1.0), $t_{CF}$ is the transmittance of the colored filter, and $t_{ND}$ the total transmittance of any neutral density filters in place during testing.

This formula is consistent with the experimental methodology of this study. When a colored filter made the scene appear brighter (or more glaring), neutral density filters were stacked on top of the colored filter to “neutralize” the brightness/glare effect. Thus the brightness of the scene with the naked eye could be described as the product of the colored filter transmittance, the neural density filter transmittance, and any enhancement factor of the lens.

Likewise, when a colored filter made the scene appear dimmer (or less glaring) as compared to the naked eye, neutral density filters were placed in front of the naked eye until the dimness (or glare reduction) of the colored filter matched that of the naked eye plus neutral density filters.

Thus, the enhancement factor permits a direct comparison among different filters of the relative perceptual effect on brightness and discomfort glare. For example, a $W_{CF} = 1.2$ indicates
that the colored filter enhanced brightness or discomfort glare perception by 20% as compared to the naked eye, taking into account transmittance of the colored filter.

**Data Analysis**

The experimental data were organized by test condition – Brightness Outdoors, Brightness Indoors, Discomfort Glare Outdoors, and Discomfort Glare Indoors. For each colored filter in a given condition, the probability of giving a “brighter” or “more glaring” response was plotted as a function of filter and $W_{CF}$. This was accomplished by making the assumption that, given a subject’s enhancement factor for a single condition and filter, the subject would have responded “dimmer” or “less glaring” to any possible lower value and “brighter” or “more glaring” to any possible higher value.

For each of the four testing conditions, the composite $W_{CF}$ probability function for all 30 subjects was plotted by colored filter, generating 20 data curves, each resembling a logistic function. In order to better utilize these data, we produced a best-fit logistic curve for each data set (see Appendix A), and the inflection point of the best-fit curve (50th percentile value) was used as a measure of the enhancement factor for each filter for a given condition. Theoretically, this value approximates an observer’s perception through the yellow filter. The data curves for each testing condition are displayed in Figures 7-10, and the enhancement factor for each test condition by $S/(M+L)$ ratio is displayed in Figure 11. Table 3 below displays the significance of the findings.
Figure 8. WCF for Brightness Outdoors condition. Filters labeled by S/(M+L) ratio.

Figure 9. WCF for Brightness Indoors condition. Filters labeled by S/(M+L) ratio.

Figure 10. WCF for Glare Outdoors condition. Filters labeled by S/(M+L) ratio.
Figure 11. $W_{cf}$ for Glare Indoors condition. Filters labeled by $S/(M+L)$ ratio.

Figure 12. Enhancement Factor by log $S/(M+L)$ value for all test conditions.
<table>
<thead>
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<th>Condition</th>
<th>Filter log S/(M+L)</th>
<th>95% CI</th>
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<tr>
<td>Glare Indoors</td>
<td>-2.79</td>
<td>0.56-1.40</td>
<td></td>
</tr>
<tr>
<td>Glare Indoors</td>
<td>-2.52</td>
<td>0.68-1.31</td>
<td></td>
</tr>
<tr>
<td>Glare Indoors</td>
<td>-2.28</td>
<td>0.35-1.40</td>
<td></td>
</tr>
<tr>
<td>Glare Indoors</td>
<td>-2.19</td>
<td>0.31-1.47</td>
<td></td>
</tr>
<tr>
<td>Glare Indoors</td>
<td>-2.02</td>
<td>0.69-1.56</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Significance of Findings. 95% confidence intervals not overlapping 1.0 are significant at P<0.05.

Discussion

Figure 11 clearly shows that, at high luminance levels in an outdoor setting, yellow filters can increase brightness perception up to nearly 100% for the filter with the lowest S/(M+L) value (darkest yellow filter, cutoff 475nm). For the Brightness Outdoors condition, the curve agrees quite well with the results predicted by the hypothesis of this experiment, with decreasing S/(M+L) ratio associated with an increase in the enhancement factor (perceived brightness). The BG39 (blue) filter, with an S/(M+L) value slightly higher than the naked eye, was found to have a brightness enhancement not significantly different from the naked eye using our
equation. These data for the Brightness Outdoors Condition appear to agree well with the subjective findings of Wolffsohn et al. (2000) pertaining to yellow filter brightness enhancement of an outdoor scene.

With reference to Figure 11, the enhancement factor curves for the other three test conditions (Brightness Indoors, Discomfort Glare Outdoors, and Discomfort Glare Indoors) do not match our predictions based upon an S-cone hypothesis. With the exception of the darkest yellow lens on the Glare Outdoors condition, no other filter exhibited brightness or glare enhancement that was statistically significant. However, it is intriguing to note that the curves for each of these three conditions follow the same general trend, with the high S/(M+L) value filter (blue filter) being associated with a higher enhancement factor. Although not significant, this is puzzling when considering that our hypothesis predicts that, for the two Discomfort Glare conditions, the yellow filters with lowest S/(M+L) values should generate the lowest enhancement factors (<1.0), giving a trend exactly opposite that seen with the Brightness Outdoors curve.

Noting the significance of the darkest yellow filter in the Brightness Outdoors setting, it is possible that, for the Discomfort Glare conditions, the effect of yellow filters diminishes beyond a certain S/(M+L) range; or that beyond a threshold level, brightness enhancement interferes with the perception of discomfort glare. This would predict that lighter yellow filters would reduce discomfort glare, but a heavier yellow (longer cutoff wavelength) may reverse the effect. It is also possible that, given the experimental conditions used in this study, viewed objects were not sufficiently glaring to realize the effect. Kooi and Alferdinck (2004) suggest a similar problem at lower luminance levels with regard to a pilot study that preceded their experiment on discomfort glare. Indeed, in this experiment, several subjects remarked that they did not perceive either scene as particularly glaring, especially the outdoor scene with its relatively even illumination. Other studies on discomfort glare have used isolated car headlamps in a darkened room and similar viewing targets. The possibility that viewed objects were not sufficiently glaring to elicit an appropriate response must be considered in designing any future experiments to further test our hypothesis.

With reference to the Brightness Indoors condition result in Figure 11, it is apparent that the enhancement effect of yellow lenses is very different from that of the Brightness Outdoors condition. In fact, this finding may be related to that described by Septon (1968) in his thesis work, in which he noted an increase in brightness perception with yellow light at high luminance levels, with an opposite effect at lower luminance levels. Similarly, as discussed earlier, Rabin and Wiley (1996) noted that the contrast-enhancing effect of yellow light was reduced significantly at lower luminance levels. Even more, Ripamonti et al. (2009) discovered that S-cones contribute negatively to luminance channels when a high-luminance M- and L-cone adapting background was present. Although strict attention was not paid in this
experiment to specific chromatic backgrounds and adaptation controls, the results of this study with regard to Outdoor vs. Indoor luminance levels may be related to such findings.

**S-cones and Discomfort Glare Perception**

For both indoor and outdoor conditions of discomfort glare testing in this experiment, the data do not support an outright S-cone role. This finding seemingly opposes the results of Bullough and others, which suggest an S-cone mechanism to discomfort glare perception.

It must be acknowledged that this experiment relied on the ability of participants to perceive discomfort from glare in an outdoor viewing environment where no experimental control over luminance was exercised. In addition, some participants voiced difficulty perceiving any discomfort from the viewing target (particularly in the outdoor condition); thus, these results would be best substantiated with testing at luminance levels where all subjects perceived initial discomfort glare.

**Conclusion**

Yellow lenses have previously been noted to increase brightness perception and decrease discomfort glare in a variety of experimental conditions. Most experiments addressing this phenomenon have used artificial control environments in order to test the effect, with varying results. The objective of this experiment was to determine if the S-cones play a role in the effect of yellow lenses on brightness and discomfort glare. This experiment may be the first to show that yellow lenses can cause a perceptual increase in the brightness of a real outdoor scene of up to 100%. In this outdoor viewing condition, results are consistent with a model for inhibitory input of S-cone response to a luminance channel. This model does not appear to apply to lower luminance testing conditions with a white target, suggesting that luminance or possibly background adaptation may modify S-cone luminance contribution.

With regard to an S-cone role for discomfort glare perception, the results of this experiment are inconclusive. Although not significant, mild (low-wavelength cutoff) yellow lenses trended toward a reduction in discomfort glare perception in low and high luminance test conditions, but the same trend was not noted for medium yellow lenses associated with relatively more S-cone stimulation. It is possible that the sources of discomfort glare were not sufficiently glaring to permit results uncontaminated by brightness perception, at least at lower luminance levels. Further experimentation is advised to better elucidate the impact of luminance levels and
adapting background on proposed S-cone involvement in brightness and discomfort glare perception.
References


Appendix A – Comparison of Raw and Best-Fit Data Curves for Colored Filters

Rawp = raw proportion, Predp = Best fit proportion, and filters labeled by S/(M+L) value.