Display Considerations for Night and Low-Illumination Viewing

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Abstract

An inadequately designed display viewed in the dark can easily cause dazzling glare and affect our night vision. In this paper we test a display design in which the spectral light emission is selected to reduce the impact of the display on night vision performance while at the same time ensuring good display legibility. We use long-wavelength light (red) that is easily visible to daylight vision photoreceptors (cones) but almost invisible to night vision photoreceptors (rods). We verify rod-cone separation in a psychophysical experiment, in which we measure contrast detection in the presence of a colored source of glare. In a separate user study we measure the range of display brightness settings that provide good legibility and are not distracting under low ambient lighting. Our results can serve as a guidelines for designing the displays that change their color scheme at low ambient light levels.

CR Categories: I.3.3 [Computer Graphics]: Picture/Image Generation—Display algorithms;

1 Introduction

Most digital displays are primarily designed to be used under office lighting. This is the reason why the prevalent color scheme uses black letters on a white background, which reduces the impact of ambient light reflections on the screen. In order to minimize the strain caused by frequent adaptation changes between the display and environment, the peak luminance of displays is designed to closely match the luminance of a diffuse reflective white color under normal office lighting. These steps make the displays easier to use in bright environments, but at the same time make them less usable in dark environments, in which we need to rely on our night vision. Unfortunately displays are rarely optimized for viewing under such conditions. As a result, most mobile displays can be quite unpleasant to use, if not dazzling, at night.

When a display is intended to be at the center of a viewer's attention, for example when watching a movie or playing a video game, the display brightness is usually set high, in order to extend the perceived color gamut and therefore improve image quality. For such applications, retaining good vision in the environment where the display is used is not necessary. In this paper we focus on another group of applications, in which retaining good vision outside the display is essential. Such applications may include navigation system displays used while driving, mobile phones used at night, cockpit displays, monitoring instruments, electronic book readers, and augmented telescopes. We consider the performance of a display that should be the least obtrusive when used in the dark. Such a display may need to be dim to reduce adaptation strain, disability and discomfort glare, but at the same time it should be bright enough to be legible.

The two common approaches for improving display usability in the dark are backlight dimming and the use of color schemes that reduce emitted light. Some devices that employ the first approach are equipped with a light sensor that can detect dark environments and dim the display backlight accordingly. The second approach involves changing the color scheme to negative text polarity (bright letters on dark background) so that the least amount of light is emitted from the screen and the glare or fatigue caused by the display is reduced.

In this paper we study another method of improving display usability in dark environments, which involves using a spectral light distribution that is perceived well by human daylight vision photoreceptors (cones), but has very little effect on night vision photoreceptors (rods). By employing long-wavelength light (amber to red), the display can be seen by the daylight vision mechanism, which offers sufficient resolution to read information, while the night vision mechanism is mostly unaffected by the light emitted from the display. As a result, the display has a smaller effect on the user's dark adaptation, causes less fatigue, and does not interfere with other tasks, such navigating around in dark environments. This property of the visual system has been well known since World War II, and utilized in vehicles such as submarines, whose control rooms were illuminated in red to preserve the night vision necessary for lookout or use of a periscope at night [Schratz 2000, p.44]. Red illumination is also common in civilian aviation, to illuminate instruments, charts, and the rest of the cabin area, without diminishing night vision. This was particularly necessary for celestial navigation, which was commonly used by some pilots before the widespread use of radio navigation aids. Interestingly cockpit displays for military aircrafts must not emit long-wavelengths because such wavelengths may interfere with night vision goggles [Abileah 1993].

Although the advantage of long-wavelength light at night seems to be well known, the effect has not been well quantified in the literature. This is especially true for the case in which the observed scene contains large variations in luminance levels, including a mixture of photopic (seen by cones) and scotopic (seen by rods) stimuli. This is the case when a much brighter display is used in dark environments, and so we design our experiments to mimic this situation. The purpose of this paper is to confirm and quantify the advantages of the long-wavelength color scheme at night and give guidelines for the design of a display that adapts to an ambient light level.

In Section 3 we show that displays that employ separate red, green and blue LEDs in the backlight are capable of producing desirable emission spectra for night viewing so that no other hardware modifications in the display design are necessary to implement our approach. In the first experiment (Section 4) we test how glare due to a chromatic light source affects night vision. The goal is to show that different colors cause different amount of veiling glare, and that in particular long-wavelengths light is the least prone to cause disability glare. In Section 5 we demonstrate that the measure-

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ments of the photophobic reactions to colored light indicate that long-wavelength light also causes the least amount of the discomfort glare. The study discussed in Section 6 shows that red colored letters are also more legible at low luminance levels. We further investigate the design of a display for dark environments by conducting a second experiment on the range of preferable display brightness settings (Section 7). Our results can serve as a guideline for selecting display brightness and color scheme.

2 Related work

Display ergonomics. Although ergonomic requirements for office displays have been well studied and standardized as in ISO 9241-303:2008, little research has been devoted to displays intended for night or low illumination use. In Section 6 we discuss the study of Okabayashi et al. [2006], who measured legibility of Snellen figures shown at low luminance.

Disability and discomfort glare. A display seen in the dark will always cause a certain amount of disability and discomfort glare. Disability glare is due to the light that is scattered in the eye optics and on the retina, which elevates adaptation luminance and reduces contrast by increasing the retinal luminance of the stimuli[1]. Discomfort glare is observed when a bright source of light either is distracting or evokes a dazzling effect that causes the eyes to squint or avert (sometimes referred as dazzling glare) [Vos 2003]. Vos and van den Berg [1999] proposed a comprehensive model of disability glare.

Backlight dimming. The majority of the work on dimming the display backlight is motivated by energy saving rather than improved display usability at low light. The basic idea involves compensating for the dimmer backlight with increased transparency of the LCD layer, so that the difference between the original image and the image with dimmed backlight is minimal [Chang et al. 2004]. The compensation methods may account for both temporal aspects to reduce flicker visibility [Iranli et al. 2006], and spatial aspects to reduce contours due to hard clipping [Kerofsky and Daly 2007].

Mesopic vision. Mesopic vision, in which both cones and rods are active, is an important factor in display design because displays intended to be used at low ambient light levels need to operate in the mesopic luminance range. The mesopic range starts at about 10^{-3} cd/m^2(photopic) and ends at about 5 cd/m^2, although reported ranges vary [Wyszecki and Stiles 1982, p. 406]. Interactions between cones and rods are complex and not fully understood. A good review of the work on mesopic vision can be found in [Hess et al. 1990, p. 34–37] and [Wyszecki and Stiles 1982, p. 549–552]. To quantify visual performance at scotopic light levels, a practical model for mesopic photometry has been proposed to CIE for standardization [Eloholma and Halonen 2005]. The model assumes that the mesopic luminance is a linear combination of scotopic and photopic luminance, which has been shown to well approximate the measurement data for relatively broad-band light sources (about 100 nm). The authors also note that mesopic luminance for narrow-band light sources is too complex to be modeled as a linear combination of scotopic and photopic luminance, but more complex models do not provide a better match to the data for broad-band light sources. We attempted to use their model to analyze our experimental results, but found that the range of photopic to scotopic luminance ratios described by the model is too small to apply the model on our data.

3 Display considerations

The requirements for displays viewed in bright and dark lighting are very different. Displays intended for bright lighting must reduce the effect of ambient light that is reflected from the screen. This is usually achieved by boosting display brightness or using positive polarity of the text (dark letters on bright background) [Spenkelink and Besuijen 1994]. Contrary to that, displays intended for viewing under low ambient lighting must be dark to reduce disability glare and discomfort glare, which is associated with dazzling or distraction caused by a bright source of light (a display in our case) [Vos 2003]. At the same time, such displays must be bright enough to activate cones, since the low acuity of rod vision would render the display useless at scotopic light levels. Reading text or the fine details of a map with low-resolution rod vision is very difficult and only possible with large magnifications. Overall, displays viewed in the dark must minimize the effect of disability and discomfort glare while maximizing photopic luminance for legibility.

An increasing number of LCD displays use colored (red, green and blue) light emitting diodes (LEDs) for the backlight illumination. LEDs offer several advantages over conventional cold cathode fluorescent lamp (CCFL) backlights: they result in more saturated color primaries due to their narrower spectral emission bands, can consume less power, can be built into thinner displays and can be dimmed to very low light levels, which is especially important for our application. This is a significant advantage over CCFL backlights, which can be dimmed to only 20 % of their peak brightness. To match the color primaries of the ITU-R BT.709-5 (sRGB) standard, the spectral peak of the red LEDs is selected to be within the 620–640 nm range. This property, which allows the display to emit long-wavelength narrow band light, accidentally makes displays with LED backlights ideal for our night mode scheme. This observation suggests that a nighttime display can utilize existing LED display hardware, but with only the red primary active. In fact, we employ a prototype of such a display for our following experiments.

4 Experiment 1: Disability glare

Since the display must emit photopic luminance levels to be legible, it is going to cause disability glare in dark environments. The disability glare is caused by inter-ocular light scatter, which is considered to be mostly wavelength-independent [Whitaker et al. 1993][2]. Therefore, we can expect that the wavelength effects are explained by the rod-cone sensitivity curves shown in Figure 1. For a dark adapted eye, rods can be over 100 times more sensitive than cones (as seen in the left-most pane in Figure 1). However, the cone thresholds above 610 nm are either below or very close to the rod thresholds, suggesting that rods in this wavelength range are less sensitive than cones. Therefore, a display emitting only long-wavelength light should remain legible (i.e. be seen by cones) and should reduce the undesired glare in scotopic vision (i.e. be less visible to rods).

Some studies conducted with red and blue filtered light arrive at the opposite conclusion, indicating that the spectral light composition of the source of glare has no effect on disability glare [Steen et al. 1993]. We argue that these results are valid only for the photopic

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[1] Contrast reduction is caused by the scattered light L_s, which elevates background luminance L: $\Delta L/(L+L_s) < \Delta L/L$, where ΔL is a luminance difference and $\Delta L/L$ is the contrast without scattering.

[2] van den Berg et al. [1991] report a small wavelength dependency of the inter-ocular light scatter caused by the selective transmission through the iris and the sclera. We do not consider chromatic aberration in the eye, which is very localized and does not cause disability glare.

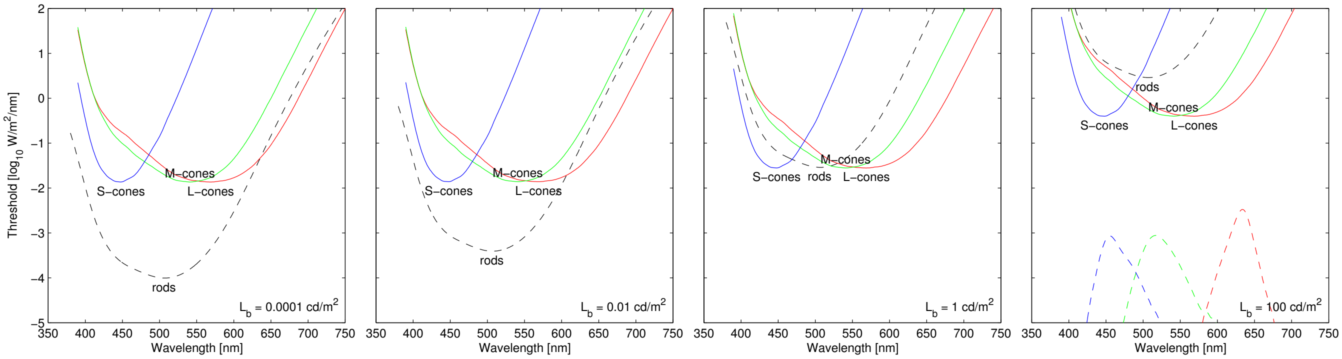

Figure 1: *Absolute thresholds for four types of photoreceptors in the human retina. Each plot corresponds to a different background luminance. Cone sensitivities are from the Stockman and Sharpe [2000] measurement and rod sensitivities are based on CIE 1951 scotopic luminosity function. Absolute thresholds are adjusted for the scotopic and photopic t.v.i. functions [Hess et al. 1990]. The rightmost plot includes also the spectral emission curves for the red, green and blue LED backlight display used in the experiments.*

luminance range, since the target used in these experiments had a mean luminance level of 23 $\mathrm{cd/m^2}$, which was too high to evoke rod response. These experiments indicated a lack of wavelength dependency on inter-ocular light scatter, but not a lack of wavelength dependency on disability glare.

Still, the rod-cone sensitivity curves (Figure 1) alone do not prove convincingly that long wavelength light reduces disability glare at scotopic light levels. Since rods and cones share the same visual pathways, scattered red light that is sensed by L-cones could potentially inhibit rod signals. To examine if spectral light composition has an effect on disability glare, we conducted a detection experiment in the presence of a colored source of glare.

Stimuli. Figure 2 shows the setup used for this experiment, which was conducted in a dark room (< 0.1 lux) with no illumination other than that described here.

The device used to create the glare was a prototype display consisting of a backlight of colored LEDs and a 23-inch 1920 × 1200 LCD panel. The display was suitable for the experiments because of its narrow-band emission spectra, shown as the dashed curves in the rightmost pane of Figure 1, and its red LEDs emitting long-wavelength light with the peak close to 640 nm. In this experiment, the image displayed on the LCD display was a uniform field of white, while the LEDs were modulated to produce the necessary colored stimuli.

The detection target was a 7×7 cm Gabor patch with a spatial frequency of 1.0 cycles per degree. The spatial frequency was selected to maximize sensitivity at scotopic light levels. The patch was displayed on a conventional 18-inch 1280×1024 LCD monitor. The brightness setting on the monitor was set to the minimum, and the Gabor patch was shown through a neutral density (ND) filter with an optical density of 3.0 D. The part of the monitor not showing the patch was covered with black matte paper. The baseline of the patch was set at the medium gray value and the amplitude of the patch was adjustable by keyboard control. All the experiments in this paper were written in Matlab using the Psychophysics Toolbox extensions [Brainard 1997].

Subjects. The subjects in this experiment were two of the authors, which was mandated by the tedious and objective nature of this experiment. The pilot study confirmed that the results for two subjects are consistent and repeatable. We did not find it necessary to include more subjects in this study since our goal was to measure the relative effect, rather than to estimate the mean detection thresholds for a larger population. Both subjects have normal or corrected-to-normal vision and normal color vision.

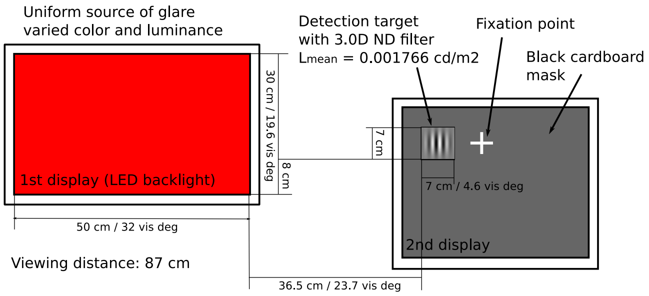

Figure 2: *Experimental setup for the Experiment 1.*

Experimental procedure. The task was to adjust the amplitude of the Gabor patch to a point where it was just barely visible (i.e. distinguishable from a uniform field). For each glare setting, the subjects performed this task twice, once from a point of maximum amplitude and once from a point of minimum amplitude. Prior to the experiment, the subjects spent approximately 5 minutes in the dark room in order to adapt to the scotopic environment. The subjects then performed the experiment with the source of glare turned off to measure the absolute detection threshold, and then again with the source of glare in each of 4 colors (red, green, blue, white) and set to each of 4 intensity levels presented in order of increasing luminance to minimize adaptation effects.

Results. Figure 3 shows the detection thresholds as a function of the scotopic and photopic luminance of the glare source. The left plot shows that the disability glare is wavelength dependent, as different colors of glare result in different thresholds at the same photopic luminance level. The long-wavelength light (red) results in the lowest detection threshold for a given photopic luminance. Therefore, a display that emits long-wavelength red will cause the least scotopic glare compared to other colors at the same photopic luminance level. Comparison of both plots shows that the detection thresholds across all colors are more strongly correlated with scotopic than photopic luminance of the glare. Therefore, neural interactions between rod and cone signals have only minimal effect on

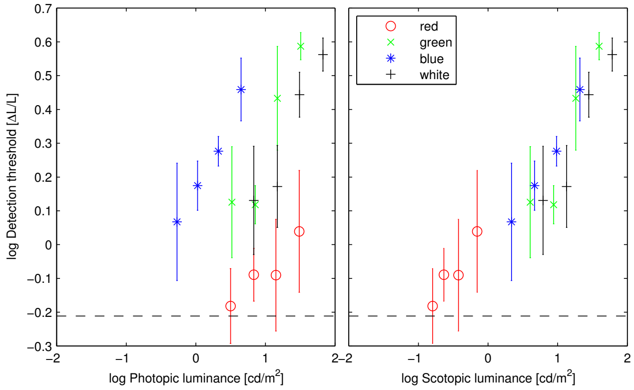

Figure 3: *Detection thresholds in the presence of glare. Colors indicate different colors (spectral composition) of the glare sources and the x-axis represents its photopic (left) and scotopic (right) luminance (each luminance measure computed using different luminosity efficiency function). The dashed line represents the absolute detection threshold without a glare source.*

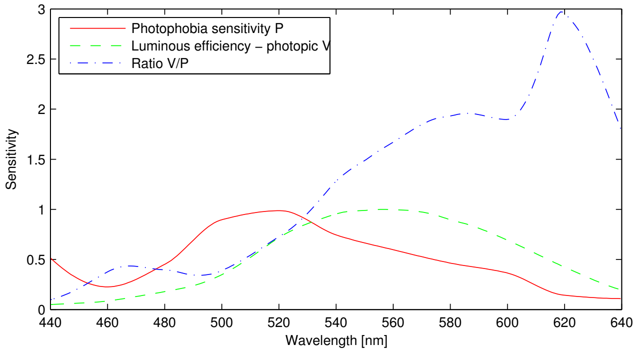

Figure 4: *Photophobia sensitivity compared with the photopic luminous efficiency function. Wavelengths close to 620 nm evoke the least discomfort glare when adjusted for their photopic luminance level. Photophobia sensitivity data from [Stringham et al. 2003].*

the disability glare in the scotopic luminance range. In the context of display design it means that the displays intended for viewing in the dark should minimize scotopic luminance to reduce glare while maximizing photopic luminance to improve legibility.

5 Discomfort glare

Our first experiment confirmed that long-wavelength red induces the least amount of scotopic disability glare. But does it also reduce discomfort glare? The subjective measures of discomfort glare, based on the 9-point Boer glare rating scale (from unnoticeable to unbearable), are usually very noisy and are not good at describing the wavelength dependency of the discomfort glare [Fekete et al. 2006]. Therefore, we refer to the data from more accurate objective measurements based on electromyography, in which muscular activity associated with squinting is tested. Stringham et al. [2003] measured the action spectrum of photophobia, which is a similar condition to dazzling glare. In Figure 4 we plot their results represented as the photophobia sensitivity P together with the photopic luminous efficiency function V and the ratio V/P. The ratio peaks at about 620 nm, suggesting that the long wavelength red produces the least amount of discomfort glare at the same luminance level. This result must, however, be interpreted with care, since the data for narrow band stimuli, used to measure the action spectrum of photophobia, does not need to be valid for broad-band glare sources.

6 Recognition rate

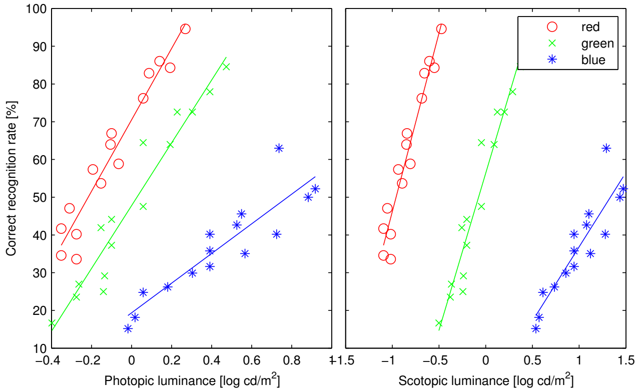

Figure 5: *Character recognition rate for color Snellen figures shown on a CRT monitor. Red color gives the highest recognition rate at the same luminance level as green and blue colors. Data from [Okabayashi et al. 2006].*

Okabayashi et al. [2006] measured the legibility of Snellen figures shown on a CRT display at low luminance levels (0.3–10 $\mathrm{cd/m^2}$) and under low ambient light (2 lux). In Figure 5 we plot their data showing character recognition rate for the three primary colors of the display. In addition to photopic luminance, we found the corresponding scotopic luminance values assuming typical CRT phosphor emission spectra. Their results indicate that red figures had a higher rate of correct responses than green and blue figures, even when shown at the same photopic luminance level. Their results bring forward another argument showing that long-wavelength light is more suitable for displaying information at low luminance levels.

7 Experiment 2: Preferred brightness

After demonstrating that long-wavelength light is the least obtrusive for the night vision, the next question to answer is that of how bright the display intended for viewing in the dark should be. We measured the preferred brightness (backlight intensity) in the following experiment.

Stimuli. This experiment used one display, which is the same prototype display used for the previous experiment. A monochrome full-screen image was displayed on the LCD panel, while subjects used keyboard controls to adjust the intensity of the LED backlight to a level they found preferable. The backlight could brighten or dim the display from $\approx 2000\,\mathrm{cd/m^2}$to $\approx 0.5\,\mathrm{cd/m^2}$. Two images were used for this experiment, both in their native black-on-white polarity and also in negative white-on-black polarity, as shown in Figure 6.

Subjects. Nine subjects (5 male, 4 female, ranging in age from 19 to approximately 45) were used for this experiment. Each had normal or corrected-to-normal vision and normal color vision.

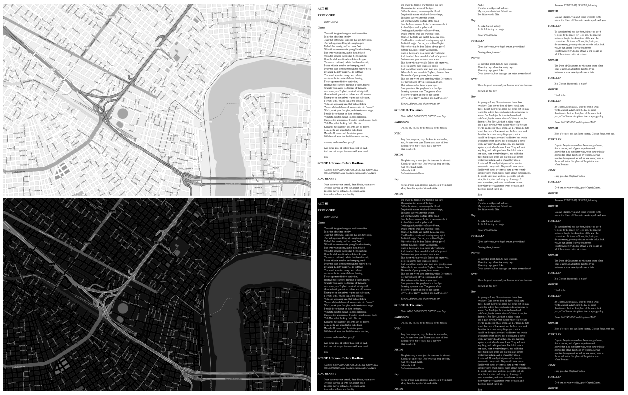

Figure 6: *The map and text images (and reverse polarities) used in Experiment 2.*

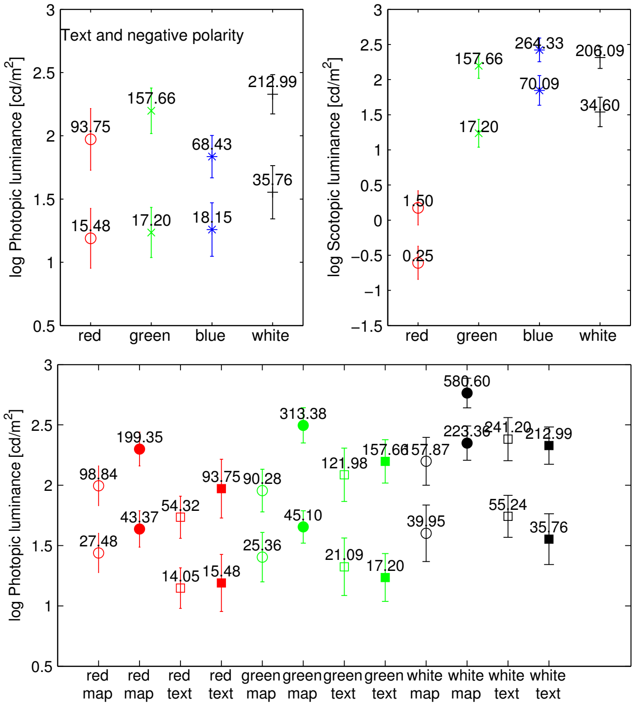

Figure 7: *Results of Experiment 2 – preferred brightness range. For easier comparison the top 2 graphs show the photopic and scotopic luminance settings only for the negative polarity text conditions. The bottom graph shows the complete results in photopic luminance units. The empty markers represent positive and the filled markers negative polarity. The upper and lower markers denote the just too bright and just too dark settings respectively. The numbers represent either photopic or scotopic peak display luminance in cd/m^2. Error bars denote the standard error of the mean.*

Experimental procedure. Each subject was shown each of the 4 images in Figure 6 in random order, with the backlight set to each of 4 colors (red, green, blue, and white) in random order. For each of those 16 conditions, the subject was asked to set the backlight intensity 3 times: first, to their most preferred luminance; second, to a luminance just too dark; third, to a luminance just too bright and thus uncomfortable to read. The first of each set of three preferred brightness settings was omitted from the results as the range provided by the light and dark settings provided a more reliable and less noisy measurement. The range generally contained the initial setting, though the location of that setting within the range varied considerably.

Results. Figure 7 shows the luminance range from "just too dark" to "just too bright" with respect to color, content (map or text) and polarity (positive: black on white or negative: white on black). The peak luminance levels are all in the photopic luminance range ($> 5\,\mathrm{cd/m^2}$) and relatively high for the dark environment. This suggests that the lower limit for dimming the display can be the transition point between photopic and mesopic vision. Despite large variations, typical for preference experiments, all factors showed statistical significance in the ANOVA test ($\log(L_{photopic})$ for color × map/text × polarity; color: $F(3,159) = 7.58$, $p < 0.01$; map/text: $F(1,159) = 4.4$; $p < 0.05$; polarity: $F(1,159) = 4.81$; $p < 0.05$). Moderate photopic luminance variations across colors may suggest that the brightness adjustments are mostly determined by photopic luminance. The luminance of the red map or red text was adjusted so that the emitted photopic luminance was comparable with other colors, while the scotopic luminance was much lower. Maps were adjusted to be brighter than text. The probable reason for this is that reading a map involves distinguishing between several luminance levels, and this task can be better performed by the more sensitive photopic vision. Positive polarity images were set to lower luminance than the negative polarity images (except white text) but the difference between both polarities was surprisingly small.

The range of preferred display luminance found in this experiment can be used as a guideline for selecting the brightness of a display used in dark environments. The lower end of that range should be used for displays that should interfere the least with night vision, while the upper end should be used for entertainment displays.

8 Discussion

In our experiments, we could test only the three primary colors of our prototype display. However, our simulation, based on the rod-cone sensitivity curves, shows that amber primaries with the peak close to 610 nm can also display colors that do not disrupt scotopic vision. When paired with the red primary, the amber primary forms the color gamut that maximizes photopic and minimizes scotopic luminance thus reducing disability glare. The fourth amber primary is often considered in the display design because it can extend the gamut of distinguishable colors and is more power-efficient than red in terms of luminance output. Our results indicate that such a 4-primary display would be beneficial under low ambient light. Such a display can adapt to ambient light by switching between 2-primary dark (red, amber) and 4-primary bright (red, green, blue, amber) modes, where the dark mode minimizes glare in the scotopic vision range.

In this study we did not investigate how viewing a colored display affects adaptation state, that is, whether a quick glance at the navigation display can temporarily impair scotopic vision. However, assuming that the adaptation is determined by scotopic luminance when detecting scotopic targets, we can speculate also that in this regard a long-wavelength display should have the least impact on visual performance.

Although we see many benefits of a display design that preserves rod vision, it may not be an essential requirement for some applications. For example, the study of Flannagan[2007] shows that the rods play little role in detecting pedestrians in a night driving scenario. However, the study does not preclude that the rod vision may influence other tasks, such as enhancing the saliency of emergency signals in the periphery.

9 Conclusions

In this paper we showed that a display that emits long-wavelength light (red to amber) offers several advantages over green and blue displays that are used under low ambient light. A red-colored display affects visual performance due to disability glare the least as it is the least likely to cause dazzling or eye aversion, even if emitting light at high photopic luminance levels. Other studies indicate that red colored letters are the most legible at low luminance levels. Our second experiment showed that a display in dark environments must emit at least low photopic luminance levels ($\approx 20\,\mathrm{cd/m^2}$) to be comfortable to read, and higher luminance ($\approx 40\,\mathrm{cd/m^2}$) if displayed content, such as maps, requires distinguishing between several brightness levels.

Acknowledgments

We wish to thank the anonymous reviewers for providing valuable comments, which we used to extend the discussion of the previous work. This work was supported by Dolby under the Dolby Research Chair in Computer Science at the University of British Columbia. We would also like to thank Dolby Canada for use of their facilities in conducting the studies.

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