Display Considerations for Improved Night Vision Performance

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Abstract

Most displays viewed in dark environments can easily cause dazzling glare and affect a viewer's dark adaptation state (night vision). In previous work we showed that legibility could be improved and dark adaptation preserved in low-light environments by using a display design with a specially selected spectral light emission. We used long-wavelength light (red) that is easily visible to daylight vision photoreceptors (cones) but almost invisible to night vision photoreceptors (rods). In this paper we conduct an experiment in which we show that negative polarity (bright text on a dark background) produces better performance in a legibility task than does positive polarity (dark text on a bright background). Our results can serve as a guidelines for designing displays that change their color scheme at low ambient light levels.

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 our previous work [8], we conducted an experiment to show that glare sources of different colors produced differing levels of disability glare which inhibits legibility in low-light environments, and found in particular that long-wavelength (red) light is the least prone to cause such glare. We then conducted a second experiment to determine subjects' preferred brightness settings for different colors of text and observed that subjects preferred settings that resulted in similar photopic luminance levels across colors, but lower scotopic luminance levels for red. In this paper we conduct an experiment to quantify the performance improvement of negative polarity over positive polarity on a legibility task. Together with previous work showing the advantages of long-wavelength (red) light for viewing in low-light environments, our results can serve as a guideline for designing displays for such environments.

Related work

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) [12]. Vos and van den Berg [11] 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 [2]. The compensation methods may account for both temporal aspects to reduce flicker visibility [6], and spatial aspects to reduce contours due to hard clipping [7].

[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.

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 $10^{-3}\,\mathrm{cd/m^2}$(photopic) and ends at about $5\,\mathrm{cd/m^2}$, although reported ranges vary [13, 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 [5, p. 34–37] and [13, p. 549–552]. To quantify visual performance at scotopic light levels, a practical model for mesopic photometry has been proposed to CIE for standardization [3]. 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.

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) [9]. 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) [12]. 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 night-time 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.

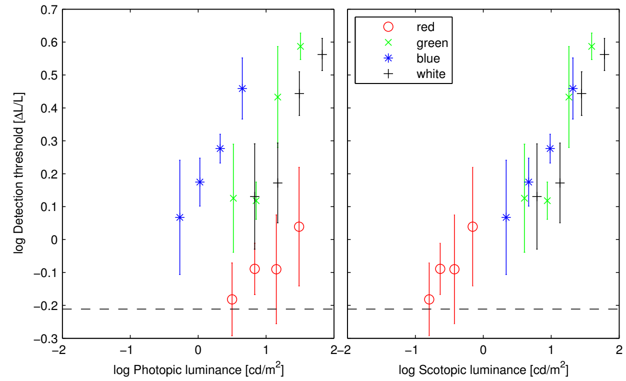


Figure 1. Detection thresholds in the presence of glare. Colors indicate different colors (spectral composition) of the glare sources and the x-axis represents its photopic (left) and scotopic (right) luminance (each luminance measure computed using different luminosity efficiency function). The dashed line represents the absolute detection threshold without a glare source.

Legibility in environments with colored glare

In this section we review our previous results [8] which show the varying levels of legibility that result from glare sources of varying color.

Disability glare. In this experiment, subjects adjusted the amplitude of a Gabor patch to a level where it was just barely visible, in the presence (or absence) of a colored glare source. Figure 1 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 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.

Preferred brightness. In this experiment, subjects viewed map and text images while adjusting the intensity to their preferred levels, and then to levels they deemed to be "just too dark" and then "just too bright" and uncomfortable to read. Figure 2 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

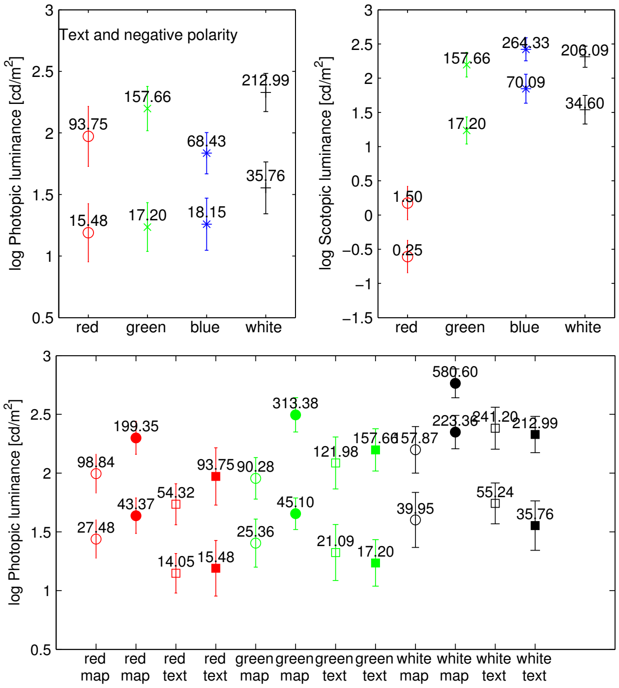


Figure 2. Preferred brightness of different colors. For easier comparison the top 2 graphs show the photopic and scotopic luminance settings only for the negative polarity text conditions. The bottom graph shows the complete results in photopic luminance units. The empty markers represent positive and 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.

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.

Reading performance experiment

Stimuli. This experiment used one display, a prototype high dynamic range display consisting of a backlight of tri-color LEDs and a 23-inch 1920×1200 LCD panel. The bands of the emission spectra of the three colors were quite narrow, and the red LEDs emitted long-wavelength light with the peak close to 640 nm. A series of images (monochrome LCD images with color produced only by the LED backlight) was presented to the subjects, where each image was composed of four smaller images arranged in a 2×2 pattern as shown in Figure 3. Three of the four images were identical, but the fourth contained an additional word “not” in the left column, which is highlighted in the figure. The fourth would appear in any of the four quadrants at random. Both positive polarity and negative polarity images were used. The experiment was conducted in a dark room (< 0.1 lux) with no illumination other than that described here.

For each image displayed, the intensity of the LED backlight was set to the mean preferred value for that image, which was determined by the results of the experiment described in the previous section. In that way, comparisons between colors were made between the optimal values for each of those colors.

Subjects. Five subjects (4 male, 1 female, ranging in age from approximately 25 to approximately 45) participated in this experiment. Each had normal or corrected-to-normal vision and normal color vision.

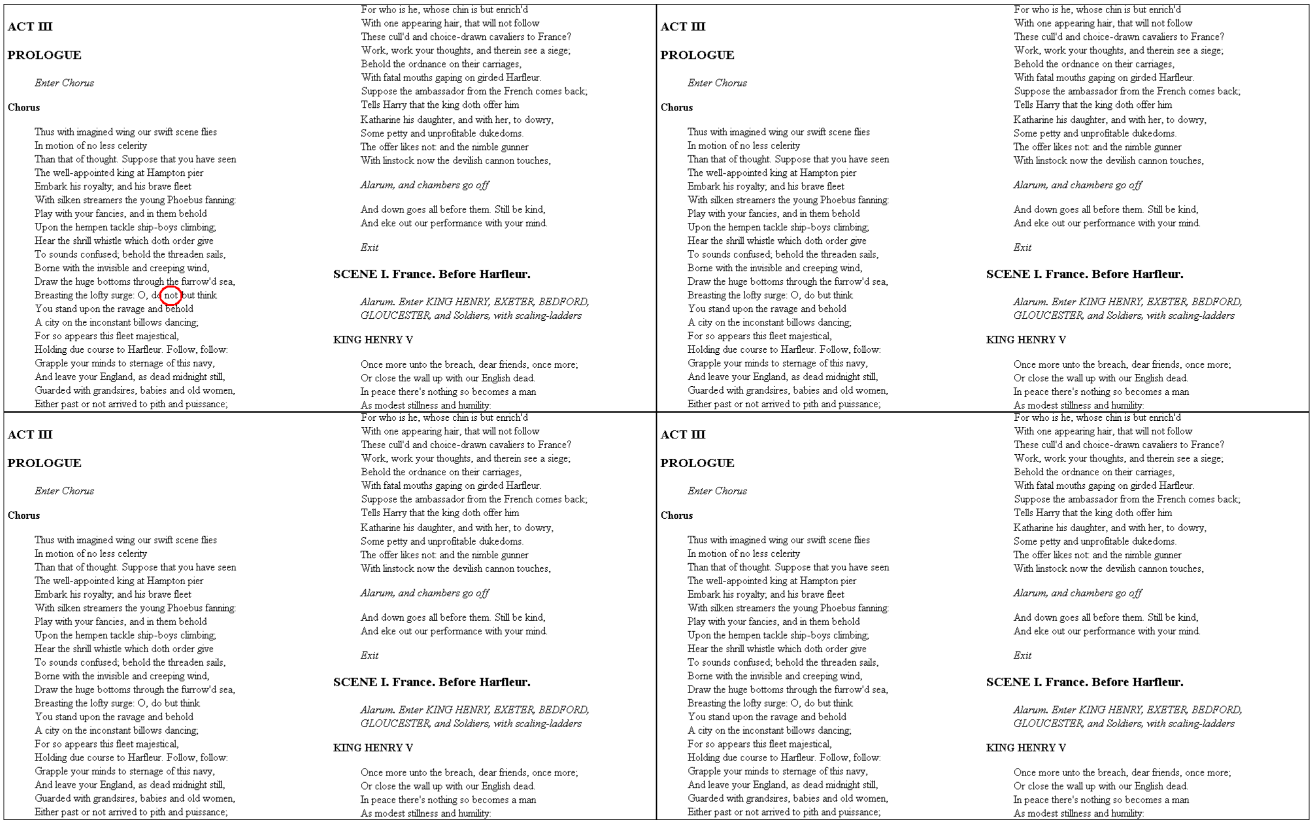
Experimental procedure. Each subject was shown 30 images, half of which were positive polarity and half were negative. For each polarity each subject was shown images with red, green, and white backlight. For each condition, each subject was shown 5 images. The orderings of polarity and color were randomized.

At the beginning of the task, subjects were familiarized with the images and the placement of the word “not”. Subjects were told that this was a timed task, and that they were to locate the quadrant and press the appropriate button as quickly as possible for each image. For ease of use, the buttons used were F1, F12, left-Ctrl, and right-Ctrl. The experiment was written in Matlab using the Psychophysics Toolbox extensions [1].

Results. The ANOVA test on the response time for color × polarity indicated no statistically significant difference for displays of different color ($F(2,329) = 0.9$, $p = 0.4$), but a statistically significant difference for different color polarities ($F(1,329) = 8.77$, $p < 0.01$). This result did not indicate any disadvantage of using a colored display as compared to a white display in a text reading task. The response time for negative polarity (white on black, 2.71 s average response) was on average 0.37 second shorter than for positive polarity (3.08 s). This shows that using negative polarity color scheme for dark environments can improve text legibility.

Conclusion

In this paper we conducted experiments which quantified the performance improvements that can result from the use of negative polarity images rather than positive polarity images on displays viewed in very dark environments. These results coupled with those of previous work showing the advantages of red light can be used to guide the design of displays which provide high levels of legibility in low-light environments and maintain viewers’ levels of dark adaptation.


ACT III

PROLOGUE

Enter Chorus

Chorus

Thus with imagined wing our swift scene flies
In motion of no less celerity
Than that of thought. Suppose that you have seen
The well-appointed king at Hampton pier
Embark his royalty; and his brave fleet
With silken streamers the young Phoebus fanning:
Play with your fancies, and in them behold
Upon the hempen tackle ship-boys climbing;
Hear the shrill whistle which doth order give
To sounds confused; behold the threaden sails,
Borne with the invisible and creeping wind,
Draw the huge bottoms through the furrow'd sea,
Breasting the lofty surge: O, do not but think
You stand upon the ravage and behold
A city on the inconstant billows dancing;
For so appears this fleet majestical,
Holding due course to Harfleur. Follow, follow:
Grapple your minds to sternage of this navy,
And leave your England, as dead midnight still,
Guarded with grandsires, babies and old women,
Either past or not arrived to pith and puissance;
For who is he, whose chin is but enrich'd
With one appearing hair, that will not follow
These cull'd and choice-drawn cavaliers to France?
Work, work your thoughts, and therein see a siege;
Behold the ordnance on their carriages,
With fatal mouths gaping on girded Harfleur.
Suppose the ambassador from the French comes back;
Tells Harry that the king doth offer him
Katharine his daughter, and with her, to dowry,
Some petty and unprofitable dukedoms.
The offer likes not: and the nimble gunner
With linstock now the devilish cannon touches,

Alarum, and chambers go off

And down goes all before them. Still be kind,
And eke out our performance with your mind.

Exit

SCENE I. France. Before Harfleur.

Alarum. Enter KING HENRY, EXETER, BEDFORD, GLOUCESTER, and Soldiers, with scaling-ladders

KING HENRY V

Once more unto the breach, dear friends, once more;
Or close the wall up with our English dead.
In peace there's nothing so becomes a man
As modest stillness and humility:

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Figure 3. *The text image used in Experiment 3.*

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