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Impacts of Ambient Brightness Control and Short-Wavelength Spectral Content on Display Screen User Responses

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Abstract

The computer display screen is an increasingly important and ubiquitous part of the modern visual environment. The photometric and colorimetric characteristics of computer display screens can have important consequences for the performance, visual fatigue and visual comfort of users. In the present study, two aspects of display screen performance were evaluated in terms of objective and subjective outcomes: an ambient brightness control designed to adjust the display luminance to the ambient lighting conditions in the space, and reduced short-wavelength spectral content designed to minimize visual discomfort and fatigue associated with this spectral region. Participants performed a visual task under different combinations of lighting, screen luminance and spectral content; in addition to task performance, flicker fusion frequency, galvanic skin response and subjective ratings of fatigue, preference and visual comfort were assessed. The results indicate that the tested visual display functions yielded several measurable improvements compared to a display without these functions.

Keywords: visual performance, visual displays, human factors, visual comfort

INTRODUCTION

Computer display screens are important and ubiquitous parts of the modern built environment. Over the past several decades, these devices have increased in their brightness and consequently in the amount of short-wavelength ("blue") spectral output they produce. These developments can have important implications for visual ergonomics in spaces where computers are used, and which are briefly discussed in this section.

Published guidelines for lighting in workplaces (Rea, 2000; IES, 2022) include luminance ratios between the visual tasks performed by occupants and nearby surfaces in these spaces, in order to maintain visual comfort and reduce fatigue. Although these luminance ratios predate the widespread use of computers in the workplace and computer display screens are self-luminous, it is nonetheless important for the brightness of display screens to be in harmony with the lighting in the visual environment (IES, 2022).

Several studies have been undertaken to investigate the relationship between the ambient illumination in a space and the brightness or luminance of visual display screens to maintain visual comfort and minimize visual fatigue. Boff and Lincoln (1988) reported that the optimal luminance for a visual display screen increased as the luminance of the area surrounding the display increased, a finding that was confirmed by Zhou et al. (2021). Merbah et al. (2020) investigated posture while using a display varying in luminance under different ambient light levels and found that under a high ambient illuminance and with a low-luminance display, posture was worse than other conditions when the screen brightness and ambient illuminance were balanced.

These findings suggest that a function whereby a visual display screen adjusts its luminance based on the light level in the ambient light level could be beneficial at improving visual comfort and reducing visual fatigue for the display user. Laboratory measurements of a commercially available display

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screen with such a function (Dell Ultrasharp U2724DE) under different ambient illuminance levels were made to understand how the function operated. It was found that the screen luminance (of a white background) was 35 cd/m^2 when the ambient illuminance was 10 lux (a low level that might be used at home or in a computer drafting environment), and was 165 cd/m2 when the ambient illuminance was 570 lux (a level typical of office lighting [Rea, 2000; IES, 2022]).

Hou et al. (2021) carried out investigations of visual fatigue under various combinations of ambient illumination (1 to 2700 lux) and while using a display screen that varied in luminance from 1 to 1000 cd/m2. From their results they developed a mathematical model by which it was possible to predict the improvement in visual fatigue scores based on subjective ratings of eye fatigue symptoms as devised by Hayes et al. (2007). For a screen that behaved as described in the previous paragraph, the improvement in visual fatigue scores was 7%-17% compared to a display screen that would maintain a high luminance (e.g., 165 cd/m^2) at the lower ambient illuminance, or a low luminance (e.g., 35 cd/m^2) at the higher ambient illuminance.

The role of short-wavelength spectral content in visual comfort has been investigated in several contexts (Bullough, 2022). Bright lights, such as automotive headlights, which contain a higher proportion of spectral output near 440 nm (the peak sensitivity for short-wavelength cone photoreceptors), result in greater visual discomfort than lights with lower spectral output at this wavelength, even when matched for luminous intensity (Bullough, 2009). A visual display with greater spectral content in this region will have increased brightness appearance (Rea et al., 2011) and this could in turn contribute to increased discomfort glare. One way to quantify the relative amount of short-wavelength spectral output from a visual display screen is by determining the percentage of radiant power between 400 and 500 nm that falls between 415 and 455 nm (Ji et al., 2022), defined here as the blue-light percentage.

Empirical investigations have been conducted to estimate the impacts of shifting spectral energy from a visual display screen outside the 415-455 nm range. Chen et al. (2017) asked study participants to perform a searching task on displays with peak short-wavelength spectral content centered at 450 nm and at 462 nm, and matched for luminance. Users rated the latter display, with shifted short-wavelength output, as resulting in lower fatigue by 16%, and increased visual comfort by 9%. A similar comparison was carried out (Shi et al., 2021) in which users viewed video clips on a display screen having peak short-wavelength spectral content centered at 447 nm and one with the short-wavelength peak shifted to at 458 nm. The shifted display resulted in approximately 20% lower visual fatigue scores.

Together, the findings from the published studies reviewed here suggest that measurable reductions in visual fatigue and improvements in visual comfort can be achieved while using a display screen equipped with an ambient brightness control function and with its spectral content shifted away from the 415-455 nm range. In order to validate these findings and understand if and how these functions might interact with one another, a human factors laboratory study was conducted.

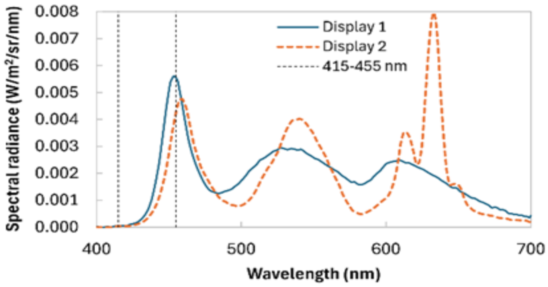

Figure 1. Spectral radiance distributions of Display 1 and Display 2 with a white background set to a luminance of 165 cd/m^2. Vertical dotted lines show the range between 415-455 nm.

MATERIAL AND METHOD

Two computer workstations were set up in the Human Factors Laboratory at the Light and Health Research Center, Icahn School of Medicine at Mount Sinai. One workstation used a visual display screen (Dell Ultrasharp U2721DE, denoted Display 1) without an ambient brightness control function and with a short-wavelength spectral component having a peak wavelength of 453 nm. The percentage of radiant power between 400-500 nm that fell between 415-455 nm for Display 1 (the blue-light percentage) was 39.1%. The other workstation used a visual display screen (Dell Ultrasharp U2724DE, denoted Display 2) equipped with an ambient brightness control and having a short-wavelength spectral component shifted to 459 nm. The blue-light percentage for Display 2 was 29.3%. Figure 1 shows the spectral radiance distribution of each display when the luminance of each (with a white background) was 165 cd/m^2.

General illumination in the test laboratory was provided by ceiling-mounted, 60 cm square overhead LED luminaires with a correlated color temperature (CCT) of 4000 K, typical of commercial workplace lighting. When the general illumination was switched on it provided a horizontal illuminance of 570 lux on the desktop at each workstation, denoted the high ambient lighting condition. The low ambient lighting condition was created by switching the overhead lighting off and switching on a portable table lamp at each workstation that provided a horizontal illuminance of 10 lux on the desktop. Figure 2 shows a workstation under the high ambient illuminance and with the display luminance adjusted to 35 cd/m^2 and a workstation under the low ambient illuminance and with the display luminance set to 165 cd/m^2.

As described in the Introduction, Display 2 had an ambient brightness control function that adjusted the screen luminance (with a white background) to 165 cd/m^2 under the high ambient lighting condition and to 35 cd/m^2 under the low ambient lighting condition. The two ambient light levels (570 lux and 10 lux) and two display luminances (165 cd/m^2 and 35 cd/m^2) were used in each combination with Display 2 to assess the impacts of ambient brightness control under each ambient light level, while holding the relative short-wavelength spectral output constant. To assess the impacts of the short-wavelength spectral output, Display 1 and Display 2 were used under the same ambient light level (10 lux) and with the same screen luminance (165 cd/m^2). To assess the combined impacts of ambient brightness control and short-wavelength spectral output, Display 1 under the low ambient light level and with a screen luminance of 165 cd/m^2 was compared to Display 2 under the low ambient level but with a screen luminance of 35 cd/m^2. In all there were five experimental conditions:

- Ambient illuminance 570 lux, display luminance 165 cd/m^2, blue-light percentage 29.3%.
- Ambient illuminance 570 lux, display luminance 35 cd/m^2, blue-light percentage 29.3%.
- Ambient illuminance 10 lux, display luminance 165 cd/m^2, blue-light percentage 29.3%.
- Ambient illuminance 10 lux, display luminance 35 cd/m^2, blue-light percentage 29.3%.
- Ambient illuminance 10 lux, display luminance 165 cd/m^2, blue-light percentage 39.1%.

Figure 2. Workstations under high (left) and low (right) ambient light levels.

Ten subjects (4 male/6 female, ages 19-58 years, mean 35, s.d. 15) completed the experiment. After signing an informed consent form approved by the Mount Sinai Institutional Review Board, subjects entered the laboratory and sat at a workstation with each display connected to a laptop computer (Lenovo, ThinkPad) and corresponding to one of the experimental conditions listed above. Conditions were presented in randomized order for each subject. Subjects were fitted with electrodes on two fingers of their left hand to measure galvanic skin response (GSR; Neulog NUL-217) and performed a numerical verification task (NVT; Rea, 1981) consisting of screens each containing two matching columns of 20 five-digit numbers (developed in Microsoft Excel and shown in Figure 2). Each digit in the right column had a 3% chance of mismatching the corresponding digit in the left column; subjects were asked to click on the numbers with a mismatched digit and to complete as many screens as quickly and accurately as possible for a duration of 20 minutes. GSR was recorded during the last minute of their trial for each condition.

Following the completion of the NVT, subjects also responded with their level of agreement (-2: totally disagree, -1: slightly disagree, 0: neither agree nor disagree, +1: slightly agree, +2: totally agree) to several statements related to visual fatigue (My eyes feel dry/are aching/are tired/are irritated), visual comfort (I am visually comfortable), and preference (I like this combination of lighting and screen brightness). Scores for the visual fatigue questions were averaged to obtain a visual fatigue score; visual comfort and preference scores were based on the responses to the comfort and preference statements. Subjects also performed a flicker fusion test by viewing an LED source connected to a waveform generator (Agilent, 33220A) that switched the LED on and off with a 50% duty cycle, beginning at a frequency of 10 Hz, so that it was obviously flickering. An experimenter increased the flicker frequency until the subject reported that it no longer appeared to be flickering and this frequency was recorded. GSR conductance (in μS) during the last minute of the NVT, speed of performing the NVT, and flicker fusion frequency (in Hz) were used as physiological/psychophysical measures of visual fatigue (Lin *et al.*, 2008; Kim *et al.*, 2013; Lin *et al.*, 2017). After completing all five conditions, subjects received a $50 gift card. Experimental sessions took about 120 minutes to complete for each subject.

RESULT AND DISCUSSION

The results were analyzed by comparing each outcome under two combinations of ambient light level, display luminance and blue-light percentage, depending upon which independent variable (screen function) was being evaluated. Paired Student's t-tests (McGuigan, 1990) were utilized with a criterion probability (p) for rejecting the null hypothesis of 0.05.

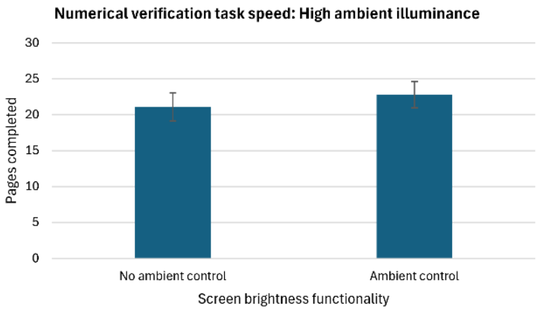

Figure 3. NVT speed under the high ambient light level without (display luminance 35 cd/m^2) and with (display luminance 165 cd/m^2) ambient brightness control.

Under the high ambient light level (570 lux), there were several statistically significant differences between the display luminances of 165 cd/m^2 and 35 cd/m^2. NVT speed (the number of screens completed) was 8% faster (t_{11}=5.87, p=0.0001; Figure 3), flicker fusion frequency (t_{11}=5.00, p=0.0004; Figure 4) was 7% higher, and visual comfort agreement scores were 43% higher (t_{11}=5.44, p=0.0002; Figure 5) for the visual display using ambient brightness control (with a luminance of 165 cd/m^2) compared to the display not using it (and with a luminance of 35 cd/m^2). Neither the GSR conductance, visual fatigue score, nor the preference score differed reliably (p>0.05) between the display luminances at the high ambient light level.

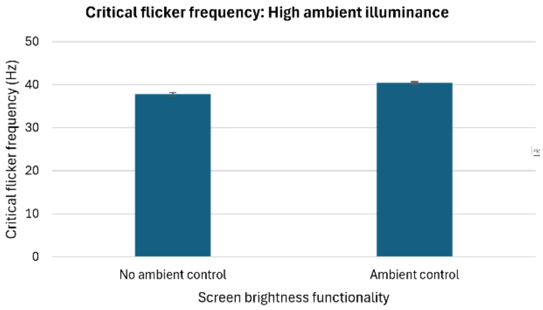

Figure 4. Flicker fusion frequency under the high ambient light level without (display luminance 35 cd/m^2) and with (display luminance 165 cd/m^2) ambient brightness control.

Under the low ambient light level (10 lux), there was a statistically significant difference between the display luminances of 165 cd/m^2 and 35 cd/m^2 in terms of the visual comfort score. The visual comfort score was 18% higher (t_{11}=2.60, p=0.025; Figure 6) for the visual display using ambient brightness control (with a luminance of 35 cd/m^2), compared to the display not using it (and with a luminance of 165 cd/m^2). Neither NVT speed, flicker fusion frequency, GSR conductance, visual fatigue score, nor the preference score differed reliably (p>0.05) between the display luminances at the low ambient light level.

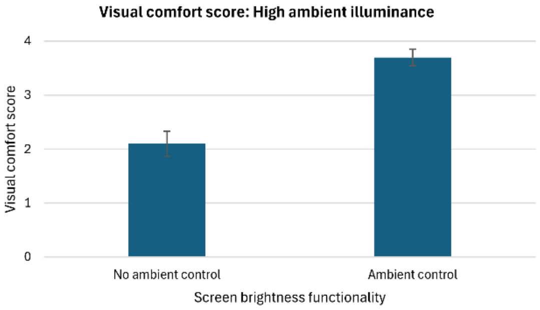

Figure 5. Visual comfort score under the high ambient light level without (display luminance 35 cd/m^2) and with (display luminance 165 cd/m^2) ambient brightness control.

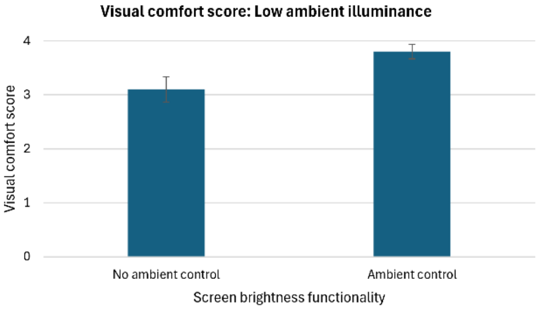

Figure 6. Visual comfort score under the low ambient light level without (display luminance 165 cd/m^2) and with (display luminance 35 cd/m^2) ambient brightness control.

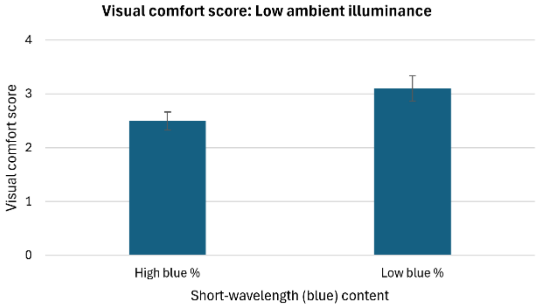

Figure 7. Visual comfort score under the low ambient light level for each blue-light percentage value.

The effects of short-wavelength spectral output were only assessed for the low ambient light level (10 lux). At this light level, there was a statistically significant difference between the display screens with lower (29.3%) and higher (39.1%) blue-light percentages in terms of visual comfort score. The comfort score was 19% higher for the visual display with the lower blue-light percentage (t_{11}=2.62, p=0.024; Figure 7) compared to the display with the higher blue-light percentage. Neither NVT speed, flicker fusion frequency, GSR conductance, visual fatigue score, nor the preference score differed reliably (p>0.05) between the two blue-light percentages at the low ambient light level.

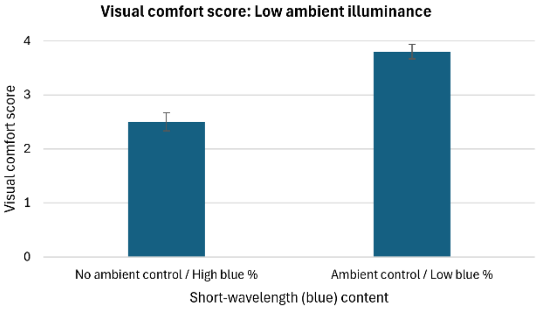

Figure 8. Visual comfort score under the low ambient light level without ambient brightness control (display luminance 165 cd/m^2) and with a higher blue-light percentage, versus the score with ambient brightness control (display luminance 35 cd/m^2) and a lower blue-light percentage.

The combined effects of ambient screen brightness control and short-wavelength spectral output were only assessed for the low ambient light level (10 lux). There was a statistically significant difference between the display screen with a luminance of 35 cd/m^2 and with a blue-light percentage of 29.3%, and the display screen with a luminance of 165 cd/m^2 and with a blue-light percentage of 39.1% in terms of the visual discomfort score (t_{11}=5.52, p=0.0002; Figure 8). The visual comfort score with the display with the higher luminance and lower blue-light percentage was 34% higher than for the display with the lower luminance and higher blue-light percentage.

IMPACT OF ACTIVITIES

The results identified in this study can be of use to those planning the lighting and visual display functionality of comuter users to ensure visual comfort and minimize visual fatigue of workers.

CONCLUSION

Together, the results from the present study (Figures 3 through 8) suggest that there are visual benefits to using a visual display screen equipped with ambient brightness control and having reduced short-wavelength spectral output between 415-455 nm.

Based on these findings, the following preliminary conclusions can be drawn about the impacts of these functions on visual fatigue and visual comfort:

Ambient Brightness Control

- At a high ambient light level (570 lux), an ambient brightness control function resulting in a display screen luminance of 165 cd/m^2 yielded a visual task (NVT) performance speed that was 8% faster, and a flicker fusion frequency that was 7% higher, than a display screen without this function and producing a luminance of 35 cd/m^2. Both of these outcomes are consistent with lower visual fatigue for the ambient brightness control function.
- At a high ambient light level (570 lux), an ambient brightness control function resulting in a display screen luminance of 165 cd/m^2 yielded a visual comfort score that was 43% higher than a display screen without this function and producing a luminance of 35 cd/m^2.
- At a low ambient light level (10 lux), an ambient brightness control function resulting in a display screen luminance of 35 cd/m^2 yielded a visual comfort score that was 18% higher than a display screen without this function and producing a luminance of 165 cd/m^2.

Short-Wavelength Spectral Output

- At a low ambient light level (10 lux), a visual display screen with reduced short-wavelength spectral output (having a blue-light percentage of 29.3%) yielded a visual comfort score that was 19% higher than a display screen with greater short-wavelength spectral output (having a blue-light percentage of 39.1%).

Combination of Ambient Brightness and Short-Wavelength Spectral Output Control

- At a low ambient light level (10 lux), a visual display screen with an ambient brightness control function and with reduced short-wavelength spectral output (having a luminance of 35 cd/m^2 and a blue-light percentage of 29.3%) yielded a visual comfort score that was 34% higher than a display screen without the ambient brightness control (having a luminance of 155 cd/m^2) and having greater short-wavelength spectral output (a blue-light percentage of 39.1%).

Interestingly, the combined effect of ambient brightness control and reduced short-wavelength spectral content was an increase in the visual comfort score of 34%. This value is close to the sum of the increases found individually for each visual display function assessed separately (18% for ambient brightness control and 19% for reduced blue-light percentage). Such a result suggests that the beneficial impacts of these functions may be largely independent of each other.

This study has several important limitations. The sample size of 10 subjects is relatively small, even though the statistical procedures used to assess significance take sample size into account (McGuigan, 1990). Further, because all conditions were experienced by all subjects within their experimental sessions, fatigue over the approximately 2-hour session length could have gradually accumulated and served as a source of noise in measuring the responses. Such an effect would be mitigated by the randomizing the order of conditions experienced by each subject as was done in this study, but could still have influenced the results. In addition, the impacts of the short-wavelength spectral content were only investigated at the low ambient light level (10 lux) used in the present study, and could be different under a higher ambient light level. Nonetheless, the present results are largely consistent with those from previously published research (Chen *et al.*, 2017; Shi *et al.*, 2021; Hou *et al.*, 2021).

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REFERENCES

Boff, K.R., Lincoln, J.E. 1988. Engineering Data Compendium. Harry G. Armstrong Aerospace

Medical Research Laboratory. Wright-Patterson Air Force Base, OH.

Bullough, J.D. 2009. Spectral sensitivity for extrafoveal discomfort glare. Journal of Modern Optics. 56. 13:1518-1522.

Bullough, J.D. 2022. Understanding Glare in Exterior Lighting, Display, and Related Applications. SPIE Press. Bellingham, WA.

Chen, Y.L., Zhang, Y.H., Jia, L., Yong, Y., Yang, Y.B., Xu, P. 2017. Evaluate fatigue of blue light influence under general LCD, nice blue LCD displays. Society for Information Display Digest. 48. 1:1367-1370.

Hayes, J.R., Sheedy, J.E., Stelmack, J.A., Heaney, C.A. 2007. Computer use, symptoms, and quality of life. Optometry and Vision Science. 84. 8:E739-E745.

Hou, D., Zu, W., Jing, S., Lin, Y. 2021. Display dimming model characterized by three-dimensional ergonomic study. Optical Engineering 60. 3:035110.

Illuminating Engineering Society. 2022,. Recommended Practice: Lighting Office Spaces, ANSI/IES RP-1-22. Illuminating Engineering Society. New York, NY.

Ji, H., Li, P., Fu, W., Ge, Z. 2022. The application of wide spectrum low peak blue light technology in health TV display. Journal of the Society for Information Display. 30. 7:567-573.

Kim, C.J., Park, S., Won, M.J., Whang, M., Lee, E.C. 2013. Autonomic nervous system responses can reveal visual fatigue induced by 3D displays. Sensors. 13. 10:13054-13062.

Lin, J.B., Gerratt, B.W., Bassi, C.J., Apte, R.S. 2017. Short-wavelength light-blocking eyeglasses attenuate symptoms of eye fatigue. Investigative Ophthalmology and Visual Science. 58. 1:442-447.

Lin, Y-H., Chen, C-Y., Lu, S-Y., Lin, Y-C. 2008. Visual fatigue during VDT work: Effects of time-based and environment-based conditions. Displays. 29. 5:487-492.

McGuigan F.J. 1990. Experimental Psychology, 5th edition. Prentice-Hall. Englewood Cliffs, NJ.

Merbah, J., Gorce, P., Jacquier-Bret, J. 2020. Effects of environmental illumination and screen brightness settings on upper limb and axial skeleton parameters: How do users adapt postures? Ergonomics 63. 12:1561-1570.

Rea, M.S. (editor). 2000. Lighting Handbook: Reference and Application, 9th edition. Illuminating Engineering Society. New York, NY.

Rea, M.S., Radetsky, L.C., Bullough, J.D. 2011. Toward a model of outdoor lighting scene brightness. Lighting Research and Technology. 43. 1:7-30.

Shi, Y., Tu, Y., Wang, L., Zhang, Y., Zhang, Y., Wang, B. 2021. Spectral influence of the normal LCD, blue-shifted LCD, and OLED smartphone displays on visual fatigue: A comparative study. Displays. 69. 2021:102066.

Zhou, Y., Shi, H., Chen, Q-W., Ru, T., Zhou, G. 2021. Investigation of the optimum display luminance of an LCD screen under different ambient illuminances in the evening. Applied Sciences. 11. 9:4108.