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Optimum display luminance depends on white luminance under various ambient illuminance conditions

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Abstract. This paper reports display luminance levels for good visibility under nine ambient illuminance conditions (50, 100, 200, 500, 1000, 2000, 5000, 10,000, and 20,000 lx) for a given white luminance level, chosen from five candidates (100, 200, 500, 1000, and 2000 cd/m^2), through a psychophysical experiment. This work reveals that the luminance levels for good visibility increase as the maximum white luminance of the display increases. The white luminance dependency of display luminance is caused by the fact that the human visual system adapts to the maximum white luminance and evaluates the brightness of the display based on it. Based on the experimental results, an appropriate luminance zone under various illuminance conditions is proposed. The appropriate luminance zone varies with the maximum white luminance of the displays. This may be understood to mean that there is no absolute luminance level under a given lighting condition. To solve this issue, a new method is proposed to determine optimum luminance levels by considering both visibility and power consumption. By the proposed method, it is reported that the optimum maximum luminance lies between 200 and 500 cd/m^2 for indoor use (below 500 lx). These results were verified by young adults with normal vision.
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Keywords: optimum luminance; maximum white luminance; ambient illuminance; automatic brightness control.

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1 Introduction

Recently, the use of displays in everyday life has increased several fold in almost every environment. In particular, mobile displays used in cell phones and tablet PCs can be used in any situation because of their portability and are widely used indoors as well as outdoors. When people look at these displays, they want to have consistent visibility at every location. However, most users are still dissatisfied because of insufficient display brightness in bright environments and too much brightness in dark environments. Visibility is worsened when a display is viewed under high illumination conditions without increasing the display luminance. On the other hand, viewing the display in low-light conditions without controlling the brightness causes uncomfortable glare.[1–5] To maintain the visibility of the displays in all conditions, it is necessary to adjust the brightness of the displays according to the ambient light.

Automatic brightness control (ABC) technology has been widely developed to automatically adjust the display luminance for consistent visibility under various ambient lighting conditions.[6,7] Most mobile phones on the market feature ABC. Another purpose of ABC is to increase the battery life of mobile devices, because users want to use mobile devices as long as possible. By adjusting the brightness according to the ambient illumination, battery consumption can be reduced in comparison with when the display maintains the same brightness regardless of ambient illuminance conditions. From the perspective of power consumption, the lower brightness of the display is better, provided this low brightness does not affect the visibility of the display. Therefore, it is necessary to investigate the proper luminance range according to the surrounding illuminance to improve both visibility and power consumption of displays.

Our research group reported the optimum display luminance depending on ambient illuminance by using a liquid crystal display whose maximum luminance was 838 cd/m^2.[8] Figure 1 shows the appropriate luminance zone investigated in the previous work. The upper limits of the appropriate luminance zone were 516, 574, 612, 664, 737, 790, and 836 cd/m^2 for ambient illuminances of 50, 100, 200, 500, 1000, 2000, and 5000 lx, respectively. On the other hand, the lower limits of the zone were 113, 116, 130,154, 177, 204, and 246 cd/m^2 for the same illuminance conditions. In the previous work, we used a method of three ordinal scales: (1) too dark, (2) appropriate, and (3) too bright. In addition, the white luminance of the LCD panel was fixed to 868 cd/m^2. Figure 1 represents the appropriate luminance zone of the LCD whose white luminance was 868 cd/m^2 using a three-ordinal-scale method. The appropriate luminance zone was determined from score 1.5 to 2.5 in the previous work. However, it was necessary to subdivide scales more than three for more accurate analysis. So, we used seven ordinal scales instead of three in this experiment. In this paper, the appropriate luminance zone was determined from score 3 to 5 using seven ordinal scales. Furthermore, the illuminance range of 50 to 5000 lx in the previous work was extended from 50 to 20,000 lx in this study. The details of the seven ordinal scales are described in Sec. 2. The appropriate luminance zone was considered to be an absolute range that could be applied universally regardless of the maximum white luminance level of the display.

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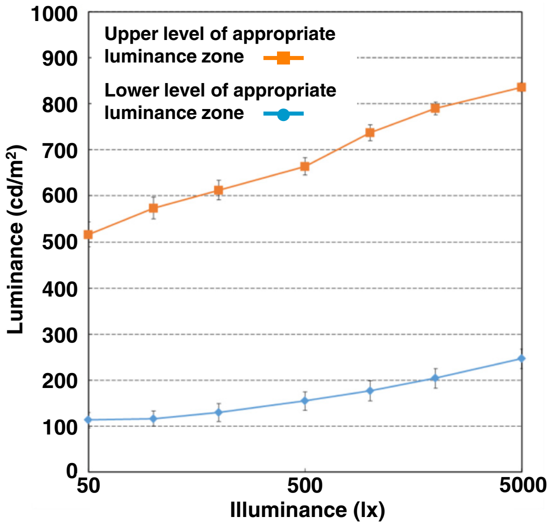


Fig. 1 Investigated appropriate luminance zone in the previous work,[8] when the maximum white luminance level is 868 cd/m^2. The error bars represent the standard errors of the mean.

However, it was found out that the results are only valid when the maximum white luminance of the display is 868 cd/m^2.[8] Therefore, it is necessary to investigate how the appropriate luminance varies depending on the maximum white luminance of the display.

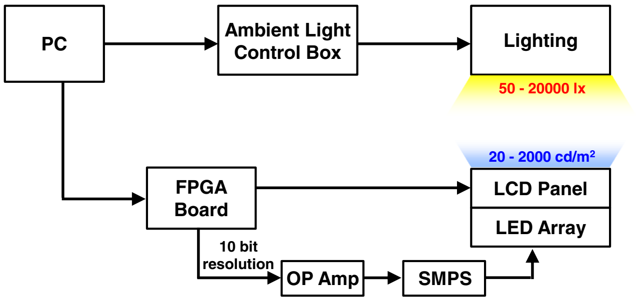


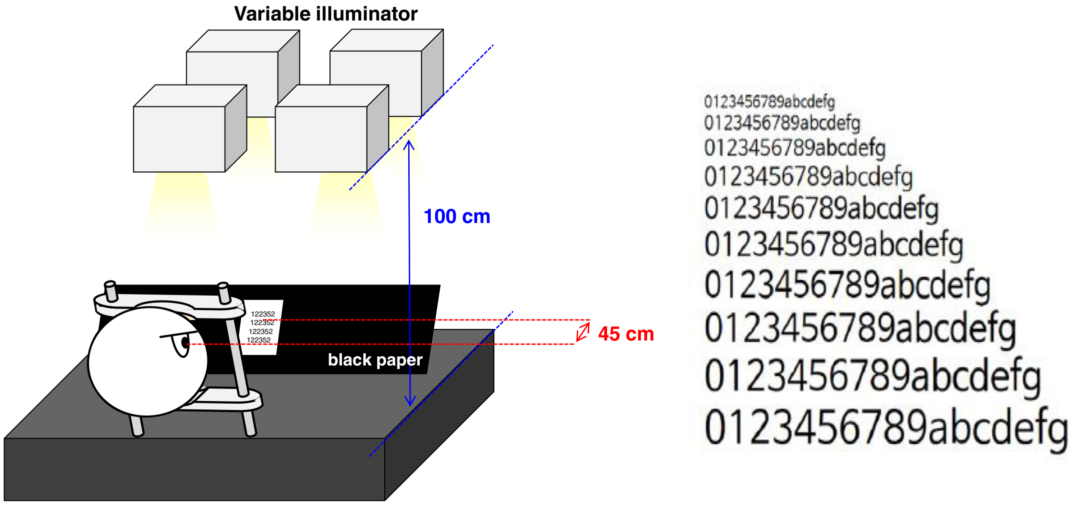
Fig. 2 Block diagram of the entire system.

In this paper, it will be reported that the appropriate luminance levels under various illuminance conditions depend on the maximum white luminance levels. In Sec. 2, the details of the experimental setup will be organized. In Sec. 3, the experimental results of the appropriate luminance levels and how these are related to the maximum white luminance levels and surrounding illuminance will be shown. Finally, the conclusion is drawn in Sec. 4.

2 Experimental Set-Up

A 16-in. LCD panel was used in the experiment. The edges of the LCD panel were masked with black paper to limit the horizontal × vertical screen size to 13 cm × 22 cm. In order to realize various levels of display luminance, the backlight unit of the LCD module was removed and a new LED array was fabricated. The new LED array consisted of 840 white LEDs and was driven by three switching-mode power supplies (SMPS). The diagram of the entire system is shown in Fig. 2. The brightness of the LED array was controlled by modulating the width of the signal generated from a field programmable gate array board with 10-bit resolution. Thus, the luminance of the LCD ranged from 20 to 2000 cd/m^2. Figure 3(a) shows a graphical expression of the psychophysical experiment. The LCD panel displayed an image containing black letters on a white background, as shown in Fig. 3(b).

Table 1 summarizes the 22 luminance levels used in the experiment. Five maximum white luminance conditions were determined: 100, 200, 500, 1000, and 2000 cd/m^2. The luminance levels were measured using a contact-type spectrophotometer (Konica Minolta CA-210). CIELAB (also known as CIE$L*a*b*$) color space was used to define a lightness. To calculate CIELAB coordinates, the tristimulus values of the stimuli (XYZ) and those of the reference white ($X_nY_nZ_n$) are needed as inputs. Using them, CIELAB provides $L*$, $a*$, and $b*$, as shown in Eqs. (1)–(3). The $L*$, $a*$, and $b*$ represent lightness, red–green, and yellow–blue components, respectively:



(a)

(b)

Fig. 3 (a) A graphical expression of the psychophysical experiment. (b) Image used in the experiment.

Table 1 Luminance levels used in the experiment.

Lightness (%)	Luminance levels (cd/m^2)				
20	N.A.	N.A.	15.0	29.9	59.8
40	N.A.	22.5	56.3	112.5	225
60	28.1	56.3	140.6	281.2	562.5
80	56.7	113.4	283.4	566.8	1134
100	100	200	500	1000	2000

$$L^* = 116 f\left(\frac{Y}{Y_n}\right) - 16, \tag{1}$$

$$a^* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right], \tag{2}$$

$$b^* = 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right], \tag{3}$$

where

$$f(t) = \begin{cases} \sqrt[3]{t} & t > \delta^3 \\ \frac{t}{3\delta^2} + \frac{4}{29} & \text{otherwise} \end{cases}, \quad \delta = \frac{6}{29}$$

The experiment was performed for one maximum white condition per day. Therefore, it took 5 days to complete the experiment. Five lightness conditions were used: 20%, 40%, 60%, 80%, and 100%, as shown in Table 1. Lightness 20% and 40% for $Y_{\mathrm{MAX}} = 100\ \mathrm{cd/m^2}$ correspond to 2.99 and 11.3 cd/m^2, respectively. Lightness 20% for $Y_{\mathrm{MAX}} = 200\ \mathrm{cd/m^2}$ corresponds to 5.98 cd/m^2. The three luminance levels were impossible to implement because of the limitations of SMPS. Nine ambient illuminance conditions were used: 50, 100, 200, 500, 1000, 2000, 5000, 10,000, and 20,000 lx. For each illuminance condition, the five different luminance levels of the test image were presented to subjects in a random sequence. For example, on a day for the maximum white condition of 1000 cd/m^2, five luminance levels of 29.9, 112.5, 281.2, 566.8, and 1000 cd/m^2 were used, as shown in Table 1.

Six university male students participated in the experiment. The average age of the subjects was 25.2 years. All students had normal or corrected-to-normal visual acuity. Subjects were asked to rest their chin on a chin support and fix their eyes on the image displayed. The viewing distance was 45 cm. For each subject, the experiment was conducted in nine sessions, corresponding to the nine chosen illuminance levels. The subjects progressed from the lowest illuminance session (50 lx) to the highest illuminance session (20,000 lx) because light adaptation is much faster than dark adaptation in human visual system.

Before the subjects participated in the experiment, each maximum white luminance level was displayed to make the subjects fully adapt to the maximum luminance level. In other words, the experiment was conducted after the subjects adapted to each maximum luminance level. Immediately after viewing the LCD screen with a randomly selected luminance level (among the five defined levels), the subjects were asked to classify the LCD brightness with seven ordinal scales: (1) too dark, (2) dark, (3) slightly dark, (4) appropriate, (5) slightly bright, (6) bright, and (7) too bright. The method of seven ordinal scales was repeated until the subjects completed the five different luminance conditions. The display luminance levels were randomly given to subjects. This cycle was repeated five times for each ambient illuminance condition, meaning that each subject answered the seven ordinal scales 25 times for each illuminance condition. Each subject answered 225 times (5 repeats × 5 luminance levels × 9 illumination conditions) per day for one maximum white luminance level. It took ~30 min for a subject to complete the experiment for one maximum white luminance condition each day. Because there were five maximum white luminance conditions, each subject participated in the experiment for two and a half hours over 5 days. To assess the consistency of the five repetitions for all subjects, a one-way analysis of variance was performed. It was found out that subjects responded to stimuli regardless of their repeating sequence ($P > 0.05$).

3 Results and Discussion

The results which will be discussed in this chapter were verified by the young male adults with normal vision. Figure 4 graphically explains how to extract the corresponding luminance levels of scores 3, 4, and 5 from the experimental results. Figure 4 shows that the average scores of six participants were 1.8, 2.7, 3.3, 4.3, and 5.6 at lightness 20%, 40%, 60%, 80%, and 100% for $Y_{\mathrm{MAX}} = 1000\ \mathrm{cd/m^2}$, respectively, under 1000 lx.

The value 3 of the seven ordinal scales means that the display brightness was slightly dim but acceptable, 4 means that the display brightness was appropriate, and 5 means that the display was slightly bright but acceptable. As shown in Fig. 4, using a linear interpolation, the luminance levels were calculated corresponding to a score of 3 and found that it was 201.8 cd/m^2. The luminance levels corresponding to scores 4 and 5 were 490.7 and 811.2 cd/m^2, respectively. As a result, the value of 490.7 cd/m^2 is the appropriate luminance level under 1000 lx, when people look at a display whose maximum luminance level is 1000 cd/m^2. Assuming that the appropriate luminance zone could be determined by the score range of 3 to 5, the appropriate luminance zone could be built from 201.8 to 811.2 cd/m^2 in this case.

According to the maximum white luminance levels, the luminance curves of scores 3, 4, and 5 were plotted in Fig. 5. The error bars in Fig. 5 represent the standard errors of the mean. Figures 5(a)–5(e) represent the experimental results when the maximum white luminance levels were 100, 200, 500, 1000, and 2000 cd/m^2, respectively. As shown in Fig. 5, the appropriate luminance zones determined by the score range between 3 and 5 were completely different from one another. For example, under 1000 lx, the appropriate luminance zone ranged from 201.8 to 811.2 cd/m^2 when $Y_{\mathrm{MAX}} = 1000\ \mathrm{cd/m^2}$. However, the counterparts for $Y_{\mathrm{MAX}} = 500\ \mathrm{cd/m^2}$ and $Y_{\mathrm{MAX}} = 2000\ \mathrm{cd/m^2}$ were from 176.3 to 490.2 cd/m^2 and from 225.0 to 1332 cd/m^2, respectively. When $Y_{\mathrm{MAX}} = 200\ \mathrm{cd/m^2}$, the average scores of all lightness conditions were lower than score 4 under 1000 lx, which means that all subjects perceived it dark

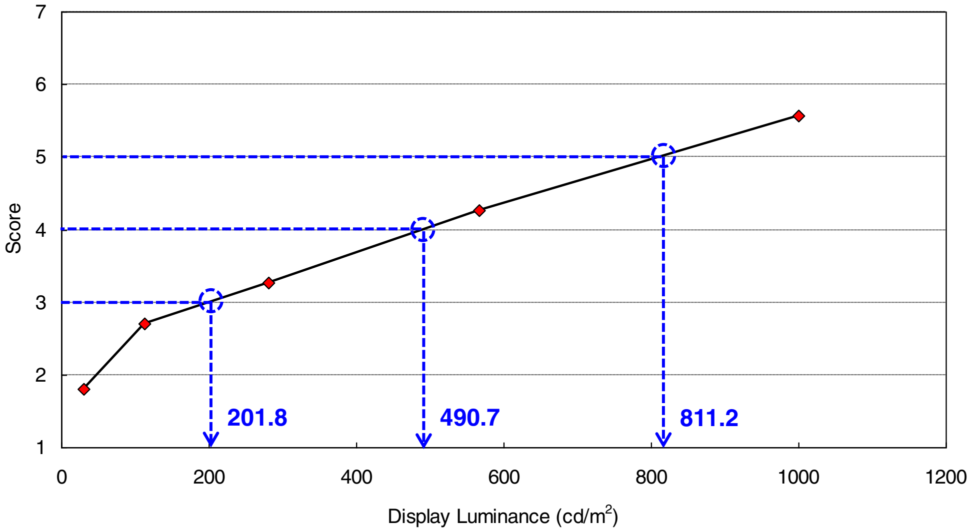


Fig. 4 Graphical expression of how to extract luminance levels corresponding to scores 3, 4, and 5.

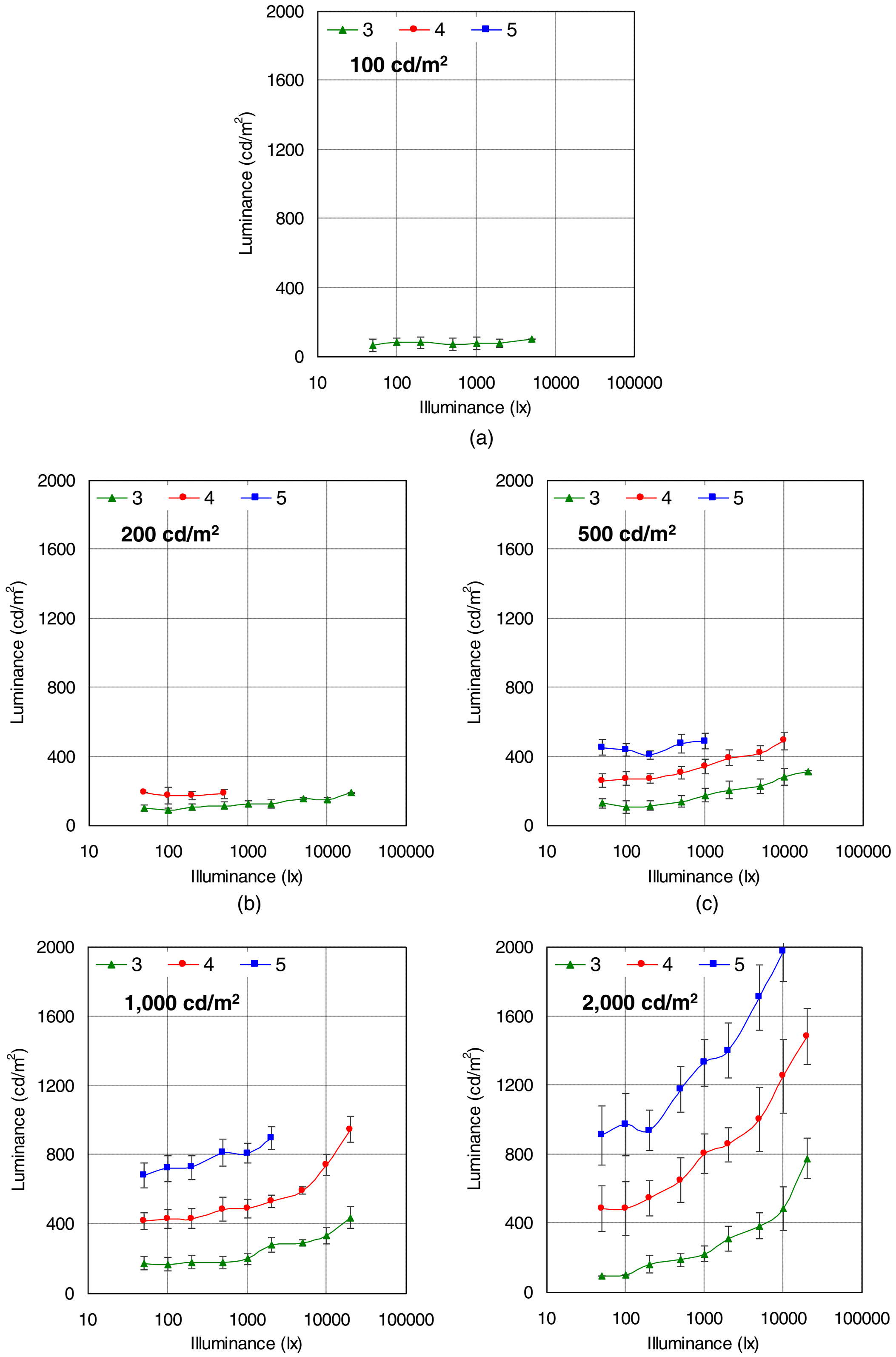
for all lightness conditions, as shown in Fig. 5(b). In the same manner, in the case of $Y_{\mathrm{MAX}} = 100\ \mathrm{cd/m^2}$, the luminance curves of scores 4 and 5 were not plotted. This means that the average scores of all lightness conditions were lower than score 4 under all illuminance conditions from 50 to 20,000 lx. In other words, the luminance level of $Y_{\mathrm{MAX}} = 100\ \mathrm{cd/m^2}$ was insufficient even under an illuminance condition of 50 lx.

It is found out that the luminance levels that were perceived as appropriate were not the same when the white luminance changed. The appropriate luminance zone is highly related to the maximum white luminance level of the display. That is because human eye evaluates the brightness of the display in compliance with the display's maximum brightness. That is, once the visual system is fully adapted to a particular white luminance level, people evaluate the brightness based on the white luminance level. That is a well-known natural color appearance phenomenon called color constancy.[9] Let us consider the following situation, in which a display is looked at, whose maximum white luminance level is $500\ \mathrm{cd/m^2}$ after looking at another display, whose maximum white luminance level is $2000\ \mathrm{cd/m^2}$ (assuming that the whites of both displays have the same chromaticity coordinates). Subsequently, the $500\ \mathrm{cd/m^2}$ display is not seen as gray because of the lower brightness. No matter what other devices have been seen before, the maximum white luminance for the device currently being viewed will be taken as the new reference white. This is why the appropriate luminance zone varies according to the maximum white luminance level.

Figures 6(a)–6(c) show luminance curves corresponding to scores 3, 4, and 5, respectively. The error bars in Fig. 6 represent the standard errors of the mean. As shown in Fig. 6(c), the curve of score 5 did not exist when $Y_{\mathrm{MAX}} = 200\ \mathrm{cd/m^2}$. This means that a white luminance of $200\ \mathrm{cd/m^2}$ might be inadequate for the users who prefer a bright screen. Thus, the complete appropriate luminance zones (scores between 3 and 5) should be discussed for a global application of the ABC, even though the white luminance of $200\ \mathrm{cd/m^2}$ might be adequate for users who prefer average or dim screens. Therefore, it is proposed that the appropriate luminance zones formed by the luminance range corresponding to a score between 3 and 5 according to the white luminance levels, as shown in Fig. 7.

Next, it is determined what Y_{MAX} is necessary when the highest illuminance is 500 lx (indoor use only). The appropriate luminance zones (scores between 3 and 5) were formed when $Y_{\mathrm{MAX}} = 500\ \mathrm{cd/m^2}$ and higher, as shown in Fig. 7. It is reasonable to select a monitor with $Y_{\mathrm{MAX}} =$ 500, 1000, or $2000\ \mathrm{cd/m^2}$ because they all have the appropriate luminance zones under 500 lx. If only visibility is taken into consideration, any of the three conditions of $Y_{\mathrm{MAX}} =$ 500, 1000, and $2000\ \mathrm{cd/m^2}$ can be used. However, considering not only visibility, but also power consumption, $Y_{\mathrm{MAX}} = 500\ \mathrm{cd/m^2}$ is the best choice among them because lower power consumption is better when visibility is guaranteed. In addition, it is not necessary to consume more power if it is possible to find lower Y_{MAX} that guarantees the appropriate zone. Figure 5(b) shows the luminance curves of scores 3 and 4 were plotted, while missing that of score 5 when $Y_{\mathrm{MAX}} = 200\ \mathrm{cd/m^2}$. As a result, it could be concluded that the minimal optimum Y_{MAX} lies between 200 and $500\ \mathrm{cd/m^2}$, which guarantees the lowest power consumption while maintaining good visibility for indoor use.

Figure 8 shows that the subjects' scores were different despite similar luminance levels. As shown in Fig. 8, the blue line with solid diamonds represents the average scores of lightness 60% when $Y_{\mathrm{MAX}} = 1000\ \mathrm{cd/m^2}$ (Y1000–L60). The blue line with open circles represents the average scores of lightness 80% when $Y_{\mathrm{MAX}} = 500\ \mathrm{cd/m^2}$ (Y500–L80). Their actual luminance levels were 281.2 and $283.4\ \mathrm{cd/m^2}$, respectively. Even though their luminance levels were almost the same, the average scores were different, as shown in Fig. 8. Likewise, the red line with solid squares represents the average score of lightness 60% when $Y_{\mathrm{MAX}} = 2000\ \mathrm{cd/m^2}$ (Y2000–L60). The red line with open squares represents the average score of lightness 80% when $Y_{\mathrm{MAX}} = 1000\ \mathrm{cd/m^2}$ (Y1000–L80). Their actual luminance levels were 562.5 and $566.8\ \mathrm{cd/m^2}$, respectively. Their average scores also showed a large difference despite the similar luminance levels. Furthermore, the curves of the average



(a)

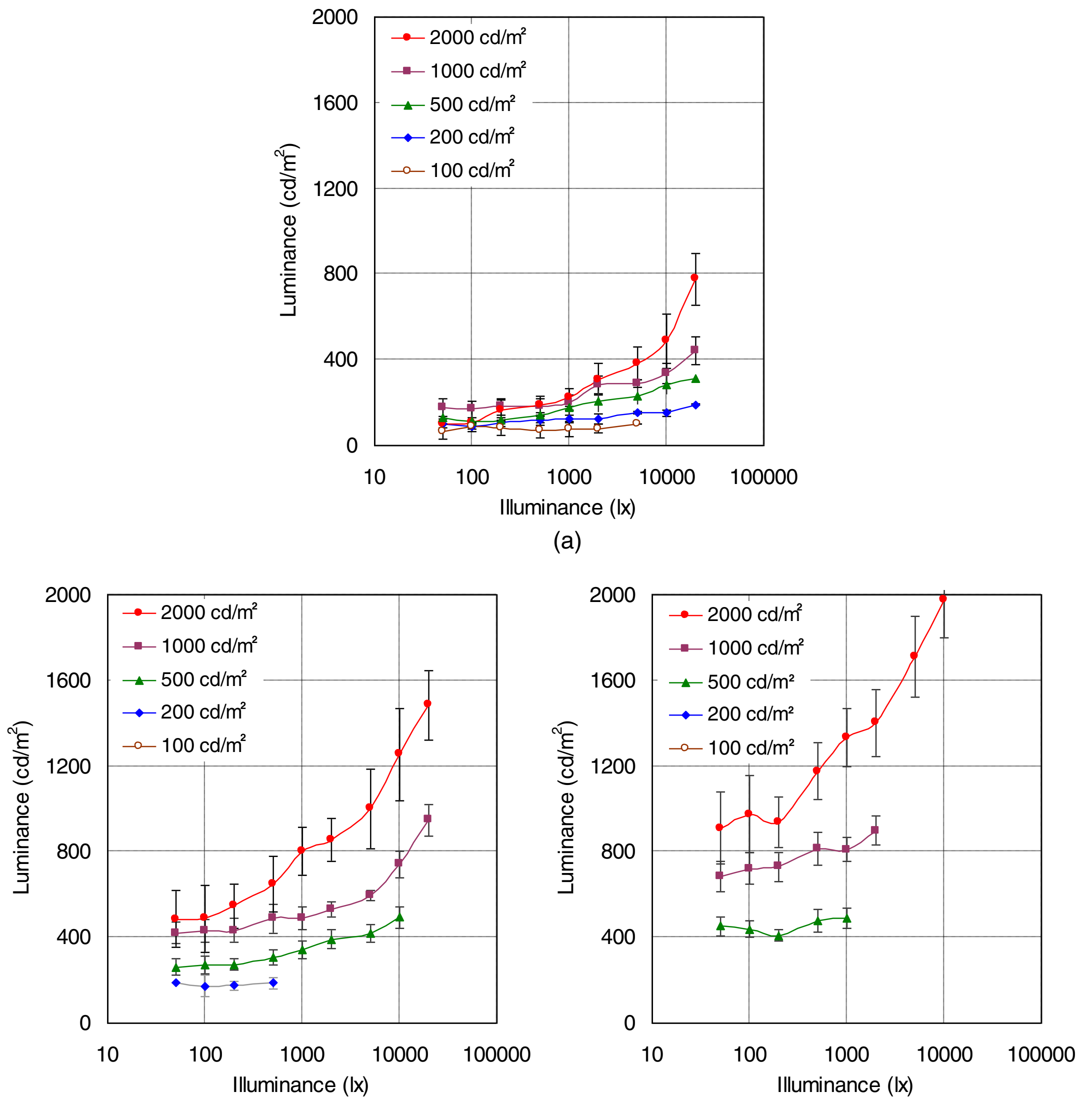
(b)

(c)

(d)

(e)

Fig. 5 Luminance curves corresponding to scores 3, 4, and 5 when the maximum white luminance level was (a) 100, (b) 200, (c) 500, (d) 1000, and (e) 2000 cd/m^2. The error bars represent the standard errors of the mean.



(a)

(b)

(c)

Fig. 6 Luminance curves for the maximum white luminance levels of 100, 200, 500, 1000, and 2000 cd/m^2 corresponding to scores of (a) 3, (b) 4, and (c) 5. The error bars represent the standard errors of the mean.

score of Y500–L80 and Y2000–L60 matched well, even though their luminance difference was nearly double. Therefore, it is also clear that the luminance levels of the display which people perceive as appropriate are not absolute.

4 Conclusion

In previous work, an appropriate luminance zone depending on ambient illuminance was investigated with a fixed white luminance level. It was expected that the appropriate luminance zone could be applied universally regardless of the white luminance of the display. However, in this study, it was found out that the appropriate luminance zone varies depending on the maximum white luminance levels because of the adaptation of the human visual system. Therefore, automatic brightness technology should be applied to the display devices with the proper curve, corresponding to the maximum white luminance of each display. The appropriate luminance zones that vary with the maximum white luminance of displays, proposed in this paper, could be used as a reference. However, these results were verified by young adults with normal vision. In addition to automatic brightness technology, it is recommended that display devices have the function of setting the manual luminance baseline so that any observers of various ages can be satisfied with their devices' brightness levels. Luminance levels that ensure good visibility increased as the maximum white luminance of the display increased. A new method was proposed to determine optimum luminance levels by considering both visibility and power consumption. By the proposed method, it was reported that the minimal optimum white luminance that guarantees a good visibility lies between 200 and 500 cd/m^2, which leads to the greatest reduction in power consumption for indoor use (below 500 lx). In the future, more investigation needs to be done on people of all ages and people with vision problems.

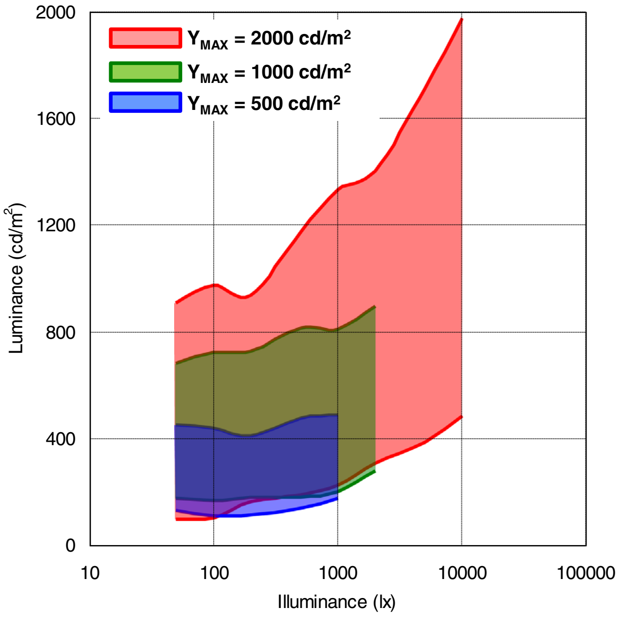


Fig. 7 Appropriate luminance zones (scores between 3 and 5) when $Y_{\mathrm{MAX}} = 500$, 1000 and 2000 cd/m^2.

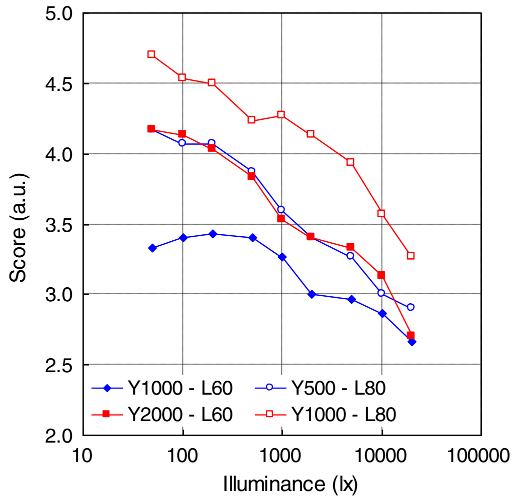


Fig. 8 Average scores of four different combinations between the maximum white luminance level (Y_{MAX}) and the lightness: The luminance level of Y1000–L60 was 281.2 cd/m^2 indicating that the Y_{MAX} was 1000 cd/m^2 and lightness was 60. The luminance levels of Y500–L80, Y2000–L60, and Y1000–L80 were 283.4, 562.5, and 566.8 cd/m^2, respectively.

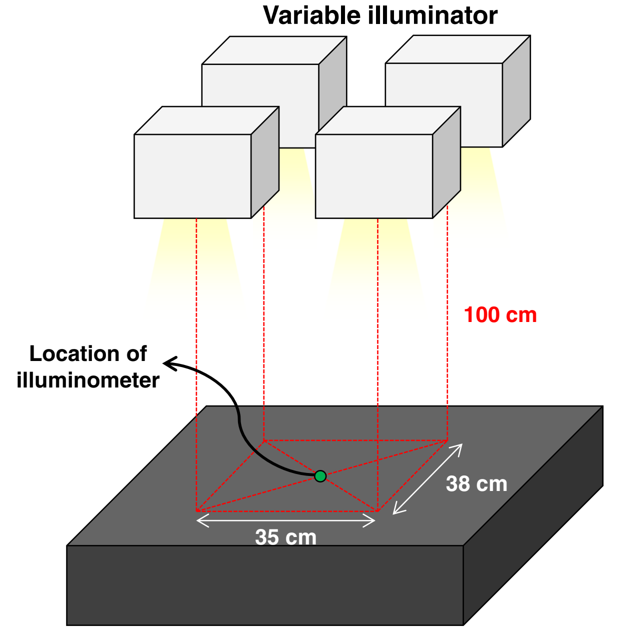


Fig. 9 The geometry setup to measure the level of ambient illuminance by an illuminometer.

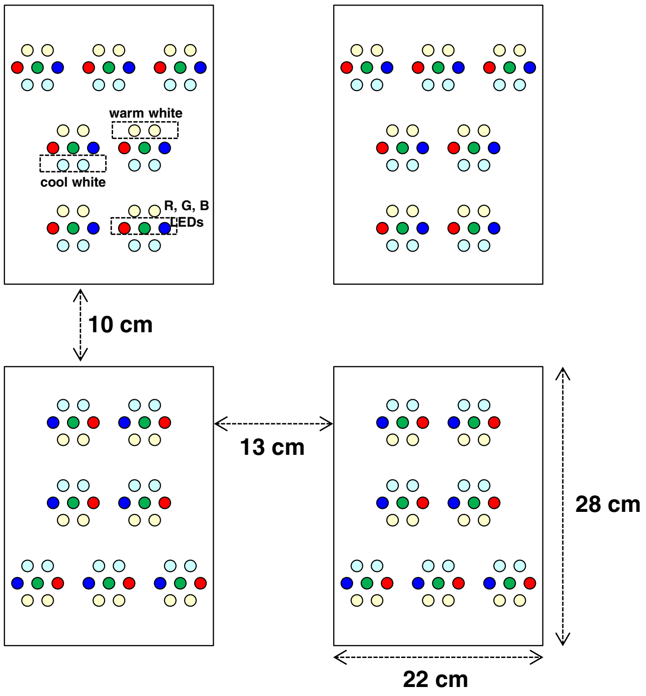
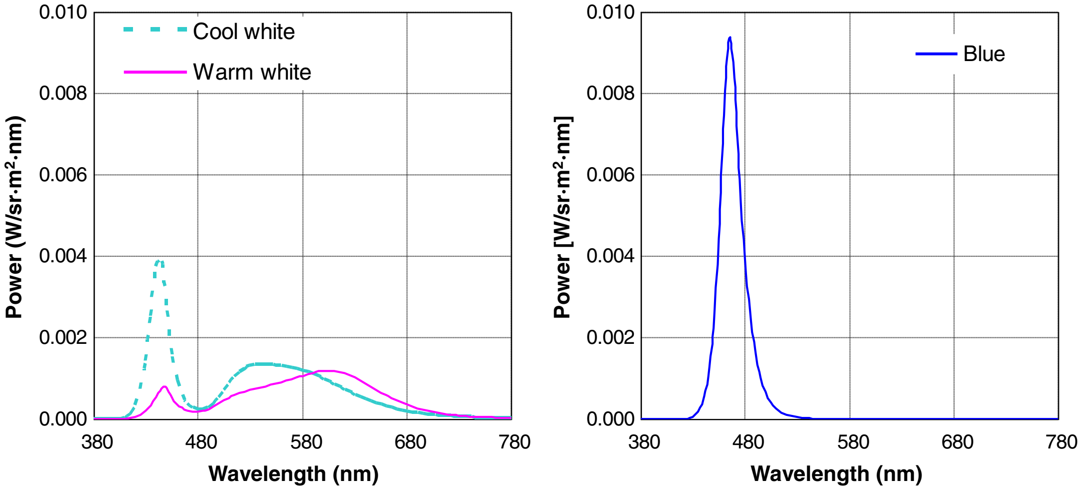


Fig. 10 Bottom view of the variable illuminator.

Appendix: Description of Photometry

All the luminance levels measured in the paper are the results of the measurement using a contact-type spectrophotometer (Konica Minolta CA-210). As shown in Fig. 3(a), the variable illuminator was used to implement various ambient illuminance conditions. To measure the illumination levels of the variable illuminator, an illuminometer (Konica Minolta CL-200A) was used. The geometric information to measure ambient illuminance was specified in Fig. 9.

The CL-200A was placed on the table as shown in Fig. 9 and measured the ambient illuminance vertically upward. The vertical distance between the variable illuminator and the illuminometer was 100 cm. Figure 10 represents the bottom view of the variable illuminator. It consists of several LEDs of warm white, cool white, red, green, and blue. In this study, only warm white, cool white, and blue LEDs were used. Figures 11(a) and 11(b) show the spectral power distribution of two types of white and blue LEDs, respectively. By modulating the intensity of the three types of LEDs, the range of 20 to 20,000 lx of ambient illuminance conditions could be implemented. The color temperature of the variable illuminator was set to 6300 K.



(a) (b)

Fig. 11 The spectral power distribution of (a) cool and warm white LEDs and (b) blue LED.

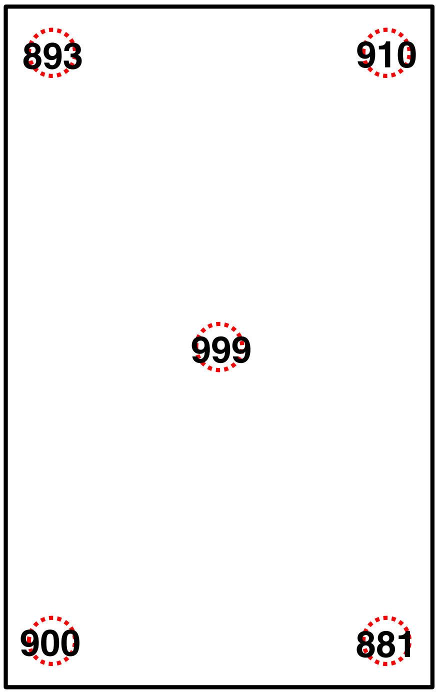


Fig. 12 Luminance levels of five points of the test screen to investigate the luminance drop (cd/m^2).

To investigate the luminance fall-off from the center to the edges of the test screen, the luminance levels of five points shown in Fig. 12 were measured by a spectrophotometer (Konica Minolta CA-210). As shown in Fig. 12, there was a luminance drop of about 10% from the center to the edges. In this paper, the analysis is based on the luminance level at the center of the test screen.

Tables 2 and 3 summarize the theoretical and measured luminance levels of the white used in the experiment, respectively. The error rate between the measured and the theoretical values was 0.01% on average. Tables 4 and 5 summarize the measured luminance levels of the black and calculated luminance ratios used in the experiment, respectively. The

Table 2 Theoretical luminance levels of the white used in the experiment.

Lightness (%)	Luminance levels (cd/m^2)				
20	2.99	5.98	15.0	29.9	59.8
40	11.25	22.5	56.3	112.5	225
60	28.1	56.3	140.6	281.2	562.5
80	56.7	113.4	283.4	566.8	1134
100	100	200	500	1000	2000

Table 3 Measured luminance levels of the white used in the experiment.

Lightness (%)	Luminance levels (cd/m^2)				
20	N.A.	N.A.	14.96	29.67	60
40	N.A.	22.04	55.11	114.03	228.34
60	29.49	55.11	139.31	278.67	562.27
80	55.11	114.03	278.67	567.16	1132.43
100	100.61	199.07	501.68	1001.04	2000.35

Table 4 Measured luminance levels of the black used in the experiment.

Lightness (%)	Luminance levels (cd/m^2)				
20	N.A.	N.A.	0.06	0.11	0.25
40	N.A.	0.10	0.21	0.51	0.82
60	0.12	0.21	0.74	1.08	1.88
80	0.21	0.51	1.08	1.89	4.16
100	0.41	0.79	1.87	3.74	6.94

Table 5 Luminance ratios between the measured white and black levels (Tables 3 and 4).

Lightness (%)	Luminance ratio (white luminance/black luminance)				
20	N.A.	N.A.	249.33	269.73	235.94
40	N.A.	212.13	262.43	223.59	278.46
60	242.32	262.43	188.24	258.03	299.08
80	262.43	223.59	258.03	300.08	272.22
100	245.37	251.99	268.28	267.66	288.23

mean of the luminance ratios was 255, with a minimum of 188 and a maximum of 299.

With the test screen off and ambient illumination on, it was confirmed that no specular reflections of light sources or other "hot spots" were visible on the screen from the subject's eye position.

Disclosures

The authors declare no conflicts of interest.

Acknowledgments

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