# Adaptive display luminance for viewing smartphones under low illuminance

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**Abstract:** The study investigates the optimal display luminance for viewing smartphones in conditions of low illuminance. This proposes a model of adaptive display in that display luminance changes gradually with the passage of watching time. It starts at a fairly low display luminance of 10 cd/m$^2$, and after 10 seconds, the luminance increases slowly until it reaches 40 cd/m$^2$ for 20 seconds and maintains the luminance. For the development of the model, an experiment was conducted to identify the optimal luminance for initial viewing and that for continuous viewing, as well as the change speed of display luminance. In order to validate the model, users' subjective judgments and activation of alpha rhythm were observed, and the result confirmed the superiority of the adaptive display luminance compared to the current display luminance in terms of physiological comfort and psychological satisfaction. It is expected that this study contributes to the pleasing use of displays at night under low illuminance by applying to diverse types of display devices.



**OCIS codes:** (330.7320) Vision adaptation; (330.0330) Vision, color, and visual optics.

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#241401 Received 11 Jun 2015; accepted 12 Jun 2015; published 18 Jun 2015

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## 1. Introduction

With the increase in various types of digital devices, people spend many hours viewing displays during the day. This usually lasts into the night, meaning that more than 80% of people use their smartphone before bedtime in a dark environment [1–3]. However, viewing mobile displays in a dark environment brings users in contact with excessively high luminance contrast due to very low ambient illuminance, resulting in adverse effects on health. Increasing luminance contrast decreases visual comfort and duration of visible persistence, as well as leading to poor visual performance [4–6]. The light emitted from displays moves directly to the eyes rather than being spread around, and it not only causes visual fatigue but also hinders people's ability to fall asleep easily or comfortably via strong involvement in the physiological system [7, 8]. It suppresses the production of melatonin, a hormone that promotes sleep in humans [9], and consequently it causes a delay in the timing of the body's circadian rhythm [10]. A research team found that two-hour exposure to light from electronic displays suppresses melatonin by about 22%, and that six in 10 people who use their smartphone at night reported that most of the time they are not getting sufficient sleep [11].

Therefore, an auto-brightness function has been applied to smartphones to provide a perceptually optimal brightness by adjusting display luminance depending on the ambient illuminance [12, 13]. This function supports practically desirable solution in most situations, but display luminance tends to be overly bright in a dark environment [14] since it was primarily designed for the operation in daytime. In other words, the ideal solution is still not fully formulated in spite of the frequent use of smartphones prior to sleep. Hence, it is necessary to examine the optimal display luminance that supports physiological comfort and psychological satisfaction for nighttime smartphone users.

In this regard, the human visual system should be concerned as well. Human vision operates on a time-dependent adaptation process [15–17], which means that the changes in visual sensitivity are controlled by the lapse of time [18, 19]. Consequently, it implies the potential for adaptive display that changes display luminance with the passage of watching time in the light of visual adaptation, rather than just maintaining a static luminance. Thus, this study attempts to find the optimal display luminance based on the hypothesis that a gradual change of display luminance provides pleasing use of smartphones under low illuminance.

## 2. Objective

The aim of this study is to investigate the optimal display luminance for comfortable viewing of smartphones in conditions of low illuminance. The study involves two experimental steps. In Experiment I, an experiment is conducted to discover the ideal display luminance in a dark environment, and the model of adaptive display luminance is developed based on the empirical results. Next, in Experiment II, the effect of the adaptive display luminance is validated in terms of physiological comfort and psychological satisfaction.

## 3. Experiment I: development of adaptive display luminance

Prior to the experiment, two levels of luminance necessary for investigation were defined: the first level is determined as the luminance for first-time viewing to avoid a harsh glare flashing into eyes (hereinafter *initial viewing*), and the second level is the luminance for constant display watching that comforts but is bright enough to make users satisfied (hereinafter *continuous viewing*). Consequently, the experiment was conducted based upon the premise that a gradual change of display luminance from the luminance for *initial viewing* to that for *continuous viewing* improves users' comfort and satisfaction.

### *3.1 Stimuli*

Various levels of luminance stimuli were prepared for the experiment. Since the minimum display luminance and maximum display luminance of the smartphone used in the experiment was 10 cd/m$^2$ and 140 cd/m$^2$ respectively, the display luminance stimuli were chosen within the range. In total, five levels of luminance were selected as follows: 10 cd/m$^2$, 40 cd/m$^2$, 70 cd/m$^2$, 100 cd/m$^2$, and 140 cd/m$^2$. The luminance and chromaticity of each stimulus were measured 10 times using a spectroradiometer (Konica Minolta CS-2000) and a coefficient of variation (CV), which indicated that a standardized measure of dispersion was calculated. The CVs of each luminance and chromaticity were less than 0.02, hence a stability of display stimuli was confirmed. The average colorimetric values are listed in Table 1. A reading article composed of black texts on a white background was displayed on a 4.8-inch-screen smartphone (Samsung Galaxy S3) with one of those types of luminance as illustrated in Fig. 1 (a).

In addition, video clips changing a display luminance at five different rates were created to find the appropriate change speed of display luminance from the luminance for *initial viewing* to that for *continuous viewing*: 1.5 cd/m$^2$·s, 3 cd/m$^2$·s, 6 cd/m$^2$·s, 10 cd/m$^2$·s, and 30 cd/m$^2$·s.

#241401 Received 11 Jun 2015; accepted 12 Jun 2015; published 18 Jun 2015

**Table 1. Luminance and CIE *xy* chromaticity of the five luminance stimuli for Experiment I***

| Stimuli | Target luminance (cd/m$^2$) | Mean values | | |
|---|---|---|---|---|
| | | Luminance (cd/m$^2$) | $x$ | $y$ |
| | 10 | 10.65 | 0.3008 | 0.3287 |
| | 40 | 39.54 | 0.3010 | 0.3285 |
| | 70 | 68.77 | 0.3009 | 0.3282 |
| | 100 | 100.11 | 0.3010 | 0.3280 |
| | 140 | 139.57 | 0.3011 | 0.3276 |

*Colored boxes in stimuli column indicate the relative brightness of displays, and they look white on displays under low illuminance

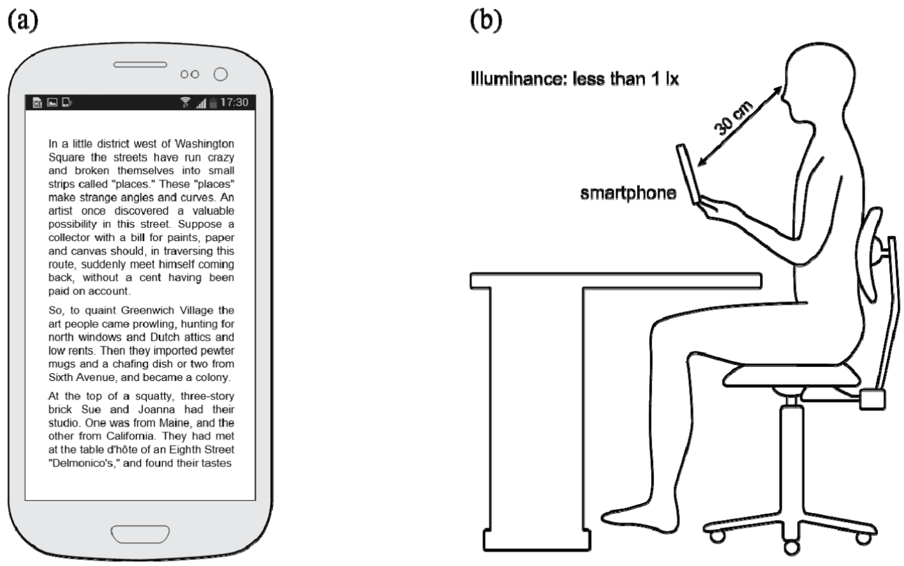


Fig. 1. (a) Stimuli for Experiment I, (b) Experimental environment.

### *3.2 Method*

A group of 50 people comprising 29 males and 21 females took part in the experiment. The average age of the subjects was 21.76 years with a standard deviation of 3.28 years. They spent five minutes in a dark room before starting each evaluation in order to adapt to a dark environment [12], and the measured illuminance at the subject's position is less than 1 lx if the smartphone was completely off. During the experiments, they were instructed to view a smartphone at about 30 cm, a typical viewing distance of a smartphone display [20, 21], as depicted in Fig. 1 (b).

To discover the optimal luminance for *initial viewing*, the subjects were asked to look at the display with one of the five luminance stimuli right after the dark adaptation. The stimuli were shown in a random order, and both physiological and psychological responses were observed. The subject's facial expression was assessed to detect the momentary physiological response, and it is divided into three levels in this study: close the eyes or turn the head to avoid light emitted from the stimulus (1 point); look at the stimulus with a frown on the face (2 points); look at the stimulus without any facial change (3 points). That is, higher score

#241401 Received 11 Jun 2015; accepted 12 Jun 2015; published 18 Jun 2015
 

reports greater physiological comfort [22]. As a psychological response, subjective discomfort glare was evaluated using the de Boer scale [23]. The subjects rated their perceived level of glare on a nine-point scale, on which the score of one point represents unbearable glare, five points means admissible limit, and nine points implies unnoticeable glare. Discomfort glare can be regarded as connected to preference, since more glare causes severe discomfort and this reduces preference on the stimulus.

To investigate the ideal luminance for *continuous viewing*, the subjects were instructed to read an article on the smartphone display for five minutes. This task was repeated five times with randomly chosen luminance among the stimuli. Eye blinks during the task were counted since it is a well-known indicator to identify the physiological comfort of the human eye in prolonged viewing of displays [24]. Besides, a preference judgment was made regarding each stimulus with a five-point Likert scale in that one point indicates not preferred and five points signifies highly preferred.

In addition, the subjects watched the video clips of luminance changing at various rates and judged their preference for the stimuli with a five-point scale to determine the change speed of display luminance.

### *3.3 Result and analysis*

The optimal display luminance for *initial viewing* was discovered from the experiment. One-way ANOVA was performed to examine the effect of display luminance on facial expression. The analysis yielded statistical significance at an alpha level of 0.05 and confirmed that the effect was statistically significant, $F(4, 235) = 59.87$, $p < 0.05$, and post hoc analysis using Scheffe's criterion reported that the score of facial expression under the display luminance of 10 cd/m$^2$ are not statistically different from the luminance of 40 cd/m$^2$. That is, there were close to no changes in the subject's facial expressions for the two display luminances, whereas a frown on the face was observed when the luminance exceeded 70 cd/m$^2$. The score fell sharply with higher luminance as described in Table 2. A similar result was obtained from the glare evaluation. ANOVA showed that the average glaring score was significantly lower for high luminance than for low luminance, $F(4, 235) = 91.45$, $p < 0.05$. For luminance of 70 cd/m$^2$ and over, the score was less than five points on average, indicating that it is the admissible threshold on display brightness. These results implied that a luminance greater than 40 cd/m$^2$ is overly bright for *initial viewing* under low illuminance since it arouses visual fatigue, as well as that a display luminance of 10 cd/m$^2$ helps the subjects to maintain visual comfort.

**Table 2. The mean scores of the evaluations to find optimal luminance for *initial viewing* and that for *continuous viewing* (the standard deviations in parentheses).**

| Display luminance (cd/m$^2$) | *Initial viewing* | | *Continuous viewing* | |
|---|---|---|---|---|
| | Facial expression (scale: 1 to 3) | Discomfort glare (scale: 1 to 9) | Eye blinks (blinks/min) | Preference (scale: 1 to 5) |
| 10 | 3.00 (0.00) | 8.50 (0.71) | 9.08 (8.17) | 3.17 (1.45) |
| 40 | 2.88 (0.33) | 6.08 (1.69) | 11.16 (8.14) | 3.77 (0.90) |
| 70 | 2.56 (0.50) | 4.92 (1.70) | 11.65 (8.10) | 3.46 (0.87) |
| 100 | 2.13 (0.67) | 4.15 (1.80) | 12.79 (7.82) | 3.23 (0.88) |
| 140 | 1.71 (0.58) | 3.00 (0.58) | 14.01 (8.69) | 2.96 (1.11) |

Next, two analyses were conducted to reveal the optimal luminance for *continuous viewing*. ANOVA confirmed that the eye blinks got significantly higher with an increase of display luminance, $F(4, 235) = 2.45$, $p < 0.05$. According to Gowrisankaran's study, the eye

#241401 Received 11 Jun 2015; accepted 12 Jun 2015; published 18 Jun 2015

blinks under a non-stress condition and a glare condition are about 10 blinks/min and 13 blinks/min, respectively. In addition, people blink their eyes more frequently when they feel visual discomfort [25]. To put it into the experiment result, it can be interpreted that the subjects feel more discomfort watching a display under low illuminance as display luminance increases. Unusually high standard deviation was reported in the result of eye blinks due to the wide individual variations, but a high degree of inter-rater reliability was found (Intraclass Correlation Coefficient = 0.96). Furthermore, there was a significant difference observed between the preference scores depending on the display luminance, $F(4, 235) = 4.06$, $p < 0.05$. A luminance of 40 cd/m$^2$ was most preferred, whereas 140 cd/m$^2$ and 10 cd/m$^2$, which are two extreme luminance levels were the least preferred. Post hoc analysis using the Scheffe post hoc criterion for significance showed that the average preference score was significantly higher in the luminance of 40 cd/m$^2$ than in the other luminance levels. By taking into account the results, a 40 cd/m$^2$ was identified as the optimal luminance for *continuous viewing* on a smartphone under low illuminance.

The result of correlation analysis indicated that the average preference score increases as the change speed of display luminance decreases, $r = 0.33$, $p < 0.05$ (see Table 3). The reason is presumed to be that the subjects did not bother with changing display at a low speed because they were not even aware of the change. Consequently, a duration of display luminance change was set as 20 seconds, and as (40 cd/m$^2$ – 10 cd/m$^2$) / 1.5 cd/m$^2$·s, reflecting the result that the subjects prefer the display with slowly changing luminance.

**Table 3. The mean scores of the preference evaluation.**

| Change speed of display luminance (cd/m$^2$·s) | 1.5 | 3 | 6 | 10 | 30 |
|---|---|---|---|---|---|
| Preference (scale: 1 to 5) | 3.59 | 3.50 | 3.39 | 3.28 | 3.08 |

### *3.4 Adaptive display luminance*

Through the empirical results of the experiment, a model of adaptive display luminance for prolonged use of smartphones under low illuminance was developed as illustrated in Fig. 2. The name of the model originates from the feature that was established in consideration of time-dependent adaptation of the human visual system.

In the model, display luminance changes gradually with the passage of display-watching time. It starts at a fairly low display luminance of 10 cd/m$^2$ to prevent sudden glare or visual fatigue caused by strong light emitted from the display, and keeps this luminance for 10 seconds, which corresponds the time taken to reach a steady state of light adaptation [26, 27]. After that, the luminance increases very slowly until it reaches 40 cd/m$^2$ for 20 seconds to enhance the aesthetic quality of the display, and it maintains the intensity continuously.

#241401 Received 11 Jun 2015; accepted 12 Jun 2015; published 18 Jun 2015

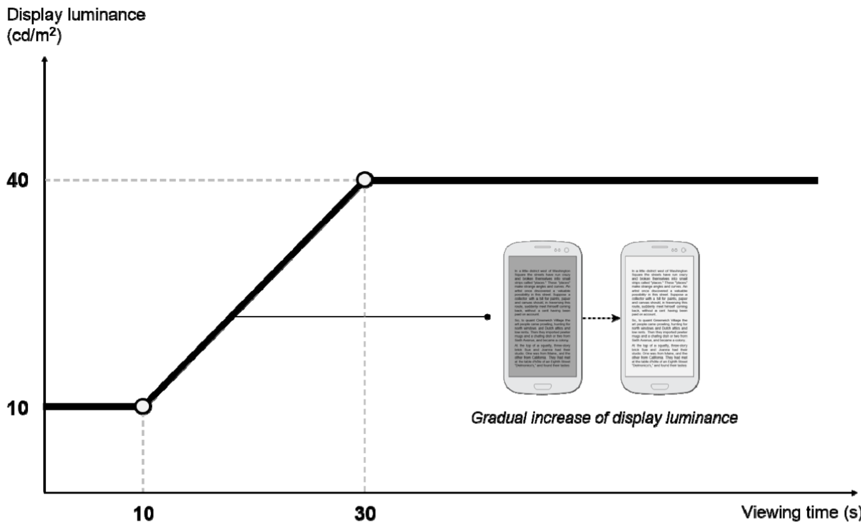


Fig. 2. Adaptive display luminance: it starts at a luminance of 10 cd/m$^2$, and 10 seconds later, the luminance increases for 20 seconds until it reaches 40 cd/m$^2$ and maintains the intensity continuously.

## 4. Experiment II: validation of adaptive display luminance

### *4.1 Stimuli*

Besides the adaptive display luminance, two additional luminance stimuli were prepared to compare the effect: a display luminance of 40 cd/m$^2$ that was judged as the most preferred luminance from Experiment I and a luminance of 80 cd/m$^2$ that is the luminance applying auto brightness function of a current smartphone in a dark environment. Accordingly, a total of three luminance stimuli were comprised for the validation test as listed in Table 4. Three different articles made up of black text on a white background were randomly provided as the reading contents.

**Table 4. Three luminance stimuli for Experiment II.**

| Stimuli | Display luminance (cd/m$^2$) | Notes |
|---|---|---|
| → | 10 → 40 | adaptive display luminance |
| | 40 | the most preferred luminance from Experiment I |
| | 80 | the luminance applying auto brightness of a current smartphone in a dark environment |

### *4.2 Method*

Twelve subjects including six male and six female participated in the experiment (mean age = 24.42 years, standard deviation = 1.66 years). The experimental environment was identical with Experiment I. As in the previous experiment, both physiological and psychological responses were assessed. In addition to counting eye blinks, brainwave analysis using electroencephalogram (EEG) was involved to quantify physiological comfort during the experiment. Subjective preference was judged with a five-point scale after each reading session to discover psychological satisfaction.

Prior to the experiment, four electrodes were carried out at positions of the frontal lobe for $F_{p1}$ and $F_{p2}$, the left lower earlobe for ground potential, and the right lower earlobe for reference potential for recording EEG signals, as shown in Fig. 3. After spending five minutes

#241401 Received 11 Jun 2015; accepted 12 Jun 2015; published 18 Jun 2015

in a dark room for adaptation, the subjects were permitted to read an article for two minutes at a natural speed on the smartphone display under the four luminance stimuli. They kept a distance of 30 cm away from the display, and a one-minute break was allowed before moving on the next session.

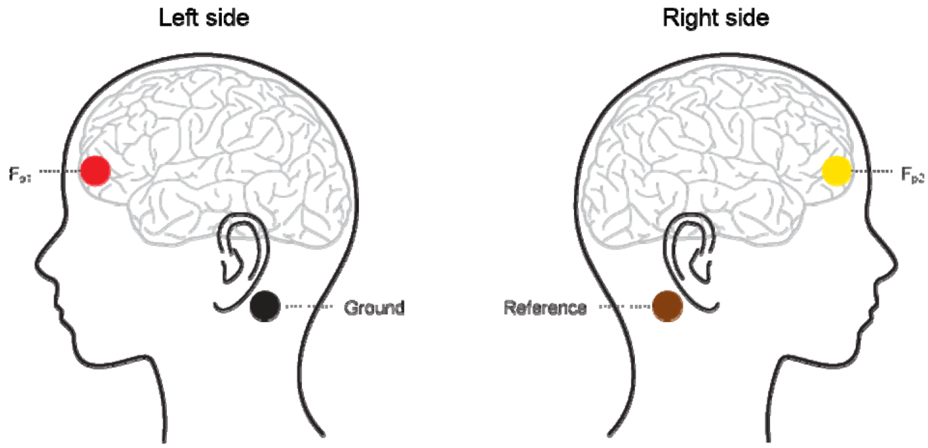


Fig. 3. Positions of the four electrodes for electroencephalogram.

### *4.3 Result and analysis*

Through the validation test, the effect of the three luminance stimuli was compared. There were considerable differences in eye blinks depending on the display luminance. Average eye blinks were remarkably lower with the adaptive display luminance than those with other luminance stimuli, as described in Table 5. The ratio of alpha waves (8 to 13 Hz) to the entire range (3.5 to 50 Hz), which indicates levels of physiological comfort [28], was the highest when the adaptive display luminance was employed. Considering that the alpha waves normally represent 15 or 20% of the total of the brainwaves while people close their eyes in comfort [29], the viewing condition under the optimal display luminance could be judged as comfortable enough. Besides, the subjects gave the highest score in preference to the adaptive display luminance. The results of the three evaluations imply that the adaptive display luminance is the most appropriate for prolonged viewing of smartphones under low illuminance.

**Table 5. The mean scores of the validation test (the standard deviations in parentheses).**

| Display luminance ($cd/m^2$) | Eye blinks (blinks/min) | Ratio of alpha wave (%) | Preference (scale: 1 to 5) |
|---|---|---|---|
| 10 → 40 | 11.73 (7.47) | 14.81 (5.07) | 3.64 (0.81) |
| 40 | 16.91 (8.93) | 12.99 (3.94) | 3.09 (0.70) |
| 80 | 17.18 (9.81) | 13.92 (4.92) | 3.55 (1.04) |

## 5. Discussion

The study examined the optimal display luminance for comfortable use of smartphones under low illuminance.

Experiment I revealed that the optimal display luminance for first sight of a display (*initial viewing*) and that for constant display watching (*continuous watching*) are different from each other and that the ideal value for each viewing condition is a luminance of 10 $cd/m^2$ and 40 $cd/m^2$, respectively. This finding is backed up by Mantiuk's study, which argued that a


Received 11 Jun 2015; accepted 12 Jun 2015; published 18 Jun 2015
29 Jun 2015 | Vol. 23, No. 13 | DOI:10.1364/OE.23.016912 | OPTICS EXPRESS 16919

display luminance of 40 $cd/m^2$ is appropriate for distinguishing displayed contents in a dark environment [12]. Based on the results, a model of adaptive display luminance, which supports time-dependent adaptation of human visual system, was developed. It provides very low luminance to prevent dazzling at first, and the luminance increases gradually when people get used to the brightness for keeping aesthetic quality of displays. Next, Experiment II validated the superiority of the adaptive display luminance in terms of physiological comfort and psychological satisfaction. Such a superiority in the concept of "changing luminance" has been discovered in previous studies [16, 30, 31].

The findings from this study provide some opportunities for further research. For example, supplementary research should be conducted for different age groups since visual ability varies substantially with age [32]. By comparing the optimal display luminance according to age groups, it can be possible to suggest a different version of adaptive display luminance fitting each group. It might also be meaningful to find the optimal display color for comfortable use of smartphones in a dark environment. Recent studies reported that the blue light emitted from displays particularly affects circadian rhythm and disrupts sleep [33, 34]. Thus, research is necessary to assess the optimal display color by reducing blue light while not distorting the perceived display quality. Such additional research can be relevant to enhance the value of the study.

## 6. Conclusion

This study investigated the optimal display luminance for viewing smartphones at night under low illuminance, and it developed a model of adaptive display luminance that supports users' physiological comfort and psychological satisfaction. In the model, the luminance increases gradually on the basis of display-watching time by considering visual adaptation. The effect of the adaptive display luminance was confirmed through a validation test. It is expected that this study contributes to a pleasing use of smartphone displays in conditions of low illuminance. Besides, we hope that it plays a decisive role in the electronics industry by increasing the product competitiveness of mobile devices.