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저조도 환경에 적합한 디스플레이 휘도 및 색도

Optimal Luminance and Chromaticity for Viewing Mobile Displays under Low Illuminance

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A thesis submitted to the faculty of KAIST in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Industrial Design. The study was conducted in accordance with Code of Research Ethics[1]

2015. 11. 16

Approved by

Professor Suk, Hyeon-Jeong

[Major Advisor]

[1] Declaration of Ethical Conduct in Research: I, as a graduate student of KAIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

저조도 환경에 적합한 디스플레이 휘도 및 색도

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ABSTRACT

With the increase in various types of electronic devices, people are spending many hours watching mobile displays. However, the light emitted by these displays exerts some adverse influences on users' visual comfort and preference, and this becomes more severe in a dark environment. Consequently, the problem caused by inappropriate luminance and chromaticity of displays has become a critical issue. In this regard, this study investigates the optimal luminance and chromaticity when viewing mobile displays under low illuminance by balancing physiological comfort and psychological satisfaction. The study involves three procedures as follows.

Firstly, the optimal display luminance was examined by evaluating physiological and psychological responses to diverse levels of luminance. The experimental results indicated that the optimal luminance for first-time viewing of a display differed from the optimal luminance for continuous viewing of a display, and the transition in display luminance between the two viewing conditions should occur slowly. Based on the results, an adaptive luminance model was established in consideration of the time-dependent adaptation of the human visual system. In the model, the display luminance changed gradually with the passage of time spent watching. It began at a luminance of 10 cd/m^2, and ten seconds later, the luminance started to increase for 20 seconds until it reached 40 cd/m^2.

Secondly, psychophysical experiments were conducted to examine the optimal display chromaticity by reducing blue light without distorting the perceived quality of displays. The subjects judged perceptibility and acceptability of the displays with different types of content and color composition. As a result, a white tinged with yellow was determined to be the optimal chromaticity, but there was some difference depending on the color composition of the content. A slight chromaticity shift to yellow is recommended if a white covers a majority of the display, whereas a large shift is permitted on a full-color display that has no white point.

Lastly, the effect of the optimal display was validated by measuring the subjects' physiological responses such as melatonin concentration, body temperature, and heart rate before and after using the different displays. The experimental result was that the display with low luminance and tinged with yellow did not affect users' circadian rhythm thus it supports restful sleep, and this confirmed the superiority of the optimal display compared with the current display for using smartphones under low illuminance.

We expect that the findings of this study will contribute to the pleasing use of mobile displays by applying to diverse types of visual display terminals, and the optimal display plays a decisive role in the display industry for increasing the design competitiveness of products.

Keywords: Optimal display, Display luminance, Display chromaticity, Low illuminance, Visual adaptation

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1. Introduction

This chapter introduces an overview of the dissertation. Section 1.1 provides background of the research. Section 1.2 lists the aims and objectives. The following section 1.3 briefly describes the relevant research methodologies to achieve the research questions. Finally, section 1.4 outlines the overall structure of this dissertation.

1.1. Background

Humans experience a variety of different kinds of light during daily lives. They meet thousands of levels of brightness and darkness due to varying degrees of sunlight and artificial light, and human visual perception begins by sensing those different levels of light, which is called luminance contrast. Luminance contrast is the ratio between higher luminance and lower luminance (Boyce, 2003; Fatin et al., 2012), in other words, the difference in luminance between ambient light and target light. The human visual system is more sensitive to contrast than to absolute luminance (Benedetto et al., 2014), so people perceive huge changes in illuminance in the course of a day, or from place to place. Namely, people are always being exposed to luminance contrast.

Nowadays, in addition to sunlight, light emitted from products such as LEDs on electronics or display backlights have begun to appear as part of a new lighting element in everyday lives as shown in Figure 1-1. Unfortunately, however, this new lighting element has created the problematic issue of luminance contrast. Since luminance and chromaticity can be easily adjusted in artificial lights, users are often exposed to inadequately high luminance contrasts which lead to visual fatigue due to dazzling or glaring light (Chen et al., 2012).

Figure 1-1. A LED on printer (left) and display backlight of electronic devices (Apple, 2014) (right)

This issue becomes a far more critical problem in displays. Contrary to sunlight and indoor lightings, the light emitted from digital displays moves directly to the users' eyes rather than being spread around. Besides, with the increase in various types of visual display terminals (VDTs), people spend many hours viewing displays such as televisions, laptops, smartphones, or tablet PCs during the day. This usually lasts into the night, meaning that about 80 % of people use their smartphone before bedtime in a dark environment (Gamble et al., 2014). However, viewing mobile displays at night brings users in contact with excessively high luminance contrast due to very low ambient illuminance, resulting in adverse effects on users' health (Yang et al., 2014). It not only leads to visual fatigue but also hinders people's ability to fall asleep easily or comfortably since it suppresses the secretion of melatonin, a hormone that promotes sleep in humans, and consequently it causes a delay in the timing of the body's circadian rhythm (Leichtfried et al., 2015). In fact, the light covering a wavelength range from 450 to 500 nanometers, which corresponds to blue light, interferes with the physiological system even more strongly (Morita and Tokura, 1996; Robertson, 2011). The definitive solution to this problem appears to be turning off a smartphone before bedtime, but it is undesirable or even impossible in many cases. Adjusting the display settings to suit users' environments can be a more reasonable solution. In this regard, this study draws the following two research questions:

Question 1. What is the optimal luminance for viewing mobile displays under low illuminance?

Question 2. What is the optimal chromaticity for viewing mobile displays under low illuminance?

where the word 'optimal' means the most favorable or desirable condition, and the range of 'low illuminance' is limited to less than 1 lx when the display is turned off.

In short, this study intends to investigate the optimal luminance and chromaticity of mobile displays for comfortable use in a dark environment, while not distorting the perceived image quality of displays. In this context, both physiological comfort and psychological satisfaction are considered as important aspects because the display that supports physiological comfort but lacks psychological satisfaction cannot be a good solution and vice versa. For example, a smartphone display with high luminance has a harmful impact on visual health despite the high level of preference. Similarly, users might not prefer the vivid red or yellow displays even though the displays are advantageous in a physiological aspect. Thus it is necessary to examine the optimal display that balances physiological comfort and psychological satisfaction for viewing mobile displays at night in conditions of low illuminance. With this, it contributes to a pleasing use of displays as well as it plays a decisive role in the electronics industry by increasing the design competitiveness of electronic display devices.

1.2. Aims and Objectives

The primary goal of this dissertation can be summarized as follows:

· *To investigate the optimal display luminance and chromaticity for viewing mobile displays under low illuminance by balancing physiological comfort and psychological satisfaction*

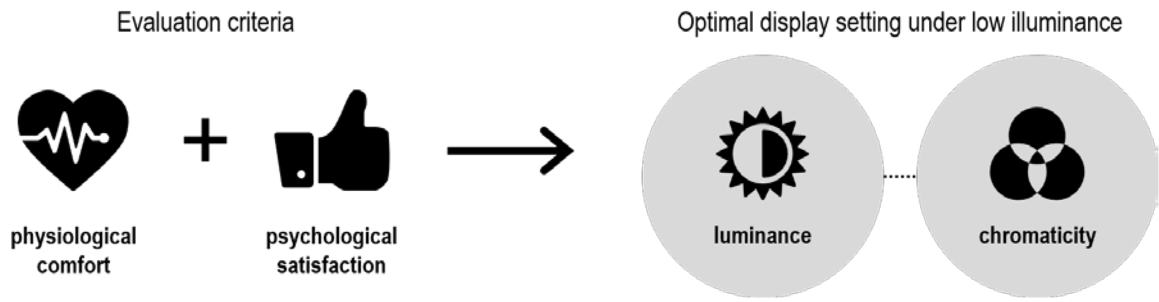


Figure 1-2. The primary goal of the study: an investigation of the optimal display luminance and chromaticity by evaluating physiological comfort and psychological satisfaction

The specific aims and objectives listed below include research questions and embrace the complete scope of the research.

Aim 1: To understand the need for adjusting luminance and chromaticity on mobile displays

Objective 1: To investigate definition and related knowledge about luminance and chromaticity

Objective 2: To explore the role and importance of display luminance and chromaticity

Objective 3: To identify the potential strengths of display adjustment for using smartphones at night

Aim 2: To investigate the decisive aspects for achieving the optimal display

Objective 4: To comprehend fundamental notions of the human visual system

Objective 5: To collect and synthesize key factors for judging display quality

Objective 6: To define the meaning of the optimal display in the context of research

Objective 7: To establish evaluation criteria for finding the optimal luminance and chromaticity

Aim 3: To examine the optimal luminance and chromaticity for viewing mobile displays under low illuminance

Objective 8: To design research methodologies for discovering the optimal display

Objective 9: To determine a numerical value or range of the optimal luminance and chromaticity for using mobile displays under low illuminance

Aim 4: To verify the effect of the suggested optimal display

Objective 10: To validate the superiority of the optimal display compared to the current display

Objective 11: To identify the values of the optimal display as a design competitiveness in an electronics industry and other industries

1.3. Research Methodology

Along with the entire stage of this dissertation, appropriate research methodologies were applied. The methodologies utilized to investigate the research aims and objectives combine literature review, observational study and a series of empirical experiments. The detailed information of the methodologies chosen for each section is summarized in Table 1-1.

Table 1-1. Research methodologies applied to each section

Section	Purpose	Research Methodology	Related Research Objectives
2.1. 2.2. 2.3	Understanding the roles and needs for adjustment of luminance and chromaticity on mobile displays	Literature review	Objective 1, 2 and 3
3.1.	Exploring the potential to change display luminance based on human visual system	Observational study	Objective 4 and 5
3.2.	Establishing evaluation criteria for setting the optimal display	Literature review	Objective 6 and 7
4.1. 4.2.	Discovering optimal display luminance under low illuminance	Laboratory experiment	Objective 8 and 9
5.1. 5.2. 5.3.	Discovering optimal display chromaticity under low illuminance	Laboratory experiment	Objective 8 and 9
6.1. 6.2.	Validating a superiority of the suggested optimal display	Field experiment	Objective 10 and 11

Literature Review

Prior to the research, the first thing that needs to be done is to conduct relevant literature review. An intensive review creates a firm foundation for advanced knowledge. It enables researchers to understand the current state of related research field, to uncover the area where research is necessary, as well as to establish the scope and initial hypotheses of the overall research (Webster and Watson, 2002; Kumar and Phrommathed, 2006). Hence, a literature review was rigorously conducted at an early stage of the study. In Chapter 2, a fundamental notion of luminance and chromaticity was investigated as well as the role and importance of them in displays were described. Besides, a scope of the research was clarified based on the in-depth analysis on existing research in relation to display adjustment. Next, evaluation criteria for the experiments were constructed in Chapter 3. In order to consider the key factors for user-centered display settings, reviews on human visual system were carried out. Also the evaluation model for this study was established by collecting and synthesizing various evaluation criteria from previous research.

Observational study

To find the potential for changing optimal display luminance with the passage of time, this study collected and observed diverse instances of luminance contrast in daily lives. An observational study investigates a contemporary phenomenon within its real-life context. Although it cannot deliver reliable information about the broader class due to the examination of a single example of a class of phenomena, it is useful in the preliminary stages of an investigation since it provides hypotheses, which might be tested systematically with a larger number of instances (Lawson and Garrod, 2001). Therefore the observational study was used in Chapter 3 to set a hypothesis of the research.

Experiment

Experiment is an empirical method that examines the theoretical arguments or new hypotheses (Cooperstock and Cooperstock, 2009). It is effective in establishing cause and effect by manipulating a particular factor (Spencer et al., 2005). Experiments are categorized into two basic types: laboratory experiment and field experiment. Laboratory experiment is carried out in a well-controlled environment therefore it allows accurate measurements. In this case, a researcher decides where the experiment will take place, at what time, with which participants, in what circumstances and using a standardized procedure (McLeod, 2007). In field experiment, conversely, the outcomes are observed in real-life situation. Thus it sometimes has higher external validity than laboratory experiments, but the researcher cannot exactly control the experimental condition.

In this study, experiments comprise a large proportion of the entire research process. A total of five laboratory experiments were employed in the process of identifying the optimal display luminance and chromaticity which corresponds to the experiments in Chapter 4 and 5, and a field experiment was conducted to validate the effect of suggested optimal display in Chapter 6. Moreover, various evaluation methods were used in respective experiment for judging physiological response and psychological response in a balanced perspective.

1.4. Structure of Dissertation

The dissertation is composed of seven chapters, as shown schematically in Figure 1-3.

Chapter 1 introduces the research background, aims and objectives, research methodology and the overall structure of this dissertation.

Chapter 2 presents a fundamental notion of light focusing on luminance and chromaticity, and discusses the importance of them on mobile displays. Also it describes a review of the existing literatures as it relates to the problems that are occurred when viewing mobile displays under low illuminance. In this respect, potential strengths of display adjustment for viewing smartphones at night is clarified.

Chapter 3 explores considerations for setting the optimal luminance and chromaticity on mobile displays. Initial hypothesis of the study is formulated based on the understanding of human visual system and the result of observational study. Besides, evaluation criteria for discovering optimal display are established as well as experimental process and environment are introduced.

Chapter 4 describes the optimal display luminance for viewing mobile displays in conditions of low illuminance. An experiment is carried out to examine users' physiological and psychological responses on various levels of display luminance, and adaptive luminance model is constructed by analyzing the experimental data. After that, the effect of developed model is validated with multidimensional assessments.

Chapter 5 investigates the optimal display chromaticity in consideration of the perceived quality of displays. Three experiments are sequentially conducted to discover users' perceptibility and acceptability on displays with different shades and contents. Once this is accomplished, the optimal display chromaticity for nighttime smartphone viewing is identified on the basis of the displayed contents.

Chapter 6 verifies the effect of the suggested optimal display in real-life situation. Validation test is carried out to confirm the superiority of the optimal display in comparison with the current display in respect of prolonged physiological response.

Chapter 7 concludes with a brief summary of the major findings and contributions of this dissertation. Future directions for study are suggested at the end.

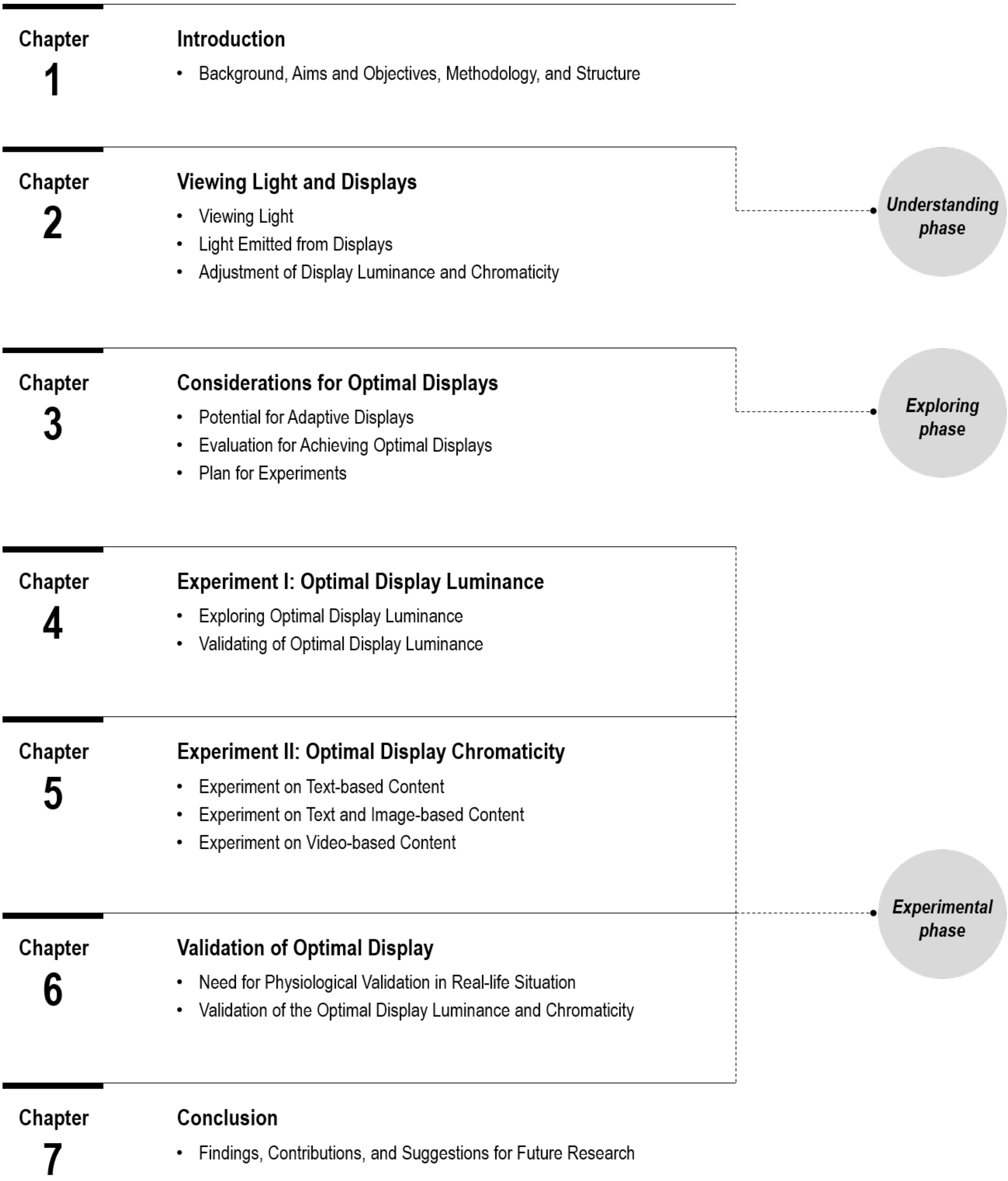


Figure 1-3. Structure of the Dissertation

2

Viewing Light and Displays

2. Viewing Light and Displays

This chapter builds a theoretical foundation for the entire stage of the dissertation by understanding light and displays. Section 2.1 describes background knowledge of luminance and chromaticity, as well as it lists possible problems caused by light in conditions of low illuminance. Section 2.2 presents the role and importance of luminance and chromaticity on displays, and the problems which occurred while viewing mobile displays in a dark environment is investigated. Based on the previous sections, section 2.3 argues the needs and potential strengths of display adjustment for viewing smartphones at night.

2.1. Viewing Light

2.1.1. Measuring the Viewing Experience of Light

Light usually refers to visible light, which is electromagnetic radiation that makes human eye possible to see things and is responsible for the sense of sight (Barbrow, 1964). It includes the natural light by capturing daylight and artificial light sources such as lamps, light fixtures, neon signs, LEDs on products, and light emitted from displays as seen in Figure 2-1. In general, light experienced by users is categorized into brightness and chromaticity (Brown and MacAdam, 1949; Nagy and Sanchez, 1992).

Brightness of light is measured with three main alternative sets of units: luminous intensity, luminance and illuminance (Taylor, 2000). Luminous intensity refers to the overall brightness regardless of the area of light source, and the unit is candela (cd), an SI (International System of Units) base unit (Komine and Nakagawa, 2004). Luminance is defined as the luminous intensity per unit area in a given direction (Oxford, 2014). It describes an amount of luminous power which is detected by eyes looking at the surface from a particular angle of view, hence it is an indicator of how bright the surface appears to be. The SI unit of luminance is candela per square meter (cd/m^2), the ratio of the luminous intensity emitted in a certain direction (candela) divided by the projected surface area in that direction (square meter) (Page and Vigoureux, 1974; Schubert et al., 2005).

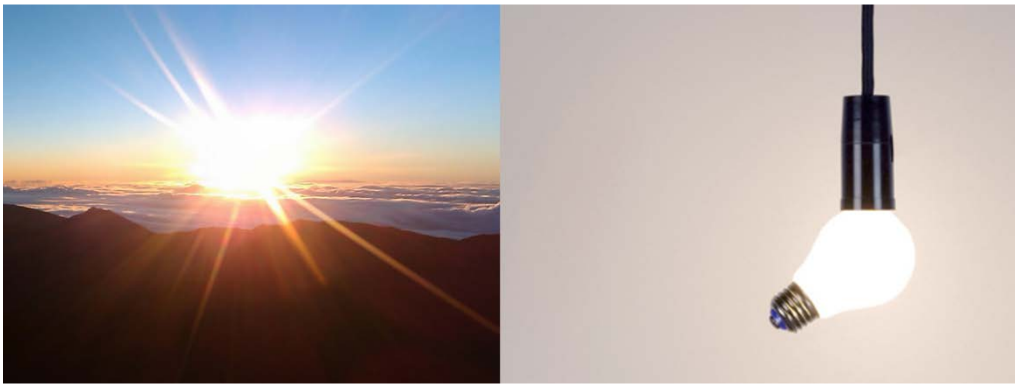


Figure 2-1. Example of natural light (Atwater, 2013) (left) and artificial light (Tsuboi, 2007) (right)

If a person is exposed to two different levels of luminance, it soon leads to luminance contrast. Luminance contrast is the difference in appearance of two luminance levels, and higher luminance contrast indicates larger brightness differences. It is normally recognized that higher luminance contrast enhances visual accuracy (Legge and Rubin, 1986; Benedetto et al., 2014), but overly high contrast reduces visual comfort and decreases visual accuracy as well (Yang et al., 2014). Luminance contrast can be specified by contrast ratio, *CR*, one of the oldest and widely used luminance contrast statistics in electronic displays field (Tadmor and Tolhurst, 2000), defined as:

$$CR = \frac{L_H}{L_L} \ with\ 1 \ \leq CR \leq \infty$$

with L_H and L_L representing higher luminance and lower luminance, respectively. There is no contrast if *CR* is one, and the maximum contrast towards infinity.

While luminance is the major parameter for display measurements and characterization since it measures an intensity of light source directly (Chen et al., 2012), illuminance is a commonly used unit for measuring brightness of lighting fixtures. It refers to the total luminous power reaching a given point on a defined surface area (Meyer-Arendt, 1968), namely a measure of how much incident light illuminates the surface. Illuminance is in inverse proportion to the distance from a light source, and the SI unit is lux (lx) or lumens per square meter (lm/m^2), dividing the luminous power (lumen) by the surface area. The outdoor illuminance of sunlight at noon is over than 100,000 lx, intensity of an office lighting is approximately 400 to 700 lx, and moonlight at night is usually less than 1 lx (Zombeck, 1990).

Likewise, brightness varies according to time or place as well as it plays an important role in our daily lives. Therefore some research have addressed to investigate the effect of the light on humans, and several practical guidelines were proposed. The Illuminating Engineering Society of North America (IESNA) suggested a luminance guideline with regard to the perceptual threshold (Rea, 2000). Goven and his colleagues (2007) examined the background luminance and color temperature for indoor activities. Similarly, Kim, Baik and Jeong (2008) presented an appropriate interior illuminance of working surface.

Aforementioned three parameters, luminous intensity, luminance and illuminance, are interconnected with each other. For example, brightness of surroundings exercises a huge influence on the perception of human vision, thus consideration of ambient illuminance is positively necessary for determining the luminance level (Fairchild, 2013; Benedetto et al., 2014). The physical relationship among three parameters is illustrated schematically in Figure 2-2. Along with the entire study, luminance is used to indicate the unit of brightness because this study mainly deals with light emitted from displays.

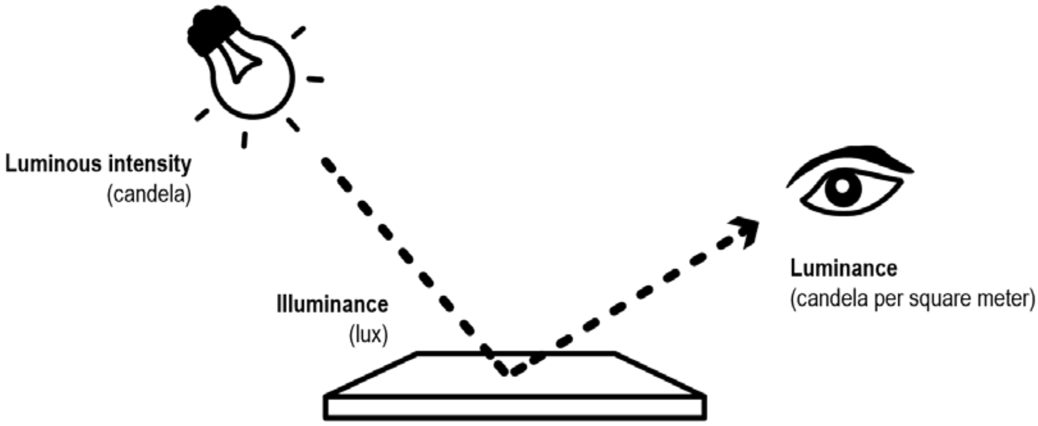


Figure 2-2. Interactions of light: Luminous intensity refers to the overall brightness, luminance indicates the luminous intensity per unit area into a given direction, and illuminance is an amount of light that covers the defined surface

Meanwhile, with the development of a light-emitting diode (LED) which allows users to change light colors freely and easily, the role of chromaticity has been increased in a field of lightings. Chromaticity is an objective specification of quality of a color as determined by its dominant wavelength and purity regardless of luminance (Wiaderek and Rutkowska, 2013). The systems for color specification include CIE XYZ color space, CIELAB color space, and CIELUV color space (Poynton, 1997). In addition, RGB color model is an essential system to understand basic color system.

RGB color model is an additive color system based on the theory that all visible colors can be created by three primary colors. It is represented by a three-dimensional cube with red, green and blue at the corner on each axis as shown in Figure 2-3, and the respective color value varies from 0 to 255 (Singh et al., 2003). The model is widely used as input values to display images in electronic systems such as televisions, computers and mobile phones. It is easy to implement, but non-linear with human visual perception. Besides it is a device-dependent model, which means that different devices detect or reproduce a given RGB value differently (Cheng et al., 2011).

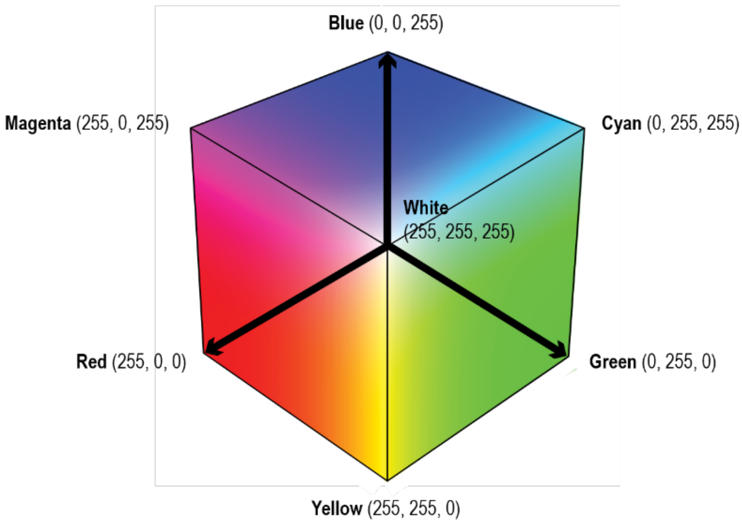


Figure 2-3. RGB color cube: a three-dimensional cube with red, green, and blue at the corner on each axis

CIE XYZ color space is established by International Commission on Illumination (CIE) in 1931 based on the tri-stimulus values which are indicated as X, Y, and Z. These values do not directly correspond to red, green and blue, but can be converted into those values. In this system, the small x and y values which have derived from the XYZ tri-stimulus are used to draw the CIE xy chromaticity diagram as seen in Figure 2-4 (Kerr, 2010). Any chromaticity can be expressed on the chromaticity diagram. CIE XYZ values are basic for colorimetry, but there is a limit that the measured value is not directly connected to the perceived color. Hence, CIELAB and CIELUV color spaces were adopted in the year of 1976.

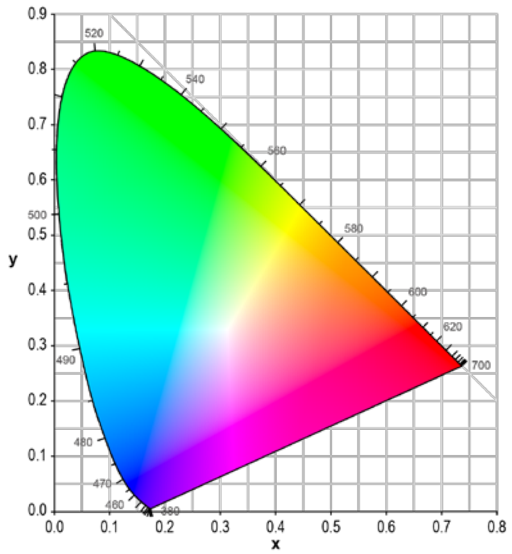


Figure 2-4. CIE xy chromaticity diagram (Schanda, 2007)

CIELAB color space is a system in which L* means brightness, and a* and b* refer to the color-opponent dimensions. Similarly, CIELUV color space is a chromatic space by using lightness L*, and a set of chromatic values with u* and v*. These systems were developed by reformulating CIE XYZ color space on the basis of human visual system to make a space perceptually uniform, which means that a distance between two colors in the space is almost identical with perceived color differences (Zhang et al., 1997).

Meanwhile, during the last few decades, a great effort has been made to investigate the emotional effect of chromaticity on human being. Some studies observed the influence of office lighting colors on employee work performance (Mills et al., 2007). Lee and Suk (2012) studied the emotional response to lighting colors focusing on relaxation and attention. Philips, one of the leading company in a lighting industry, identified the effects of LED lighting in diverse kinds of real-life contexts, including educational and medical spaces (Wessolowski, 2014).

As a way to represent chromaticity, RGB values are mainly employed throughout the study. In addition, the x and y coordinates in CIE XYZ color space is used as well for indicating chromaticity of light emitted from displays since RGB is a device-dependent color model as explained earlier. A brief description on the brightness and chromaticity is summarized in Table 2-1.

Table 2-1. A description on brightness and chromaticity (Taylor and Thompson, 2001)

Measurement	Name	Units	Description
Brightness	Luminous intensity	Candela (cd)	SI base unit, luminous flux per unit solid angle
	Luminance	Candela per square meter (cd/m^2)	Luminous intensity per unit area in a given direction
	Illuminance	Lux (lx)	Amount of light reaching on a surface
Chromaticity (Color)	CIE XYZ color space	X, Y, Z or x, y	Color space based on the tri-stimulus values: X, Y, and Z
	CIE LAB color space	L*, a*, b*	System based on Opponent-color theory Perceptually uniformed space
	CIE LUV color space	L*, u*, v*	Perceptually uniformed space
	RGB color model	R, G, B	Additive color system based on the red, green and blue

2.1.2. Viewing Light under Low Illuminance

As noted above in the previous section, luminance contrast affects visual perception. It is more likely to increase the contrast under low illuminance since ambient luminance is close to zero in that context. In the past, daylight was almost the only one that emitted light so there were not severe problems resulting from luminance contrast. In these days, however, the problem has become a serious issue due to diverse kinds of artificial light flashing day and night such as interior lightings of buildings, road lightings, and illuminated advertisings. It is called as light pollution. According to International Dark-Sky Association (IDA), light pollution is defined as any adverse effect due to man-made sources of light, including glare, light trespass, light clutter, sky glow, an absence of darkness, and waste of energy (Chepesiuk, 2009). The map of light pollution all around the globe (see Figure 2-5) convinces people the seriousness of light pollution. It obscures the view of starlight in the night sky, disrupts ecosystem and has adverse health effects on human (Longcore and Rich, 2004).

In this regard, many regulations and guidelines have been enacted to reduce the problems. For instance, the Japanese government made a Light Pollution Control Guidelines in 1998, and Clean Neighborhoods and Environment Act was legislated in United Kingdom (Narisada and Schreuder, 2004). In Korea, Light Pollution Prevention Law according to artificial light were established in 2013. With this, some research carried out to discover the impact of light pollution on human health, environments and stellar visibility (Hölker et al., 2010; Falchi et al., 2011). Studies for finding the appropriate luminance and angle of road lightings or vehicle headlights at night have been conducted actively as well (Anderson and Holliday, 1995; Eloholma et al., 2004).

Figure 2-5. The map of light pollution all around the globe (IAU, 2014)

Nowadays, light in indoor environments has begun to emerge as a part of new light pollution, which is called indoor light pollution (Hollan, 2008). Artificial light in indoor circumstance can be classified into three types: lamps, LEDs on electronics, and self-luminous displays as described in Table 2-2. Among them, lamps are not mainly responsible for indoor light pollution. It just lights up the whole space hence it is not very harmful to visual health. On the other hand, the remains of the two other light sources, LEDs on electronics and self-luminous displays are causing a rise in indoor light pollution when they are shining in a dark room. In the words of March (2008), late night visit to kitchen revealed that our living spaces are suffused with offensively bright LEDs that can trigger a visual fatigue and even migraine. However, dimming brightness of the LEDs or displays could not serve their original purpose of which is to convey specific information to users.

Table 2-2. Three types of artificial light and examples: lamps, LEDs on electronics, and self-luminous displays

Type of artificial light	Examples
Lamps	Ceiling lamp, desk lamp, night lamp
LEDs on electronics	Battery charger, electronic clock, computer, microwave oven, humidifier
Self-luminous displays	Television, computer monitor, laptop, tablet PC, smartphone, e-book

Inadequate levels of light under low illuminance bring about two serious problems: unduly low luminance reduces visual performance, whereas overly high luminance leads to visual fatigue and decline of visual performance (Murray et al., 2002). Therefore, some products were recently introduced to the market to alleviate the problems, such as a sticker to block or dim LED lights which is named ‘LightDims’ as seen in Figure 2-6, but more desirable solution has not yet been suggested. Applying guidelines for outdoor light pollution to indoor case is inappropriate either because of different environments. Thus in-depth research should be conducted to solve the fundamental problems.

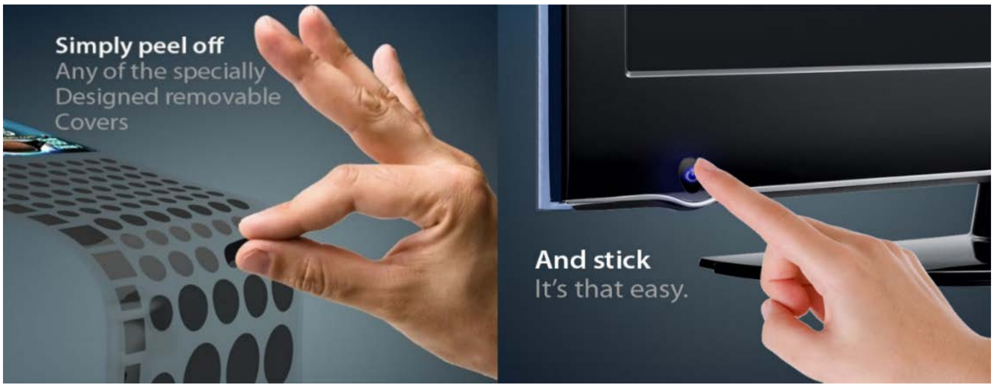


Figure 2-6. LightDims: stickers to block or dim annoying electonic LED light (LightDims, 2013)

2.2. Light Emitted from Displays

2.2.1. Luminance and Chromaticity on Displays

Display technology has been developed as the use of electronic devices increased. Particularly, display image quality is in a constant state of improvement. According to existing literatures, there are five major psychophysical attributes affecting the display image quality evaluation: naturalness, brightness, sharpness, contrast, and colorfulness (Kim, Luo, et al., 2008). Among these, brightness and colorfulness which correspond to luminance and chromaticity respectively, are not only the easiest attributes to recognize the change in displays but also they play the most influential role in order to judge the display quality (Guan and Hung, 2010). In addition, display tone mapping system is operated in the consideration of brightness, contrast, and color of image (Čadík et al., 2006).

On the aspect of a technical improvement, high luminance and wide color gamut explicitly indicate advanced displays (Chang et al., 2004; Yoshida et al., 2006; Choi et al., 2010). Consequently the competition between display manufacturers for implementing high luminance, high contrast ratio and wide color gamut has become more intense, as well as related research have been actively conducted (Ou et al., 2014) . Roth (2003) presented a multiple primaries technology that enables substantial increase in both color gamut and brightness of displays. Chino and his colleagues (2006) developed a wide color gamut for mobile displays. In study of Carroll and Heiser (2010), an algorithm was proposed to improve image quality in LCD applications. In recent years, many works have been done on the topic of LEDs for implementing higher color purity and brightness (Peng et al., 2011; Shang et al., 2012). With these hard works and efforts, today's mobile displays which usually have LCDs with LED backlight or OLEDs, facilitate to adjust the display brightness from the very low levels of luminance to the high levels of luminance with a good contrast and color rendering (Andrén et al., 2014).

When people actually use electronic display devices, however, perceptual aspect is considered more important than technical aspect in many cases because ultimate judgment for display quality is decided by user's perceptual assessment although the quality can be represented by technical values (Park et al., 2008). Ambient illuminance also wields great influence upon the perception of display images (Shieh and Lin, 2000; Rempel et al., 2009). The display with strong luminance in a dark environment causes visual fatigue, and the work with the dim display in a bright office decreases users' preference on the display device (Hultgren and Knave, 1974). Change in chromaticity reduces a display preference as well (Choi and Suk, 2014).

Therefore during the last years, numerous research have attempted to find the optimal display settings with respect to users' perceptual aspect. Guterman's research team (2010) addressed the question of user-preferred display brightness. Dixon and Di Lollo (1991) investigated the effect of display luminance on visible and schematic persistence. Some scholarly works argued that high levels of luminance improve the perceptual ability but the display with excessively high luminance decreases visual performance (Knoblauch et al., 1991; Krupinski et al., 1999; Menozzi et al., 2001), as well as Swinkel and his colleagues (2008) discovered that users prefer moderate levels of luminance whereas they dislike unduly high luminance. The studies imply that both preference and performance decrease when the display has overly high or low levels of luminance. In this context, several research suggested the appropriate range or threshold of luminance in real-life conditions as listed in Table 2-3. Meanwhile, Legge and his co-workers (1990) conducted a psychophysical method for comparing the readability on displays under different luminance contrast and color contrast. Similarly, Matthews (1989) assessed the visual performance and subjective discomfort in prolonged viewing of chromatic displays. In Zhang's study (2014), it was discovered that color performance of tablet PC is affected by display brightness settings.

In general, displays with high technology allow adjustments of luminance and chromaticity in a wide range, so it is feasible to change display settings within the range for enhancing perceptual ability and preference. Thus, technical advances and perceptual guidelines should be synergized to implement the optimal display luminance and chromaticity.

Table 2-3. Optimal luminance or luminance contrast for various kinds of activities

Authors (year)	Unit	Value	Description
Rempel et al. (2011)	Luminance	at least 20 cd/m^2	Recommended display luminance for reading on black and white screen in a dark environment
Rempel et al. (2011)	Luminance	at least 40 cd/m^2	Recommended display luminance for watching a content consisting of several brightness levels in a dark environment
ISO (2009) Inoue et al. (1998)	Luminance	100 to 150 cd/m^2	Recommended display luminance when the ambient illuminance is 500 lx
ANSI (1987) Chen et al. (2012)	Luminance contrast	3:1 to 500:1	Eye fatigue free range
ISO (1998)	Luminance contrast	10:1	Recommended for reading on displays

2.2.2. Viewing Mobile Displays under Low Illuminance

Electronic display devices are widely used with no regard to time and place. Especially, smartphones have become almost a necessity for millions of people due to portability and multi-functionality. The average amount of time that people spend using smartphones is about 195 minutes, namely more than three hours a day, and the time is concentrated in the night before sleeping (Van den Bulck, 2007; Scott and Sale, 2014). According to a recent study, people are most active on their smartphones at 9 pm, with a lull setting in between 3 am and 4 am (McKenzie, 2013). More than four fifths of people use the smartphone late at night in a dark room, being utilized in activities such as watching videos, playing games, texting or browsing the websites (Nick, 2012; Chen et al., 2013), as well as they keep their smartphones right next to the bed or under the pillow (March et al., 2008). However, the light emitted from smartphone displays exercises an adverse health effect on users, and this problem becomes a far more serious at night.

A luminous display under low illuminance gives rise to visual fatigue. It is perceived as dazzlingly bright in a dark environment comparing with the display which has same level of luminance but is seen under daylight illuminance (Guterman et al., 2010), as shown in Figure 2-7. At the same time, light emitted from displays hinders people's ability to fall asleep easily nor comfortably by strong involvement in a physiological system (Cajochen et al., 2003). It suppresses nocturnal melatonin production, a hormone that promotes sleep in humans (Monk et al., 1997; Figueiro, 2013; Leichtfried et al., 2015), and consequently delays the timing of the body's circadian rhythm (Gooley et al., 2010). A research team found that a two-hour exposure to light from electronic displays suppresses melatonin by about 22 % (Wood et al., 2013), and thus most nighttime smartphone users indeed reported that they are not getting enough sleep (Mozes, 2014). Especially the light covering a wavelength range between 450 to 500 nanometers, which corresponds to blue light, disrupts circadian rhythm even more strongly (Morita and Tokura, 1996; Lockley et al., 2003).

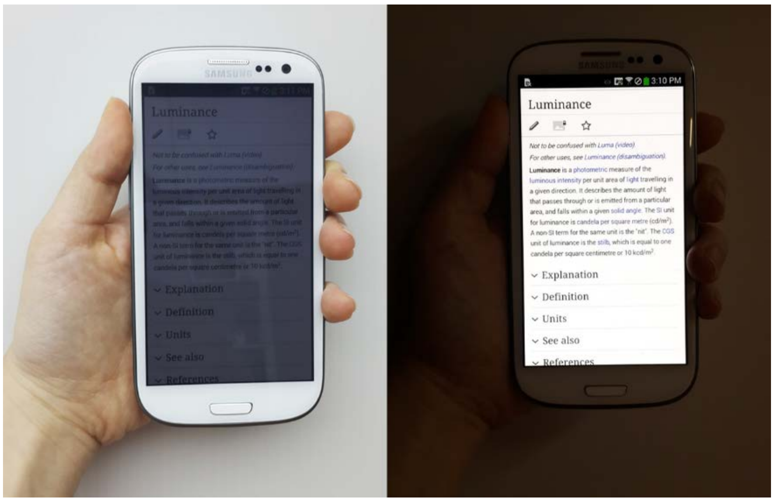


Figure 2-7. Two smartpyone displays with same luminance but under differenct levels of illuminance: too dim under daylight illuminance (left) but bright enough in a condition of low illuminance (right)

The problem gets more severe in terms of adolescents' physiological and psychological health. Some recent research demonstrated that using electronic display devices at night before sleep delays sleep-wake cycle, causes sleep disturbance, as well as it might bring about the risks of impaired academic performance and even depression (Van Dongen and Kerkhof, 2011; Gamble et al., 2014).

Although the light emitted from displays is being magnified as a critical issue in daily lives, relatively little attention was paid to examine the optimal display settings at night under low illuminance. A research revealed that the majority of users prefer lower display luminance in darker environments (Rempel et al., 2009), but the accurate luminance for comfortable use of smartphone is not yet recommended. Likewise no definitive answer has been given to the proper display chromaticity for reducing the adverse effect of blue light.

2.3. Adjustment of Display Luminance and Chromaticity

The existing problems caused by inadequate display settings under low illuminance were discussed in the previous section, and some electronic display devices provide several solutions to resolve the problem.

With regard to display luminance, an auto-brightness function has been applied to most mobile devices to offer a perceptually ideal brightness by altering display luminance depending on the ambient illuminance as presented in Figure 2-8 (Mantiuk et al., 2009; Lane et al., 2010). This function supports practically desirable solution in most cases but it is hard to implement proper display luminance in extreme environments, because auto-brightness function was primarily designed for the operation in daytime. In Ma's argument, the display brightness is always too dim with high ambient light, such as in the midday sun, whereas too bright in a dark place (Ma et al., 2012). Figure 2-9 shows the measured display luminance at different levels of ambient illuminance using Samsung Galaxy S4. According to the graph, there was almost no change in display luminance below a certain illuminance level, and display luminance rose sharply when the illuminance is over a certain level. It implies that the existing function is inappropriate to apply in conditions of low illuminance, for example when a user is lying in the bed at night. Regretfully, however, many people use their smartphone before sleeping, and they manually change the display luminance in this case.

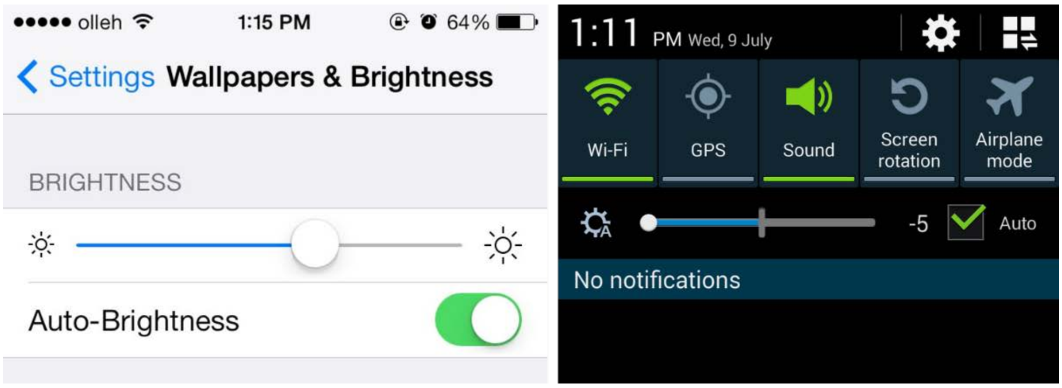


Figure 2-8. Auto-brightness function in iPhone 5S (Apple, 2014) (left) and Galaxy S4 (Samsung, 2013) (right)

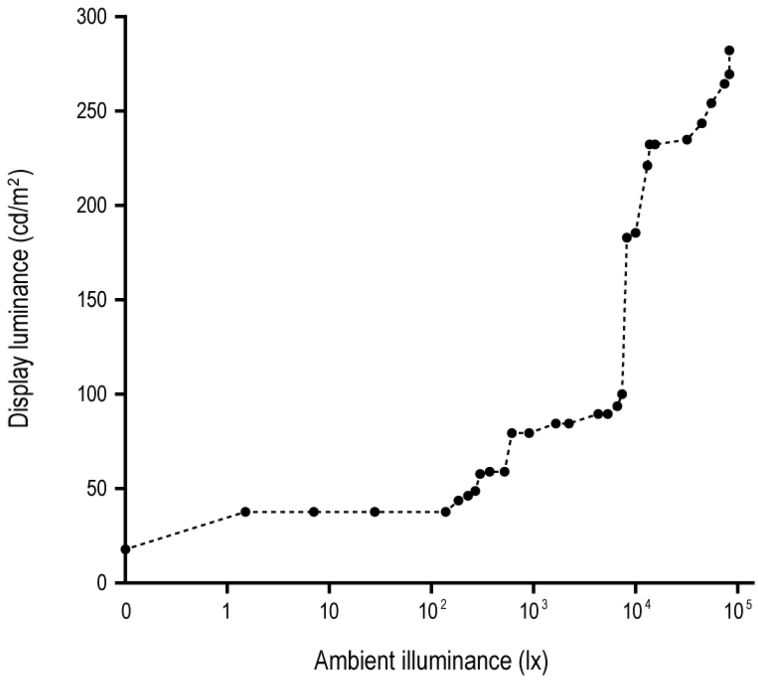


Figure 2-9. Measured smartphone display luminance at different levels of ambient illuminance

The function for preventing blue light, namely implementing the optimal display chromaticity is still not installed as a default function of mobile devices. The mobile application that covers a yellow-colored layer on display is the only solution that has been suggested so far, as illustrated in Figure 2-10. However it does not serve a specific value or threshold for layer colors, hence sometimes the display becomes too dark or too yellow as a result of unwise use.

Figure 2-10. Bluelight filter: a mobile application for reducing blue light by covering a yellow-colored layer on smartphone displays (Hardyinfinity, 2014)

In short, despite a constant increase of the hours of smartphone use at night, there is no definitive solution for setting ideal displays. Therefore it needs to be developed the optimal luminance and chromaticity for viewing mobile displays under low illuminance accompanying with objective evidence. With this, displays can be a part of design competitiveness in electronic devices.

2.4. Summary

To establish theoretical background related to the dissertation, this chapter started with fundamental knowledge of light and displays, and reviewed previous studies and existing solutions to extract potential needs for adjustment of display luminance and chromaticity.

First of all, a fundamental notion of light was represented concentrating on major units for measuring brightness and chromaticity. In-depth knowledge on luminance, CIE XYZ color space and RGB color model were studied to express display characteristics. Also the problems occurring under low illuminance due to strong light were explored, as well as the types, consequences and alleviation plans of light pollution were listed. Besides it is discovered that artificial lights in indoor environments such as lamps, LEDs on electronics, and self-luminous displays have become a new part of light pollution. Based on the discovery, roles and importance of luminance and chromaticity in displays were discussed, and a review of literature was conducted on displays in terms of technical aspect and perceptual aspect. Next, the adverse influences while viewing displays at night in conditions of low illuminance were described, and the potential needs for implementing optimal display settings for nighttime smartphone users were finally clarified.

The next chapter provides the considerations for achieving optimal display through literature review and observational study.

3

Considerations for Optimal Display

3. Considerations for Optimal Display

This chapter establishes the initial hypotheses of the dissertation and describes the considerations for achieving optimal display. Section 3.1 presents basic knowledge about human visual system and conducts an observational study to explore the potential for adaptive display which changes display luminance with the passage of time. In section 3.2, existing criteria for assessing the quality of displays and lightings are collected and evaluation model for the study is identified. Following section 3.3 explains the process of experiments and experimental environment.

3.1. Potential for Adaptive Display

3.1.1. Approach to Human Visual System

Human visual system is a matter of primary consideration in adjustment of display settings. An eye is one of the most sensitive and complicate organ in human body, and it carries out a variety of operations with regard to environmental stimulations.

The human vision is capable of seeing a huge range of intensities, from night luminance of approximately 10^{-6} cd/m^2 to daylight level of around 10^8 cd/m^2 (Pattanaik et al., 2000; Ledda et al., 2004). Although the range of perceived brightness is narrower than the range of absolute intensities since it follows a power function with a slope of around 0.33 (Anstis, 1976), the visual system still can accept a wide range of scene intensities.

There are two different types of photoreceptor cells in human retina of the eye, rod cells and cone cells. Rod cells are used for vision at low light levels, under dark conditions. They are highly sensitive to light but not mediate color vision, and have a poor visual acuity (Rodieck, 1998; Hecht, 2002). On average, there are about 120 million rod cells in human retina (Curcio et al., 1990). Conversely, cone cells are activated at much higher light levels. They are less sensitive photoreceptors than rod cells, but are responsible for color vision and provide higher visual acuity (Brown and Wald, 1964; Sigismondi, 2011). There are three types of cone cells refer to as the short-wavelength sensitive cones (abbreviated to S-cones), the middle-wavelength sensitive cones (M-cones) and the long-wavelength sensitive cones (L-cones) which are not perfectly matched but can denoted as the red-sensitive, green-sensitive, and blue-sensitive cones, respectively (Schubert et al., 2005). The number of cone cells are approximately six to seven millions, much fewer than that of rod cells.

Based on the types of activated photoreceptor, the enormous range of the vision can be divided into three modes: photopic vision, scotopic vision and mesopic vision. Photopic vision is the vision of the eye under bright environments with the range between 10 cd/m^2 and 10^8 cd/m^2 (Wyszecki and Stiles, 1982; Ledda et al., 2004). It allows color perception and is mediated by cone cells. Scotopic vision operates under very dark conditions corresponding to luminance levels of 10^{-1} cd/m^2 to 10^{-6} cd/m^2. Cone cells are nonfunctional in low light, so only rod cells are activated in scotopic vision (Hecht, 2002). Lastly, mesopic vision occurs in low but not quite dark conditions with luminance range from 10^{-3} cd/m^2 to 10$^{1/2}$ cd/m^2, and is a combination of photopic vision and scotopic vision (Stockman and Sharpe, 2006). Both rod cells and cone cells contribute to the vision, but it cannot fully support visual acuity and color discrimination. Most of night environments such as dark rooms, dim roadways and other outdoor locations fall within the range of mesopic vision (International Commission on Illumination, 1994). The aforementioned information on three vision modes are depicted in Figure 3-1.

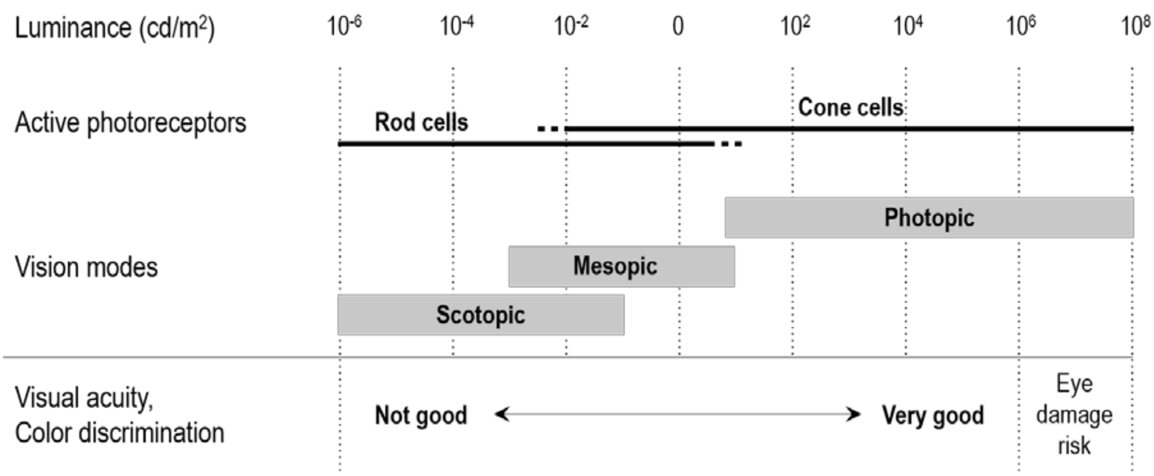


Figure 3-1. Three vision modes under different levels of ambient luminance: photopic, scotopic and mesopic visions resulting from the specific response of rod cells and cone cells (TelescopeOptics, 2014)

As referred to earlier, different vision modes activate according to the amount of ambient light. In real-life situations, light levels rapidly change since the ambient illuminance varies depending on place to place. Adaptation is a function of the body running in these situations to make observer less sensitive to a stimulus. The term visual adaptation describes the dynamic processes by which the visual system alters its operating modes in response to change in the ambient illuminance (Clifford et al., 2007). There are three subcategories of visual adaptation including light adaptation, dark adaptation and chromatic adaptation.

Light adaptation occurs when people move from dark to bright environment. The situation that turning on a room lighting in the middle of the night after awakening from sleep is one of the example. The bright light momentarily dazzles people at first so they cannot see much of anything, but after tens of seconds, people are able to see objects normally without any discomfort (Fairchild, 2013). During the light adaptation, rod cells and cone cells are both stimulated and large amounts of the photo pigment, which is called rhodopsin are separated into opsin and retinal instantaneously, producing a flood of signals resulting in the glare (Guyton and Hall, 2006). The process for light adaptation occurs under luminance greater than about 3.4 cd/m^2 and it takes place very quickly, usually less than a minute to maximum five minutes (IES, 2003; Kaiser, 2009).

Dark adaptation happens when people suddenly enter a dark area from bright environment, as the reverse of light adaptation. As an example, when people switch off the room lighting before going to bed, the room seems completely dark at the beginning hence even it is hard to recognize where the bed is. With the passage of time, however, the objects in the room become distinguishable, and a few more minutes later, there is no difficulty to see almost of the objects except some details such as pattern on the wall or color of the chair. The initial darkness is because cone cells cease functioning under low illuminance, and rod cells take up to 30 minutes to fully recover sensitivity by regenerating rhodopsin again (Hecht et al., 1937). Therefore, the time course to complete dark adaptation is approximately 30 minutes, much longer than light adaptation, and it happens under the luminance less than about 0.034 cd/m^2 (IES, 2003). Table 3-1 lists the differences between light adaptation and dark adaptation.

Chromatic adaptation makes people perceive same color differently under varying ambient illuminants (Hunt, 1950; Fairchild, 1991; Choi and Suk, 2014). However the sensitivity of color discrimination remains constant for normal observers until the ambient luminance drops about 3.4 cd/m^2, and the discrimination decreases rapidly below this luminance level (Brown, 1951). Thus there is no need to consider the effect of chromatic adaptation in the study since this study is conducted in the absence of ambient light.

Table 3-1. Comparison of light adaptation and dark adaptation

	Light adaptation	**Dark adaptation**
Ambient luminance	over than 3.4 cd/m^2	less than 0.034 cd/m^2
Active photoreceptors	rod cells, cone cells	rod cells
Biological process	rhodopsin → opsin + retinal	opsin + retinal → rhodopsin
Time course to complete	1 to 5 minutes	approximately 30 minutes

In conclusion, one of the most important feature in human visual system is a time-dependent adaptation process (Adelson, 1982; Ledda et al., 2004). As previously stated, the condition that people feel too dark at first becomes accustomed with the passage of time, and overly bright light is getting better to stare as time goes by. In other words, the changes in visual sensitivity are controlled by the lapse of time (Rushton, 1965; Zele et al., 2013). Consequently it implies the potential for 'adaptive display', which alters display luminance over time in the light of visual adaptation, rather than maintaining a static luminance. The arguments related to this issue have so far been suggested in several studies. Ledda, Santos and Chalmers (2004) presented a model of eye adaptation for display images referring physiological data. A research team designed a lighting system guideline which is based on a dynamic model of vision (New Buildings Institute et al., 2001). Swinkel and his colleagues (2008) insisted that the required speed for adjustment of the display intensity is related to the human eyes' capability of adapting to luminance change.

Accordingly, this study keeps a potential for adaptive display in mind, and conducts an observational study to explore the practical possibility in the following section.

3.1.2. Observation for Exploring Potential for Adaptive Display

Objective

The goal of the observational study is to identify whether the optimal luminance changes in the passage of time by examining the viewing appropriacy on a variety of instances which occurs luminance contrast. Based on the result, it attempts to discover the range of optimal luminance for viewing objects as well as to trace the changing pattern of the range. Hence ultimately, this study aims at finding the empirical evidence of adaptive display, namely confirming the necessity to consider display viewing time in the process of designing main experiments in Chapter 4.

Method

A large number of instances which contain two different luminance levels were collected in everyday life such as a bright computer monitor in an office and a lit sleeping lamp at night in a dark room. Next, numerical values of target luminance and ambient luminance of each instance were measured using a Konica Minolta CS-100A color and luminance meter, as shown in Figure 3-2. To obtain the more accurate value of ambient luminance, three random spots which are not influenced by target luminance as well as within a viewing angle of 30 degrees were measured, then calculated their mean values (Shin et al., 2009).

Figure 3-2. Measurement of target luminance (solid line) and ambient luminance (dotted line) using luminance meter (Na and Suk, 2014)

After that, respective instance was classified into one of two categories depending on viewing appropriacy, either appropriate condition or inappropriate condition for viewing the target. The viewing appropriacy is judged considering both visual comfort and aesthetic preference. The classification was carried out two times. First, a judgment was made at the first sight of the target object (hereafter *initial viewing*) to report the response at first-time viewing. In second classification, the judgment was carried out again in the same way but it inquires the viewing appropriacy after watching the target object for a long time (hereafter *continuous viewing*).

Results and Analysis

A total of 60 instances were collected from various environments, and all of them were positioned on a two-dimensional graph represented by an ambient luminance in the horizontal axis and a target luminance in the vertical axis, as plotted in Figure 3-3. The figure on the left shows the result of classification at *initial viewing*, and the figure on the right depicts the result of *continuous viewing*. In the figures, open circles indicate the instances categorized as inappropriate for viewing, whereas closed circles mean the instances judged as appropriate for viewing. A trend line which calculated from the instances representing appropriate for viewing is represented as a dotted line on the respective graph, and a couple of example instances corresponding to each circle are listed in Table 3-2 and Figure 3-4. The information on all instances was provided in Appendix 1.

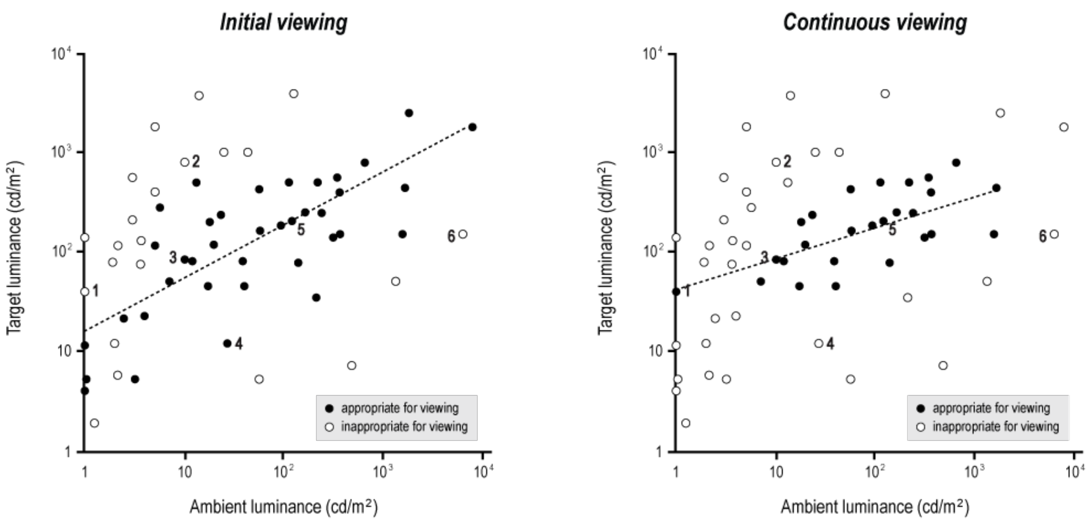


Figure 3-3. Classification of the instances for *initial viewing* (left) and for *continuous viewing* (right). The numbers on plots correspond with the numbers in Table 3-2 (Na and Suk, 2014)

Table 3-2. Target luminance, ambient luminance and viewing appropriacy of the instances

No.	Instance	Luminance (cd/m^2)		Viewing appropriacy	
		Target	Ambient	*Initial viewing*	*Continuous viewing*
1	Using a smartphone at night	40	1	inappropriate	appropriate
2	A signboard on a dim street	801	8	inappropriate	inappropriate
3	A navigation system in a car	85	10	appropriate	appropriate
4	LEDs on electronics in a dim room	12	25	appropriate	inappropriate
5	Working on a laptop in an office	204	117	appropriate	appropriate
6	Using a smartphone under sunlight	143	6240	inappropriate	inappropriate

Figure 3-4. Photograph of the collected instances: (1) Using a smartphone at night, (2) A signboard on a dim street, (3) A navigation system in a car, (4) LEDs on electronics in a dim room, (5) Working on a laptop in an office, (6) Using a smartphone under sunlight

At *initial viewing*, there were many instances in which conditions were classified to be appropriate for viewing, and they cover a wide range. In contrast, the instances with conditions that were categorized as appropriate for *continuous viewing* were not only relatively small in number but also confined within a narrower range compared to those at *initial viewing*. Accordingly a slope of the trend line based on the appropriate range was different in the two viewing conditions. Simply put, the optimal luminance is not a static thing. The ideal ratio between ambient luminance and target luminance changes gradually as a viewing time increases, and in particular, it converged into a smaller range. For example, illuminated LEDs in a dim room (instance no. 4 in Table 3-2) was regarded as an appropriate condition for viewing at first, but the judgment of the same instance shifted to inappropriate condition for viewing in a few minutes. On the other hand, in some instances such as using lit smartphone in conditions of low illuminance (instance no. 1 in Table 3-2), it was classified into an inappropriate viewing condition at the beginning but moments later it changed to appropriate condition.

On the basis of the results, two areas of changing classified group with a lapse of time were observed. The first area includes the range within which both ambient luminance and target luminance are relatively low (the gray area marked as L in Figure 3-5). At the beginning, the area was categorized as an appropriate condition for viewing target objects since it is not hard on eyes, but it soon induced an unpleasant feeling due to its darkness. To put it differently, visual comfort plays a more significant role at first, so low level of aesthetic preference does not initially has great influence on the judgment. However the importance of visual comfort and those of aesthetic preference becomes similar over time, so that the instance cannot stay high viewing appropriacy unless a level of aesthetic preference improves. Namely, the target luminance is too dark to watch in this area, hence it is necessary to increase target luminance in dark environments. As an example, in the instance of viewing a luminous display for long hours under low illuminance, it is recommended that the display luminance gets brighter with the process of time.

By contrast, another area has high ambient luminance and high target luminance (the gray area marked as H in Figure 3-5). This area is pleasurable to view target objects at first because the object is bright enough, but sooner or later it arouses visual fatigue. In comparison with the previous area, aesthetic preference holds a dominant position at the beginning of viewing. However the role of visual comfort increases as time passes whereas the comfort level remains unaffected, so the judgment on classification changed. In this case, the target luminance is too bright to watch, thus lower object luminance is more appropriate assuming the same ambient luminance. It can be translated that target luminance in bright environment needs to be decreased over time.

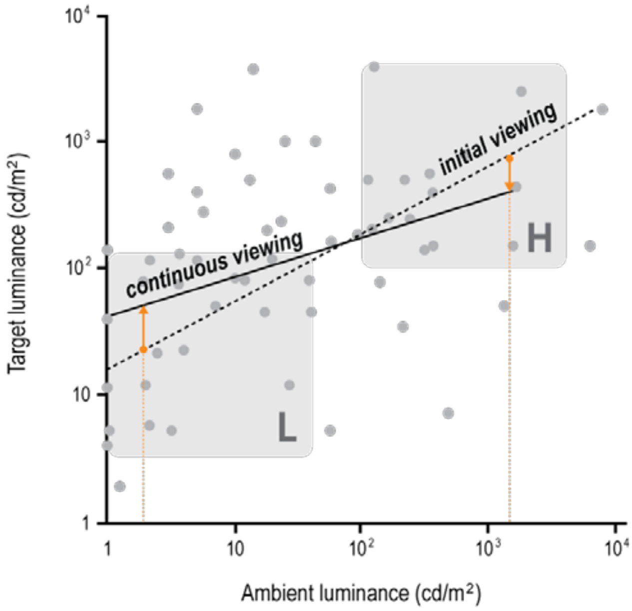


Figure 3-5. Changing of the optimal luminance with the lapse of viewng time: the target which has low luminance in dark environments (the area marked as L) needs to be increased as time passes, whereas the target which has high luminance in bright environments (the area marked as H) needs to be decreased over time (Na and Suk, 2014)

Findings

Two major findings were achieved through the observational study. First, it was discovered that the optimal ratio between ambient luminance and target luminance changes gradually as viewing time increases, and it converges into a smaller range. Second, there are two areas for which target luminance should be adjusted with the passage of time. It is therefore recommended to increase the target luminance under low ambient illuminance, such as late at night, whereas the target luminance needs to be decreased in bright environments. The former one is coincide with the scope of this dissertation, hence the scenario that changing display luminance as time passes can be assumed in the following experiments.

In conclusion, a potential for the adaptive display considering the process of visual adaptation was confirmed, consequently a solution to keep the optimal luminance consistently is necessary.

3.2. Evaluation for Achieving Optimal Display

3.2.1. Criteria for Evaluating Display Quality from Literature Review

To suggest the optimal luminance and chromaticity for mobile displays, a clear definition of the word ‘optimal’ in this study is the priority for the work. In this regard, existing criteria for evaluating display quality in previous research were investigated. Evaluation criteria for lightings were also reviewed because displays and lightings have in common in terms of emitting light.

As inferred by the description of human visual system in the previous section, visual aspect deserves consideration as the foremost attribute both in lightings and displays. Therefore during the last several years, many studies have been done on the topic of visual fatigue due to lightings. Visual fatigue, which is defined by the World Health Organization (WHO) as a subjective visual disturbance, refers to a high degree of visual discomfort typically occurring after prolonged reading, computer work or other visually intense tasks, and the symptoms include fatigue, pain around eyes, blurred vision or dry eyes (Benedetto et al., 2014). According to the book published by Boyce (2003), the visual fatigue can be divided into two types, physiological fatigue and psychological fatigue. The former is the result of muscular tension so it is easily measurable, has a clear relationship to energy expenditure, and can invariably be demonstrated. On the contrary, the latter is a general rather than specific response to stress in the body, hence it has a difficulty in quantitative measurement (Craig, 1992). Juslen and Finland (2006) made out a check list for workplace lightings, which is categorized as visual aspects including visual performance, visual comfort and visual ambience, and photo-biological aspect containing biological clock and stimulation. Also Goven and his colleagues (2007) argued that lighting design will in the future be more focused on the following three human aspects: visual aspect which covers visual performance, contrast and glare; biological aspect that includes ocular light, circadian effects as well as mental health; and emotional aspect which concerns with comfort, dynamics and colors of light. They insisted that those of three aspects play important role for not only vision but also human health. Similarly, a research team discovered the three types of impacts of light on humans which are composed of biological, emotional and cognitive effects (Braun et al., 2009).

Criteria for assessing display quality are consistent with those for lightings. Čadík’s research team (2006) introduced two approaches to evaluate display image quality: a perceptual approach to understand the details or the structure of visible images, and an aesthetic approach to make a pleasant appearance on the image. Becker (2007) argued that usability is the major requirement of visual display device to fulfil customer satisfaction, and it is consisted of three categories, effectiveness and efficiency which are related to the accuracy and completeness to achieve the goal, and satisfaction that is described as the comfort and acceptability of the work system. In the viewpoint of displays, effectiveness and efficiency can be interpreted to visual performance. Visual performance and subjective preference are determined as significant attributes for evaluating VDT display quality in Wang and Chen's research (2000). In addition, energy efficiency is regarded as one of the critical aspect to evaluate technological development of mobile displays. Reducing power consumption has become a topic of relevance in these days, since most mobile devices are supplied electric power from batteries which have limitation in capacity (Shim et al., 2004; Carroll and Heiser, 2010). Thus lots of research were conducted to improve energy efficiency of displays while maintaining the aesthetic quality (Choi et al., 2002; Pitt et al., 2002; Dong and Zhong, 2010). Aforementioned evaluation criteria are listed in Table 3-3 as follows.

Table 3-3. Existing criteria for evaluating lightings and displays

Item	Authors (year)	Evaluation criteria
Lightings	Boyce (2003)	physiological / psychological aspects
	Juslen and Finland (2006)	visual / photo-biological aspects
	Goven et al. (2007)	visual / biological / emotional aspects
	Braun et al. (2007)	biological / emotional / cognitive effects
Displays	Cadik et al. (2006)	perceptual / aesthetic approach
	Becker (2007)	effectiveness, efficiency, satisfaction
	Wang and Chen (2000)	visual performance, subjective preference
	Dong and Zhong (2010)	energy efficiency, aesthetic quality

As seen in the table, each research adopted difference evaluation criteria. On closer inspection, however, most of the criteria have similar meaning but just different in the choice of words, so they could be bound into a couple of groups as shown in Figure 3-6. First two groups include visual aspect and biological aspect, respectively. They are contained within many research as the evaluation criteria in common, as well as can be seen as part of a physiological aspects. Psychological aspect, emotional aspect, aesthetic approach, satisfaction and subjective preference belong to the third group, which is related to user’s feelings. The fourth group is connected with recognition and behavior of users, and it includes perceptual approach, performance, cognitive effect, effectiveness and efficiency. The last group deals with energy efficiency, the significant criterion in respect of technical property.

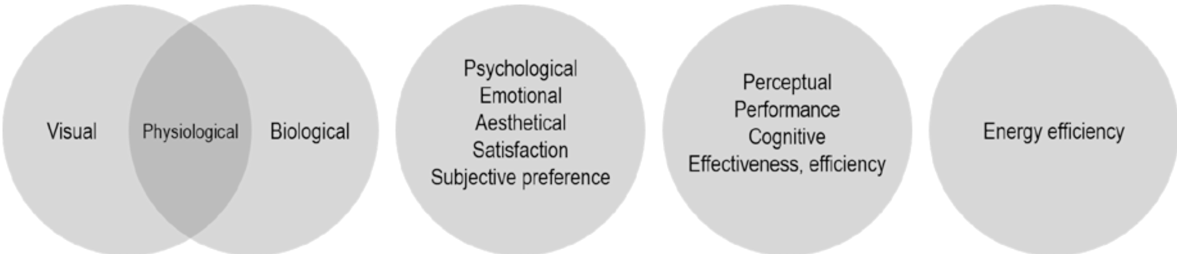


Figure 3-6. Five categorized groups from the evaluation criteria for lightings and displays

3.2.2. Evaluation Model for the Study

The criteria for assessing displays and lightings were collected from previous studies, and then they were categorized into five groups in the earlier section. In this section, those groups were reclassified based on the goal of this dissertation, and finally the evaluation model for the study was established as seen schematically in Figure 3-7.

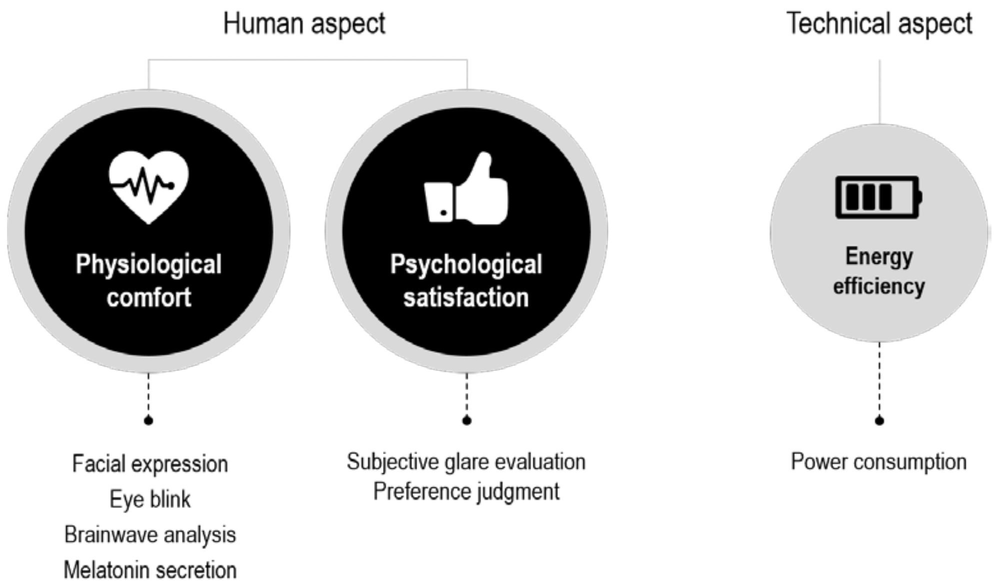


Figure 3-7. Evaluation model for the study: physiological comfort and psychological satisfaction as two major human aspects, and energy efficiency as an additional observation of technical aspect

The model is composed mainly of two major human aspects which are represented by physiological comfort and psychological satisfaction. Physiological comfort indicates how much comfortable our body is. Physiological response is an automatic unlearned reaction to a judgment of good, bad or danger, thus it refers to an instinctive physical response to an external stimulus (Andreassi, 2000). The observation of physiological response on human body facilitates quantitative measurement for stress, preference, or comfort and consequently it provides meaningful insights. Visual aspect and biological aspect among the five groups belong to this aspect. In this study, several evaluation methodologies such as analyzing brainwave signals, measuring melatonin secretions, counting eye blinks, and observing facial expressions are selectively used depending on the characteristics or purpose of each experiment.

Psychological satisfaction is concerned with how pleasant the thing is. Psychological response is subjective and conscious judgment on the experience by individual satisfaction or personal memory, and it includes two groups, visual aspect and the group related to user's feelings. Visual aspect was already affiliated in physiological aspect, but it is also recommended to judge by psychological assessment since it is directly linked with preference (Ou et al., 2014). Thus, this study uses a self-reporting questionnaire method such as preference judgment or discomfort glare evaluation for assessing psychological satisfaction. It heavily relies upon subjective opinions so there can be some possibility of inter-individual difference, but psychological satisfaction is still one of the most significant aspect for evaluating product quality or experiences, as well as it is easy to appraise.

The aforementioned two aspects should be balanced in the study. As we found from the observational study in section 3.1, the best point (e.g. luminance, chromaticity) to achieve physiological comfort and psychological satisfaction might be different from each other. However, at the point which both aspects are fairly good, the effects of two aspects are overlapped and generate a synergy, and therefore the synergy effect could be better than the effect at the best point of respective criterion, as depicted in Figure 3-8.

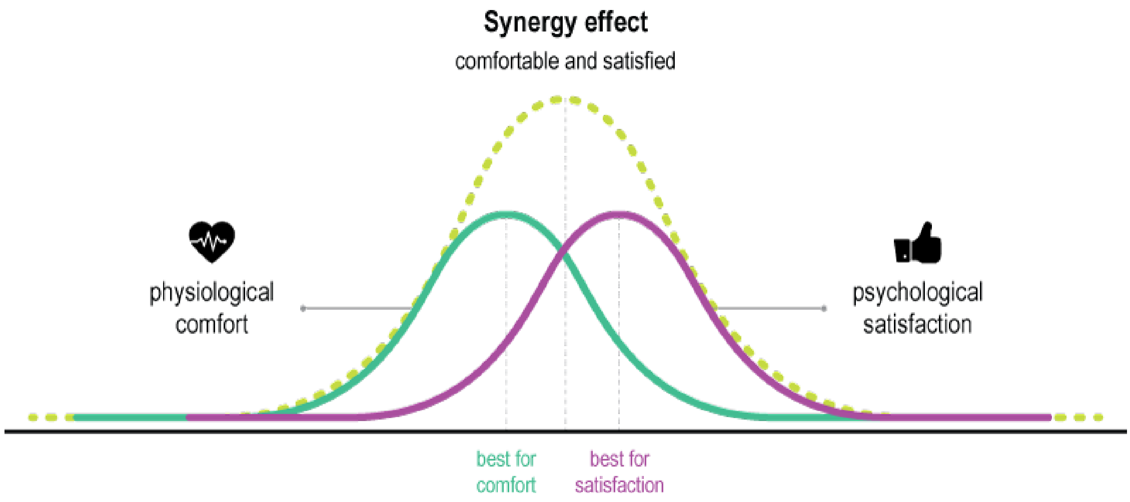


Figure 3-8. A synergy effect of physiological comfort and psychological satisfaction

Apart from the two major aspects, energy efficiency will be reported as an additional observation in the latter part of the study considering the technical characteristics of mobile devices. Mobile devices are largely dependent on batteries to be supplied electric power, and displays consume more than half of total power among the various components (Zhong and Jha, 2005; Chuang et al., 2009). Moreover this issue is closely related to aesthetic quality, which is a part of psychological satisfaction. The improvement of aesthetic quality of displays necessarily involves an increase in power consumption because both luminance and chromaticity contrast should be enhanced for achieving high level of aesthetics (Legge et al., 1990). Stated reversely, although a save on power consumption could be accomplished by display adjustment, it typically accompanies a decrease in aesthetic quality of displays (Harter et al., 2004). In this respect, a recent research discovered the fact that user acceptance on display quality changes relying on the available battery level (Dong and Zhong, 2012). Therefore it should strike a balance between the energy saving and aesthetic quality of displays.

The criterion associated with perceptual performance is excluded from the evaluation model. This study focuses on the situation of using mobile displays before sleep under low illuminance, and people usually spend the time for light entertainments such as browsing the web or sending massages, not serious works which need high cognitive load (Xu et al., 2011). Hence high performance is not a core value in this situation, but the fundamental perceptual aspect like text recognition on displays is already embodied as a part of psychological satisfaction.

On the basis of the newly established evaluation model, the meaning of ‘optimal display’ in this study was defines as follows:

“Optimal display refers to display luminance and chromaticity that support both physiological comfort and psychological satisfaction in a balanced way.”

To conclude, the goal of the study is to investigate the optimal display that enhances physiological comfort and psychological satisfaction for viewing mobile displays late at night in conditions of low illuminance.

3.3. Plan for Experiments

3.3.1. Process of Experiments

To find the optimal luminance and chromaticity of mobile displays in conditions of low illuminance, this study involves three experimental phases as illustrated in Figure 3-9.

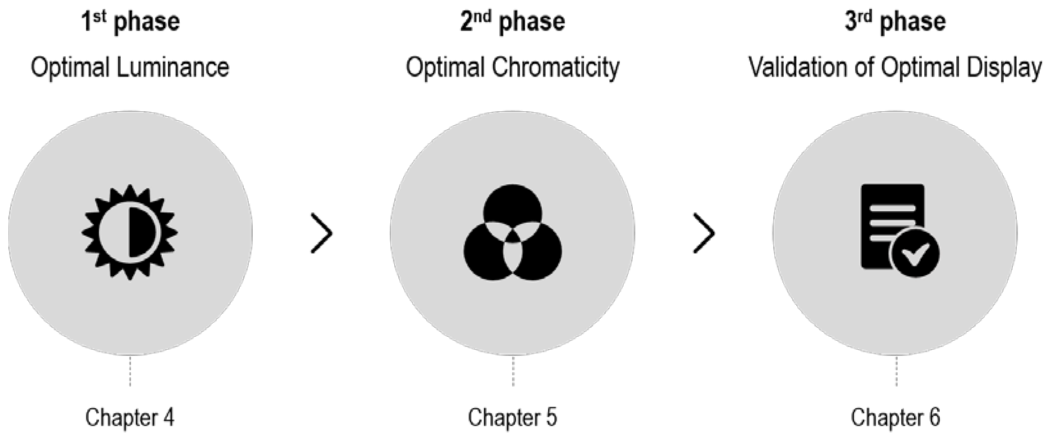


Figure 3-9. Experimental process to achieve the optimal display

The first phase covers a process of identifying the optimal display luminance for nighttime smartphone users, and it is subdivided into exploring stage and validating stage. In exploring stage, two levels of display luminance, the optimal luminance for *initial viewing* to avoid visual fatigue, and the ideal luminance for *continuous viewing* which is bright enough to keep a display quality, are examined in reference to human visual system, as well as the transition speed from the luminance for *initial viewing* to those for *continuous viewing* is revealed. Facial expression and eye blinks assessments are used to measure physiological comfort, and discomfort glare and preference are evaluated to find out the level of psychological satisfaction in this stage. Next, in validating stage, the effect of the discovered optimal display luminance is verified in comparison to the current smartphone display. Both physiological and psychological responses were collected through brainwave analysis using electroencephalogram, eye blinks and preference evaluations. Chapter 4 gives a full description of the experimental phase.

The optimal display chromaticity is investigated in the second phase of the study. It should be a subsequent step of determining the luminance because perceived display chromaticity changes depending on the display luminance (Melgosa et al., 1999). A total of three experiments on a text-based content, a text and image-based content, and a video-based content are carried out to analyze the effect of color composition of the displayed content. There is already an extensive literature devoted to explain physiological influence of blue light emitted from displays on users, hence the evaluation of the phase is rather focused on psychological satisfaction. From this, users' perceptibility and acceptability on the displays with different chromaticity types are assessed, and this is detailed in Chapter 5.

Lastly, in the third phase, a validation test is conducted to examine the excellence of the optimal display in real-life situation. To identify the practical application of the display, end users are allowed to use a smartphone implemented the optimal display in their daily life for a few days, and physiological comfort is observed by measuring nocturnal melatonin secretion, body temperature and heart rate. This phase is described in more detail in Chapter 6.

The study is not limited to experiment in laboratory, but derived the results that can be applicable in electronic display devices. All of the experimental procedures in this dissertation were ethically approved by the Institutional Review Board of KAIST (approval number: KH2014-34).

3.3.2. Experimental Environment

The experiments described in Chapter 4, Chapter 5 and Chapter 6 were conducted in a rectangle-shaped experimental room. There is a desk in the center of the room, and a subject was seated on the chair in front of the desk. During the experiments, the subject was instructed to view a smartphone at about 30 cm, a typical viewing distance of a smartphone display (Spencer et al., 2013; Park et al., 2014). Blackout curtain hanging on a window excluded sunlight into the room, so near-perfectly darkroom could be achieved.

The brightness of the experimental room was measured with a chroma meter (Konica Minolta CL-200), at the position where the smartphone was placed in the experiments. The measured illuminance at the subject's desk is less than 1 lx if the smartphone was completely off, which is similar brightness to ordinary room at night. Besides, the colorimetric values including luminance and chromaticity of each stimulus were measured 10 times using a spectroradiometer (Konica Minolta CS-2000) under the same luminous environment with the experiments, 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 stimulus was displayed on a smartphone (Samsung Galaxy S3) with display size of 4.8 inches, and the measured values of the stimuli are introduced in respective experimental phase.

The subject could not fill in the questionnaire during the experiments since the experiments were carried out in a dark environment. Thus they spoke their evaluation aloud, and an assistant sitting in a corner wrote down the subject’ answers on a laptop immediately. In this context, display angle and brightness of the laptop are carefully adjusted to prevent the influence of light from the laptop on the subject. The experimental setup is depicted in Figure 3-10.

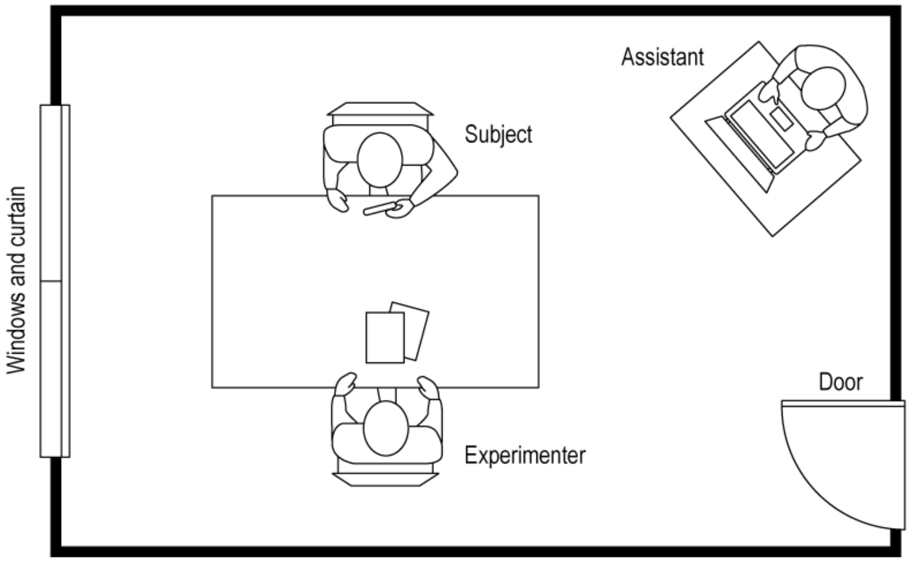


Figure 3-10. Experimental setup: experimenter leads the procedure, subject views a smartphone display and evaluates the stimuli, and assistant writes down the subject's answers in a dark experimental room

3.4. Summary

The goal of this chapter was to explore the considerations for setting optimal luminance and chromaticity on mobile displays. Basic knowledge on human visual system was accumulated and an observational study was conducted to verify the initial hypothesis of the study. As a result, a potential for adaptive display which changes optimal luminance over time was confirmed. Moreover existing criteria to evaluate displays and lightings were collected and analyzed. Based on that, the evaluation model for this study was established as well as a clear definition of the optimal display was formulated. Next the experimental process in the following chapters was listed, and environment and equipment for the experiments were described.

The next chapter introduces the experiments to identify the optimal display luminance for viewing smartphone under low illuminance. Two experiments are carried out for exploring and validating the effect of the optimal display luminance.

4

Experiment I: Optimal Display Luminance

4. Experiment I: Optimal Display Luminance

This chapter describes an experimental process to investigate the optimal display luminance for viewing smartphones under low illuminance. The process involves two experiments. In section 4.1, an empirical experiment is conducted to discover the optimal display luminance which is appropriate for initial display viewing and continuous display viewing, respectively. Next, benefits of the suggested optimal display luminance are validated in section 4.2 based on physiological and psychological evaluations.

4.1. Exploring Optimal Display Luminance

4.1.1. Objective

This section aims at collecting scientific basis to design optimal display. It intends to examine the ideal display luminance for nighttime smartphone users which supports adaptation process of human visual system as well as provides physiological comfort and psychological satisfaction.

Prior to the experiment, two levels of luminance necessary for investigation were defined based on the findings in the previous chapter. According to the result of Chapter 3, there is a potential to change the optimal luminance depending on viewing time. In this experiment, therefore, the first level is determined as the luminance for first-time viewing to avoid a harsh glare flashing into eyes (*initial viewing*), and the second level is the luminance for constant display watching that comforts but is bright enough to make users satisfied (*continuous viewing*). Consequently the experiment was conducted based upon the hypothesis that a gradual change of display luminance from the luminance for *initial viewing* to the luminance for *continuous viewing* improves user's comfort and satisfaction. Thus, the purpose of the experiment is to discover the optimal luminance for *initial viewing* and for *continuous viewing* of smartphone displays in dark environments.

4.1.2. Method

Subjects

A group of 50 people comprising 29 males and 21 females participated in the experiment. The mean age of the subjects was 21.76 years with a standard deviation of 3.28 years. All subjects were paid volunteers and they had normal vision or corrected to normal vision.

Stimuli

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 luminance stimuli of display were chosen within the range. In total, five levels of display luminance were selected as listed in Table 4-1: 10 cd/m^2, 40 cd/m^2, 70 cd/m^2, 100 cd/m^2, and 140 cd/m^2. A reading article on a webpage composed of black texts on a white background (see Figure 4-1) was displayed on the smartphone with those of the five luminance, because web browsing is the most used smartphone applications and white color takes as high as 80 % of web contents (Laaperi, 2009). The five different articles which have a same level of difficulty were prepared in order to circumvent the effect of reading contents on the experiment. The length of each article was approximately 2500 characters in Korean, and the texts consist of san serif font at 10-point size. The subjects turn the pages by scrolling down the screen.

Table 4-1. Five levels of luminance stimuli (colored boxes in stimuli column indicate the relative brightness of displays, and they look white on smartphone displays under low illuminance)

Stimuli	Expected luminance (cd/m^2)	Measured luminance (cd/m^2)	Notes
	10	10.65	Minimum luminance
	40	39.54	
	70	68.77	
	100	100.11	
	140	139.57	Maximum luminance

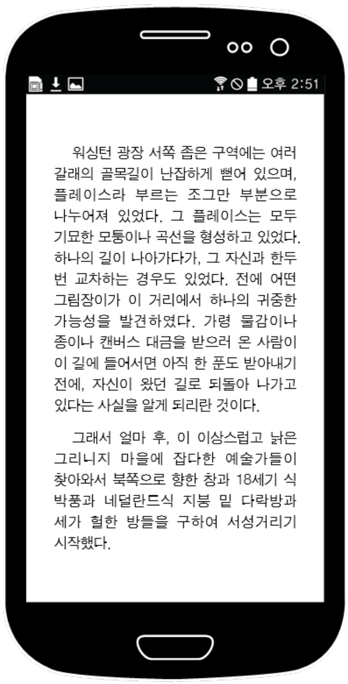


Figure 4-1. Display stimuli for the experiment: a reading article composed of black texts on a white background

In addition, video clips which change a display luminance from the optimal luminance for *initial viewing* to the optimal luminance for *continuous viewing* at five different rates were created to find the appropriate transition speed in display luminance: 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. The video stimuli were made after identifying the optimal display luminance for both of the two viewing conditions.

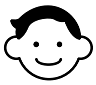
Evaluation Methodology

A total of four evaluation methodologies were conducted in this experiment for measuring the subjects' physiological comfort and psychological satisfaction as mentioned below.

Facial expression

Human facial expression is one of the most reliable part to detect the physiological response to light (Cooke and Graziano, 2004), and it is divided into three levels in this study as seen in Table 4-2. The score of one point means that the subject closes their eyes or turns the head to avoid the light emitted from stimulus. If the subject looks at the lit stimulus with a frown on the face, he or she received two points. Also the score of three points can be achieved when the subject looks at the stimulus without any facial change. Simply put, high score indicates high physiological comfort. For making a reliable estimation, facial expressions of the subjects were recorded by a video camera during the experiment, and two experimenters judged the recorded data each and confirmed agreement of the judgment results.

Table 4-2. Three levels of facial expression

Facial expression	Description	Score	Level of comfort
	Close eyes or turn head	1 point	Low
	Look with a frown on the face	2 points	Medium
	Look without any facial change	3 points	High

Eye blinks

Eye blink frequency is a well-known indicator to identify physiological comfort of human eye. An increase of light intensity is usually associated with dry eye which can easily detected by observing quick closing and reopening of the eyelid, namely eye blinks (Schleicher et al., 2008; Benedetto et al., 2014). According to a research, eye blinks under a non-stress condition and a glare condition are about 10 blinks/min and 13 blinks/min respectively, as well as the more visual discomfort people feel, the higher frequencies they blink (Gowrisankaran et al., 2007).

Discomfort glare

Discomfort glare which is included in psychological response can be assessed using the de Boer scale (De Boer, 1967). The subjects rate their perceived level of glare on a nine-point scale where five different glare index values have the descriptive meaning as shown in Table 4-3. In the scale, the score of one point represents unbearable glare whereas nine points imply few or no glare.

Preference

Preference judgment is a method which is widely used to assess psychological satisfaction. The judgment is made regarding each stimulus with a 5-point Likert scale in that one point indicates not preferred and five points means highly preferred (Likert, 1932).

Table 4-3. The de Boer scale for evaluating discomfort glare (De Boer, 1967)

Score	Glare	General impression
1	Unbearable	Bad
3	Disturbing	Inadequate
5	Just admissible	Fair
7	Satisfactory	Good
9	Unnoticeable	Excellent

Procedure

The subjects spent approximately five minutes in a dark experimental room before starting each evaluation in order to adapt to the dark environment (Mantiuk et al., 2009). There were a total of five luminance stimuli to discover optimal display luminance for *initial viewing* and for *continuous viewing*, as well as the transition speed in display luminance from *initial viewing* to *continuous viewing*.

To find the optimal luminance for *initial viewing*, the subjects were asked to look at a display with one of the five luminance stimuli for two seconds right after the dark adaptation because it is an appropriate time to observe immediate response for a stimulus. The stimuli were displayed in a random order, and both physiological and psychological responses were evaluated. The subjects' facial expression was assessed by experimenters, and they also rated how glaring the stimuli were using the de Boer glare rating scale, which is a subjective scale in discomfort glare evaluation.

To investigate the optimal luminance for *continuous viewing*, the subjects were instructed to read an article on the smartphone display for five minutes since light adaptation is completed in less than five minutes. This task was repeated five times with randomly chosen luminance among the prepared stimuli. As in the previous evaluation, both physiological response and psychological response were observed. The subject's eye blinks were counted to identify visual discomfort and a preference judgment was made regarding each stimulus.

The evaluation for finding the transition speed in display luminance was carried out after exploring the optimal luminance for *initial viewing* and for *continuous viewing*. The subjects watched the video clips of luminance changing at various rates and reported their preference for the stimuli with a 5-point scale. Time taken to complete the entire experiment was about an hour. The whole experimental procedure is summarized in Figure 4-2.

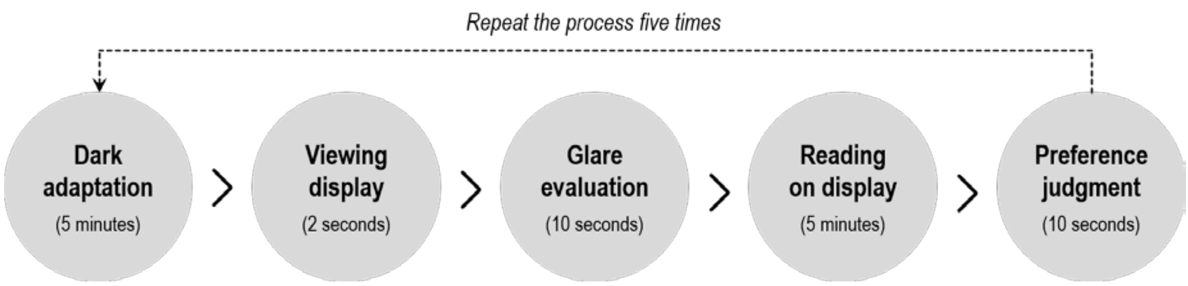


Figure 4-2. Experimental procedure for exploring the optimal display luminance

4.1.3. Results and Analysis

The optimal display luminance for *initial viewing* was explored through the experiment. One-way analysis of variance (ANOVA) was performed using SPSS statistical analysis software (IBM SPSS Statistics version 20.0 for Windows) to examine the effect of display luminance on the subject's facial expression. The analysis yielded statistical significance at an alpha level of 0.05 confirmed that the effect was statistically significant, $F(4, 235) = 59.87$, $p < 0.05$, and post hoc analysis using Scheffe's post hoc criterion for significance reported that the score of facial expression under the display luminance of 10 cd/m^2 (mean ± SD = 3.00 ± 0.00) are not statistically different from the luminance of 40 cd/m^2 (2.88 ± 0.33). Put otherwise, there were close to no change in the subject's facial expressions for the two luminance levels, whereas a frowning on the face was observed when the luminance exceeded 70 cd/m^2. The score sharply decreased with the higher levels luminance as described in Table 4-4. A similar result was obtained from the discomfort glare evaluation. ANOVA showed that the effect of display luminance was significant, $F(4, 235) = 91.45$, $p < 0.05$, and a strong negative correlation was observed between the de Boer score and the display luminance, $r = 0.99$, $p < 0.05$. The score rapidly decreased as the luminance level increased. For luminance of 70 cd/m^2 and over, besides, the score was less than five points on average, indicating that 70 cd/m^2 is the admissible threshold on display brightness. These results implied that a luminance greater than 40 cd/m^2 is inappropriate display luminance for *initial viewing* under low illuminance because it arouses visual fatigue, and a display luminance of 10 cd/m^2, which is the lowest level of brightness, helps the subjects to maintain visual comfort.

Table 4-4. The mean scores of the evaluation to find optimal display luminance for *initial viewing* and 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 identify the optimal luminance for *continuous viewing*. One-way ANOVA confirmed that the eye blinks got significantly lower with a decrease of display luminance, $F(4, 235) = 2.45$, $p < 0.05$. As mentioned above, the eye blink frequency under a non-stress condition and a glare condition are about 10 blinks/min and 13 blinks/min, respectively, and it increases when people feel visual discomfort. To put it into the experiment result, it can be interpreted that the subjects feel more uncomfortable watching a smartphone in a dark environment as display luminance increases, especially when it is over 100 cd/m^2. Unusually high standard deviation was reported in the result of eye blink frequency due to the wide individual variations, but a high degree of reliability was found among each subject's response. The mean measure of Intraclass Correlation Coefficient was 0.96 with a 95 % confidence interval from 0.89 to 0.99, F(4, 188=26.21). Furthermore, a significant difference was observed between the preference scores and the display luminance, $F(4, 235) = 4.06$, $p < 0.05$. Display luminance of 40 cd/m^2 (3.77 ± 0.90) was most preferred whereas two extreme levels of luminance, 10 cd/m^2 (3.17 ± 1.45) and 140 cd/m^2 (2.96 ± 1.11), were the least preferred. By taking into account both physiological and psychological responses, a luminance of 40 cd/m^2 was determined as the optimal brightness for *continuous viewing* on a mobile display in conditions of low illuminance. This result is consistent with the previous study which argued that a display in dark environments should emit at least 20 cd/m^2, and 40 cd/m^2 is appropriate for distinguishing displayed contents (Mantiuk et al., 2009).

Based on the result of evaluations, the optimal display luminance for *initial viewing* and for *continuous viewing* were examined. Hence in the video clips for discovering the appropriate transition speed in display luminance, the luminance starts from 10 cd/m^2 and end in 40 cd/m^2 at five different speeds. The result of correlation analysis showed that the mean preference score increases as the transition speed decreases, $r = 0.33$, $p < 0.05$, although the difference was not much large as presented in Figure 4-3. The reason is presumed that the subjects did not bother with the changing luminance at the lower transition speed, since they were not even aware of the change in displays. Consequently the time duration of luminance transition was set as 20 seconds, which was calculated by dividing the luminance difference between the two viewing conditions into selected transition speed, 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.

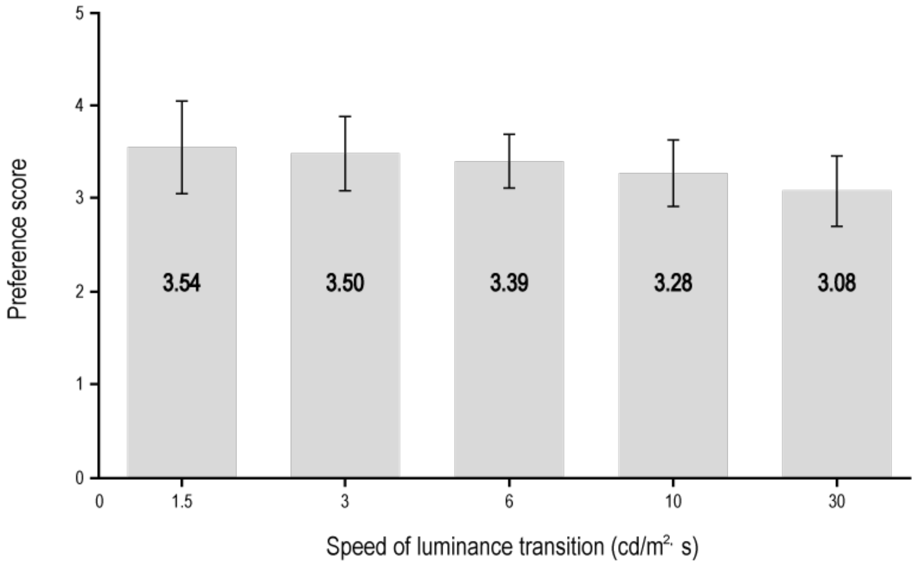


Figure 4-3. The mean scores and the standard deviations of the preference to find the optimal transition speed in display luminance

4.1.4. Findings

Through the experiment, the optimal display luminance for *initial viewing* and for *continuous viewing* were identified as 10 cd/m^2 and 40 cd/m^2, respectively. Also it was found that the transition in display luminance between the two viewing conditions should be moved slowly.

Based on the empirical results of the experiments, a model providing optimal display luminance for prolonged use of smartphones under low illuminance was suggested as illustrated in Figure 4-4. The name of the model, “adaptive luminance model,” originates from the major feature of this model that was established in consideration of the time-dependent adaptation of human visual system.

In the model, display luminance changes gradually with the passage of display watching time following the adaptation process of human visual system. When users first turns their smartphone on, it starts at a fairly low display luminance of 10 cd/m^2 to prevent sudden glare or visual fatigue caused by dazzling light emitted from the display and maintains the luminance level for 10 seconds, because the time course of light adaptation takes about 10 seconds to reach steady state (Hayhoe et al., 1992; Calvert and Makino, 2002). After that, the luminance gradually increases very slowly until it reaches 40 cd/m^2 for 20 seconds to avoid the user being disturbed by change in display luminance.

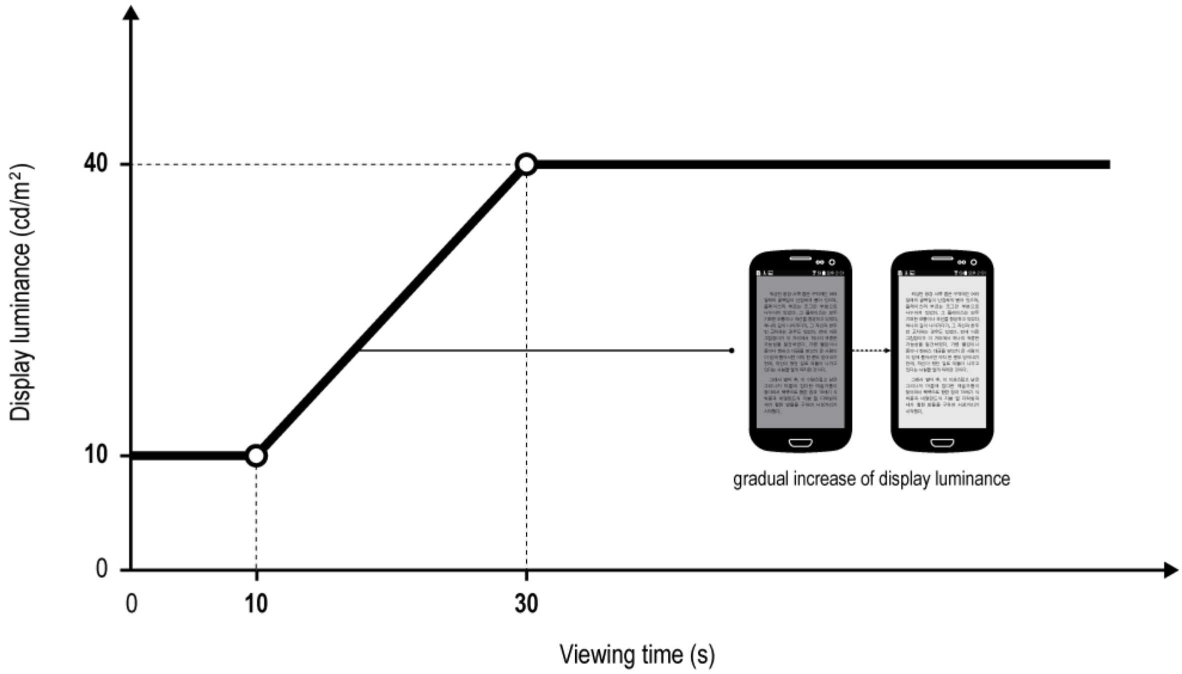


Figure 4-4. Adaptive luminance model: it begins with a display luminance of 10 cd/m^2. Ten seconds later, the luminance gradually increases until it reaches 40 cd/m^2 for 20 seconds.

4.2. Validating Optimal Display Luminance

4.2.1. Objective

The goal of this experiment is to verify the effect of the adaptive luminance model by conducting a validation test. It attempts to discover the excellence of the developed model in comparison with the current display through diverse evaluation methodologies.

4.2.2. Method

Subjects

Twelve subjects, including six males and six females took part in the experiment. The subjects ranged in age from 21 to 27 years, with the mean age of 24.42 years and the standard deviation of 1.66 years. None of them reported any ocular diseases, and they were asked to avoid consuming medicines, alcohol, nicotine, and any foods or drinks containing caffeine for eight to 12 hours before the experiment since the ingredients could affect the physiological response.

Stimuli

Besides the adaptive luminance model suggested in the previous section, three additional luminance stimuli were prepared to compare the effect. The first stimulus was a display luminance of 40 cd/m^2 that was assessed as the most preferred luminance from the experiment. The second stimulus was a luminance of 80 cd/m^2 that was the luminance applying auto brightness function on the current smartphone display in a dark environment. Last stimulus was a luminance of 140 cd/m^2 that was the maximum display luminance of the smartphone. Accordingly a total of four stimuli were comprised for the validation test as listed in Table 4-5. Four different newspaper articles made up of black texts on a white background were randomly provided as the reading contents.

Table 4-5. Four luminance stimuli for validating the effect of the adaptive luminance model

Stimuli	**Luminance (cd/m^2)**	**Notes**
→	10 → 40	The adaptive luminance model developed from the experiment
	40	The most preferred luminance from the previous experiment
	80	Luminance applied auto brightness function on a smartphone
	140	Maximum luminance of a smartphone

Evaluation Methodology

As in the previous experiment, both subjects' eye blinks and preference judgment were observed. In addition, a brainwave analysis was carried out using an electroencephalogram (EEG).

Electroencephalogram (EEG)

The electroencephalogram (EEG) is a measure of brainwaves by recording of electrical activity along the scalp (Malmivuo and Plonsey, 1995). It is a readily available test that detects evidence of how the brain functions over a short period of time as recorded from multiple electrodes placed on the scalp.

The basic waveforms of normal brainwaves are alpha (α), beta (β), theta (θ), and delta (δ) rhythms, according to the data provided by the International Federation of Societies for Electroencephalography and Clinical Neurophysiology (Schaul, 1998) as seen in Table 4-6. Alpha waves occur at a frequency of eight to 13 cycles per second in a regular rhythm, and they present the relaxed mental states. Beta waves have a main frequency between 14 and 31 cycles per second, and the waves are observed more obviously especially when the brain is performing logical thinking, computation, reasoning or sensory stimulus. Theta waves are brainwaves with a frequency between 4 and 7 Hz. They are the most common in children and associated with drowsiness and emotional suppression. Delta waves occur at a frequency less than 4 Hz, and the waves generally appear in babies or when people fall asleep deeply (Ray and Cole, 1985; Zhang, 2008; Kao et al., 2011). In this experiment, alpha waves are selected as an index for indicating the level of physiological comfort during use of smartphone displays.

Table 4-6. Comparison table of four normal brainwaves: alpha (α), beta (β), theta (θ), and delta (δ) rhythms

Brainwaves	Frequency (Hz)	Description
Delta (δ)	Less than 4	Deep sleep
Theta (θ)	4 to 7	Drowsiness, deep relaxation
Alpha (α)	8 to 13	Awake but relaxed states
Beta (β)	14 to 30	Alert or focused states, logical thinking

For measuring the brainwave signals, in this study, a total of four electrodes were carried out at positions of the frontal lobe, F_{p1} and F_{p2}, ground potential at the left lower earlobe, and reference potential at the right lower earlobe, as shown in Figure 4-5. Brainwaves were measured for two minutes and 10 seconds using an EEG measurement system (Laxtha LXE3232-RF), and the first 10 seconds of the recorded signal were deleted after the measurement to improve the accuracy of the results. The collected data were converted by 256 Hz sampling frequency and 12 bit analog-digital converter, then saved through Telescan, the brainwave analysis program developed by Laxtha Inc. The relative ratio of alpha waves (8 to 13 Hz) to the entire range (3.5 to 50 Hz), which indicates level of physiological comfort, was then observed. Each subject's data were obtained by calculating the mean ratio of the two channels. For example, if the ratios of alpha waves from F_{p1} and F_{p2} were 14.28 % and 12.74 %, respectively, the mean value of the two data, 13.51 %, was the final data from the subject. The relative ratio is commonly used for brainwave analysis rather than absolute power since brainwave powers have wide variations in different people.

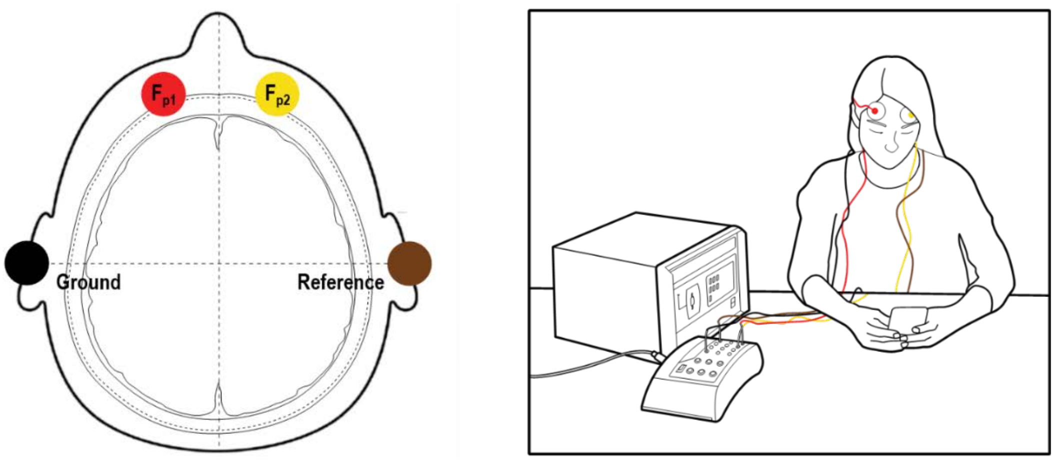


Figure 4-5. Experimental setup for EEG analysis: four electrodes at positions of the frontal lobe, F_{p1} (red) and F_{p2} (yellow), ground potential (black) at the left lower earlobe, and reference potential (brown) at the right lower earlobe (left) and experimental session (right)

Procedure

The experimental environment of the section was identical with that of previous section. As in the experiment in the first section of this chapter, both physiological comfort and psychological satisfaction were evaluated to compare the effect of the four luminance stimuli. In addition to counting the subject's eye blinks, the brainwave analysis using EEG was involved to quantify physiological response during the experiment. As a psychological response, subjective preference was judged using a 5-point Likert scale after each reading session.

Prior to the experiment, the experimenter explained the procedure to the subjects and offered them the opportunity to ask any questions related to the procedure. Then the subjects took a rest sitting on a chair while the four electrodes for recording EEG signals were attaching to their scalp, and the normality of the signals was confirmed. After spending five minutes in a dark room to dark adaptation, they were permitted to read a newspaper article for two minutes and 10 seconds at a natural speed on the smartphone display under the four luminance stimuli in a random order because a two-minute is the minimum required time to obtain reliable EEG signals. The subjects kept a distance of 30 cm away from the display during the reading sessions, and they were asked to hold themselves as far as possible because muscle movements can be detected as signals, which causes interference with EEG recording. A one-minute break was allowed before moving on the next sessions in order to eliminate the effect of the previous stimulus, and the experiment lasted for approximately 40 minutes (see Figure 4-6).

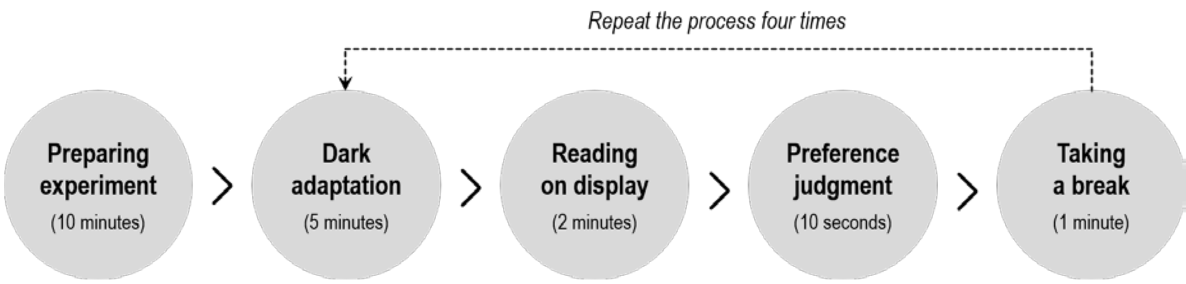


Figure 4-6. Experimental procedure for validating the effect of the optimal display luminance

4.2.3. Results and Analysis

Through the results of validation test, the effects of the four luminance stimuli were compared. The Friedman test, which is the non-parametric alternative to the one-way ANOVA with repeated measures, was applied in the analyses at an alpha level of 0.05 due to small sample size.

There was statistically significant difference in eye blinks with regard to the display luminance, $x^2(3)$ =

14.24, $p < 0.05$. Post hoc analysis with Wilcoxon signed-rank test was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.013$, which was calculated by dividing the significance level of initially using (0.05) by the number of stimuli (4). The results indicated the significant differences between the adaptive luminance model and a luminance of 40 cd/m^2, $Z = -2.95$, $p < 0.013$, between the adaptive luminance model and a luminance of 80 cd/m^2, $Z = -2.65$, $p < 0.013$, or between the adaptive luminance model and a luminance of 140 cd/m^2, $Z = -2.50$, $p < 0.013$. Mean eye blinks of the subjects were remarkably lower with the proposed adaptive luminance model than with other three luminance stimuli as described in Table 4-7. No significant differences were observed between a luminance of 40 cd/m^2 and 80 cd/m^2, $Z = -0.18$, $p = 0.86$, between a luminance of 40 cd/m^2 and 140 cd/m^2, $Z = -0.51$, $p = 0.61$, and between a luminance of 80 cd/m^2 and 140 cd/m^2, $Z = -0.36$, $p = 0.72$. The eye blink frequencies when reading an article under those three luminance stimuli were over the frequency under a glare condition, and it can be interpreted that the subjects experienced considerable visual discomfort at those luminance levels.

Table 4-7. The mean scores of the validation test (the standard deviations in parentheses)

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)
140	17.73 (10.01)	13.64 (4.65)	1.73 (0.79)

Next, EEG signals were analyzed as referred to earlier section. The original brainwave pattern takes a form as shown in Figure 4-7, and the ratio of alpha waves to the entire range, which indicates the level of physiological comfort while viewing a display, was extracted from the waveform. A Friedman test confirmed that the effect of display luminance was significant, $x^2(3) = 9.22$, $p < 0.05$. Post hoc tests revealed that there was no significant difference between the each of two luminance stimuli, despite an overall increase in the ratio of alpha waves when the adaptive luminance model was employed. Considering the alpha waves normally represent 15 to 20 % of the total of brainwaves while people close their eyes in comfort (Kim, 2012), the viewing condition under the adaptive luminance model could be interpreted as comfortable.

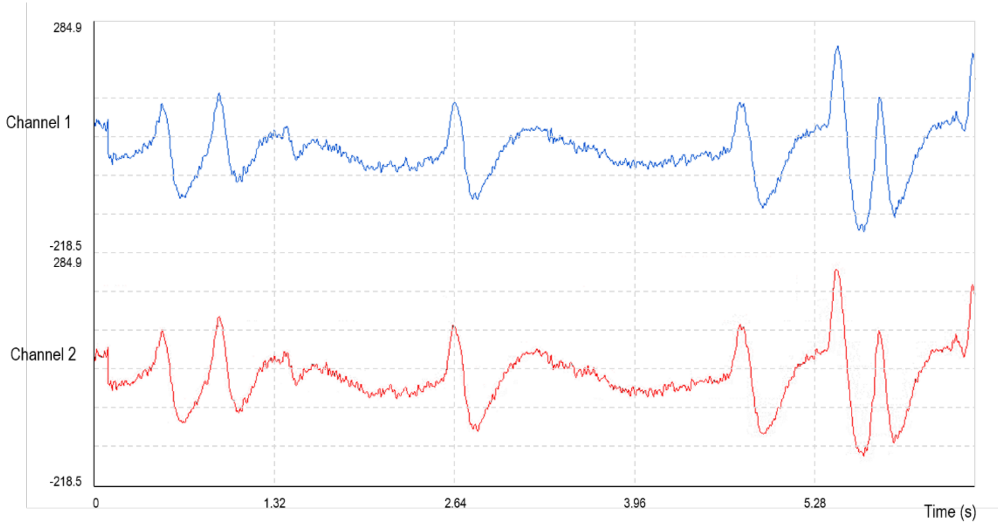


Figure 4-7. Example of the EEG signals of a subject: the signal from channel 1 (F_{p1}, blue line) and from channel 2 (F_{p2}, red line) with the passage of time

The relationship between the subjects' preference and display luminance was significant, $x^2(3) = 18.33$, $p < 0.05$. The subjects gave the highest score in preference when they use a smartphone display with the adaptive luminance model, whereas they gave a poor evaluation to a display with maximum luminance (see Table 4-7). Post hoc analyses using Wilcoxon signed-rank test indicated that there were statistically significant differences between a luminance of 140 cd/m^2 and the adaptive luminance model, $Z = -2.84$, $p < 0.013$, between a luminance of 140 cd/m^2 and 40 cd/m^2, $Z = -2.88$, $p < 0.013$, as well as between a luminance of 140 cd/m^2 and 80 cd/m^2, $Z = -2.75$, $p < 0.013$. On the contrary, no significant differences were observed between the adaptive luminance model and a luminance of 40 cd/m^2, $Z = -1.35$, $p = 0.18$, between the adaptive luminance model and a luminance of 80 cd/m^2, $Z = -0.31$, $p = 0.76$, and between a luminance of 40 cd/m^2 and 80 cd/m^2, $Z = -1.31$, $p = 0.19$.

The results of the three evaluations imply that the adaptive luminance model which is based on the optimal display luminance is the most appropriate for viewing mobile displays under low illuminance in terms of physiological comfort and psychological satisfaction.

4.2.4. Findings

Three major lessons have learned from the experiment. First at all, it was confirmed that the change in display luminance with the passage of viewing time provides not only physiological comfort but also psychological satisfaction. The adaptive luminance model which gradually increases the display luminance received the most favorable evaluation in every assessment among the four luminance stimuli, and it demonstrated the benefits of the proposed luminance model. Second, there is a positive correlation between the level of physiological comfort and the level of psychological satisfaction. In other words, a condition that highly supports physiological comfort but not provides psychological satisfaction or vice versa is hard to experience. In most cases, it is not difficult to get high level of psychological satisfaction if the case achieves physiological comfort. Last but not the least, the experimental result is indicative of impropriety of auto brightness function on the current smartphone. As Ma and his colleague argued in their study (2012), the screen brightness is usually too bright in a dark environment.

4.3. Summary

The aim of this chapter was to investigate the optimal display luminance for viewing smartphones at night in conditions of low illuminance. The study involves two experimental stages, exploring and validating stages.

The experiment in exploring stage found that the optimal display luminance for the first sight of the object (*initial viewing*) and the optimal luminance for constant display watching (*continuous watching*) are different from each other, and the level of luminance for each condition is 10 cd/m^2 and 40 cd/m^2, respectively. Besides, the transition from the luminance for *initial viewing* to *continuous viewing* should be changed at a fairly slow pace. On the basis of the findings, adaptive luminance model, which gradually changes display luminance in course of display watching time, was developed. After that, in validating stage, a validation test involving physiological and psychological assessments confirmed that the adaptive luminance model is adequate for prolonged use of smartphones in a dark environment.

The results supports the time-dependent adaptation of human visual system. In the process of light adaptation, people feel visual fatigue at first but they adapt the light as time goes. In this regard, the study provides a very low display luminance to prevent dazzling light when a user turns his or her smartphone on, and the luminance gradually increases when people get used to it for keeping the quality of the display. Once this is accomplished, it facilitates to improve physiological comfort and psychological satisfaction at once.

In Chapter 5, the optimal display chromaticity for viewing smartphone displays under low illuminance is examined.

5

Experiment II: Optimal Display Chromaticity

5. Experiment II: Optimal Display Chromaticity

This chapter introduces three experiments to identify the optimal display chromaticity for using smartphones in conditions of low illuminance. Section 5.1 describes the experiment to discover the optimal chromaticity for a text-based content which is comprised of black texts on a white background by evaluating users' perceptibility and acceptability on displays with white in various shades. Next, in section 5.2 and section 5.3, the same experiments are carried out on a text and image-based content that displays black texts and a colorful image , and a video-based content which shows colorful moving images, respectively, to examine the effect of color composition of the displayed content on optimal display chromaticity.

5.1. Experiment on Text-based Content

5.1.1. Objective

The goal of this experiment is to find the optimal display chromaticity for viewing smartphones in a dark environment by reducing blue light, as long as it can be substituted for a white display. The study intends to investigate the users' perceptibility and acceptability of different shades of display chromaticity on a text-based content.

5.1.2. Method

Subjects

A group of 50 college students comprising 26 males and 24 females participated in the experiment. Their mean age was 23.06 years with a standard deviation of 2.56 years, and all subjects had normal or corrected-to-normal vision, as evaluated by the Ishihara's test for color blindness, which is the most widely used assessment of color deficiency (Ishihara, 1917).

Stimuli

White in various shades were prepared as color stimuli for the experiment. The stimuli were comprised of one neutral color and six hues (red, green, blue, cyan, magenta, and yellow) with seven levels of RGB values (250, 245, 240, 235, 230, 225, and 220; the color looks more saturated as the RGB values drop). For example, the RGB values of the least saturated white tinged with green are 250, 255, and 250, whereas the most saturated greenish white has the RGB values of 220, 255, and 220. In the case of blue and yellow, four levels of RGB values (215, 210, 205, and 200) were added because the range which is perceived to be white in the CIE chromaticity diagram in those hue categories are relatively wider compared to others (Smith and Guild, 1931). Hence a neutral color and the four hue categories corresponding to red, green, cyan, and magenta have seven different intensities, as well as yellow and blue have 11 levels of intensities. Consequently a total of 57 color stimuli were created, as listed in Table 5-1. Colorimetric values of the stimuli were measured using a spectroradiometer, and plotted on the CIE xy chromaticity diagram as shown in Figure 5-1 (Seven stimuli in neutral color category are overlapped in a single point since the stimuli have same chromaticity).

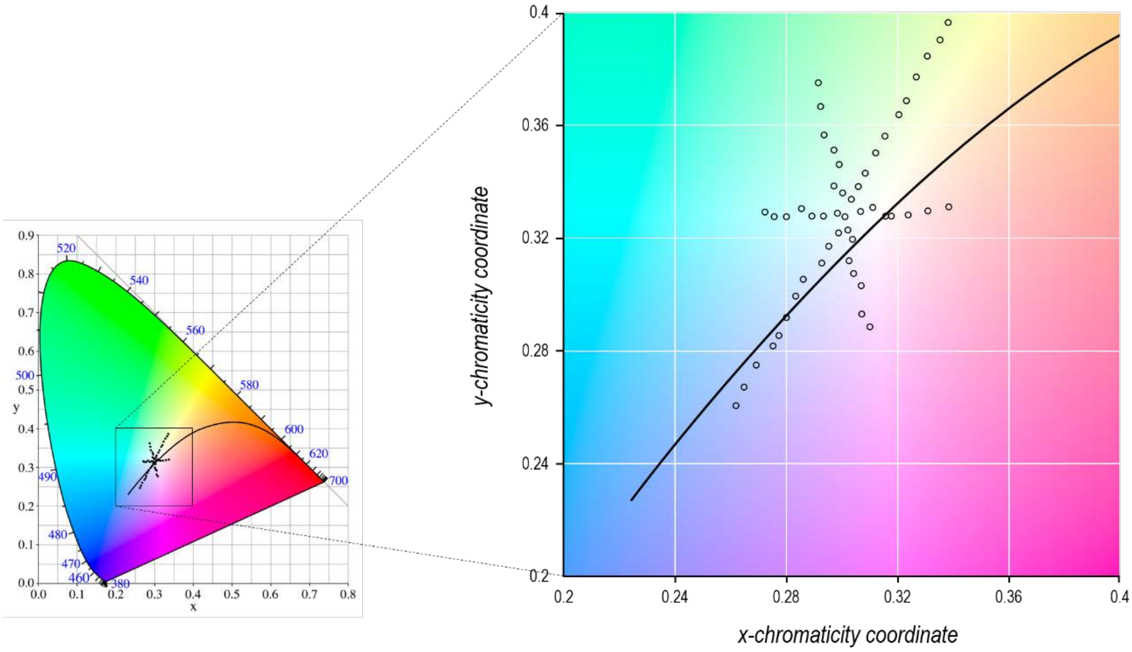


Figure 5-1. Colorimetric values of the 57 color stimuli on CIE xy chromaticity diagram (a solid line represents black body locus)

Table 5-1. Hue category and colorimetric values of the 57 color stimuli

Stimuli	Hue category	Colorimetric values						
		Red	Green	Blue	x	y	CCT (K)	Luminance (cd/m²)
	Red	255	250	250	0.3068	0.3294	6826	39.23
	Red	255	245	245	0.3112	0.3308	6571	38.50
	Red	255	240	240	0.3157	0.3277	6350	37.39
	Red	255	235	235	0.3177	0.3278	6242	36.67
	Red	255	230	230	0.3238	0.3282	5923	35.80
	Red	255	225	225	0.3310	0.3297	5564	34.57
	Red	255	220	220	0.3384	0.3311	5218	34.08
	Green	250	255	250	0.3003	0.3360	7115	40.20
	Green	245	255	245	0.2972	0.3384	7259	39.81
	Green	240	255	240	0.2991	0.3460	7063	39.50
	Green	235	255	235	0.2972	0.3511	7104	39.04
	Green	230	255	230	0.2936	0.3566	7221	38.59
	Green	225	255	225	0.2924	0.3666	7169	37.91
	Green	220	255	220	0.2916	0.3750	7121	37.55
	Blue	250	250	255	0.2989	0.3219	7394	39.73
	Blue	245	245	255	0.2952	0.3170	7725	38.55
	Blue	240	240	255	0.2928	0.3112	8022	37.75
	Blue	235	235	255	0.2861	0.3054	8171	37.20
	Blue	230	230	255	0.2834	0.2994	9178	36.44
	Blue	225	225	255	0.2801	0.2918	9862	35.30
	Blue	220	220	255	0.2774	0.2855	10558	34.52
	Blue	215	215	255	0.2753	0.2818	11105	33.78
	Blue	210	210	255	0.2691	0.2750	12730	32.43
	Blue	205	205	255	0.2648	0.2671	14804	30.95
	Blue	200	200	255	0.2619	0.2606	17043	30.03
	Cyan	250	255	255	0.2983	0.3289	7324	40.59
	Cyan	245	255	255	0.2934	0.3277	7641	40.19
	Cyan	240	255	255	0.2893	0.3277	7910	39.88

Stimuli	Hue category	Colorimetric values						
		Red	Green	Blue	x	y	CCT (K)	Luminance (cd/m^2)
	Cyan	235	255	255	0.2854	0.3304	8096	39.31
	Cyan	230	255	255	0.2801	0.3276	8518	38.92
	Cyan	225	255	255	0.2756	0.3276	8836	38.56
	Cyan	220	255	255	0.2724	0.3292	9018	38.64
	Magenta	255	250	255	0.3021	0.3229	7180	39.53
	Magenta	255	245	255	0.3038	0.3196	7125	38.93
	Magenta	255	240	255	0.3025	0.3119	7321	38.00
	Magenta	255	235	255	0.3043	0.3075	7270	37.48
	Magenta	255	230	255	0.3070	0.3031	7151	36.17
	Magenta	255	225	255	0.3072	0.2930	7315	35.52
	Magenta	255	220	255	0.3100	0.2886	7171	34.30
	Yellow	255	255	250	0.3034	0.3337	6965	39.27
	Yellow	255	255	245	0.3058	0.3382	6794	38.44
	Yellow	255	255	240	0.3084	0.3429	6621	38.04
	Yellow	255	255	235	0.3122	0.3501	6390	38.33
	Yellow	255	255	230	0.3155	0.3561	6211	38.46
	Yellow	255	255	225	0.3205	0.3638	5975	38.09
	Yellow	255	255	220	0.3232	0.3686	5858	37.97
	Yellow	255	255	215	0.3267	0.3770	5714	37.46
	Yellow	255	255	210	0.3307	0.3844	5570	36.91
	Yellow	255	255	205	0.3352	0.3902	5421	37.38
	Yellow	255	255	200	0.3382	0.3965	5331	36.88
	Neutral	250	250	250	0.3011	0.3276	7176	39.54
	Neutral	245	245	245	0.3010	0.3278	7179	38.46
	Neutral	240	240	240	0.3010	0.3280	7180	36.33
	Neutral	235	235	235	0.3009	0.3282	7180	34.54
	Neutral	230	230	230	0.3010	0.3285	7170	33.74
	Neutral	225	225	225	0.3008	0.3287	7179	32.12
	Neutral	220	220	220	0.3008	0.3289	7179	30.58

The stimuli were shown in the form of an internet webpage as illustrated in Figure 5-2. It was a text-based content which includes black texts and one of the 57 different shades of white background in order to prevent the effect of chromatic colors on the judgment. Display luminance were set at 10 cd/m^2 and 40 cd/m^2, which correspond to the optimal luminance for *initial viewing* and for *continuous viewing* under low illuminance, respectively, in reference to the experimental results from Chapter 4. Each stimulus was shown on a smartphone with display size of 4.8 inches.

Figure 5-2. A text-based content which includes black texts and different shades of white background

Evaluation Methodology

Since enough has been said about the physiological effect of blue light as introduced in the earlier chapter, the evaluation in this experiment is focused on investigating users' psychological response on display chromaticity through psychophysical assessment. Psychophysics is described as the scientific study of the relationship between the physical measurements of stimuli and the sensation (Gescheider, 2013). It also refers to a general class of methods that can be applied to study a perceptual system such as a threshold measurement of visual sensitivity (Boff et al., 1994).

A threshold experiment was designed to decide the just-perceptible change in a stimulus, namely a just-noticeable difference (JND). In this experiment, the judgments are carried out on perceptibility and acceptability, which are the most frequently used threshold units in the field of color science. Perceptibility is associated with detecting a just-noticeable difference and observers do not use an interpretation of their importance, whereas acceptability allows observers to interpret and compare the magnitude of the stimulus with that of its tolerable color difference, as described in Table 5-2 (Paravina et al., 2009; Na et al., 2014). Both two threshold units are determined utilizing the method of limits among the several types of threshold experiments because it is sensible to obtain an intuitive decision. In the method, the experimenter presents the stimuli at predefined discrete intensity levels and asks the observers to respond “yes” if they perceive it and “no” if they do not (Fairchild, 2013).

Table 5-2. Distinction between perceptibility and acceptability

Threshold unit	Question	Notes
Perceptibility	“Can I see a difference in color?”	Detecting just-noticeable differences, and not interpret of the importance
Acceptability	“Is this difference in color acceptable?”	Interpret and compare the magnitude of the stimulus with that of its tolerance

Procedure

The experiment was conducted in sufficiently dark conditions, and a viewing distance of the smartphone display was 30 cm during the experiment. The subjects were instructed to look at the 57 color stimuli with one of the two display luminance, either 10 cd/m^2 or 40 cd/m^2. The stimuli were shown in a random order, and two questions were asked to them as follows:

Question 1. Does the display color look white? (perceptibility)

Question 2. Do you intend to apply the display color to your smartphone if it supports your body comfortably? (acceptability)

The first question premised on the assumption that a neutral color was regarded to be a less bright version of white since the chromaticity of all neutral colors is identical. The subjects answered the questions with either “yes” or “no” after watching each stimulus for five seconds, and they were asked to close their eyes for 10 seconds between the stimuli in order to exclude the influence of the previous stimulus. After finishing the judgments on a first display luminance, they had two minutes break and then continued to the judgment on the other display luminance (see Figure 5-3). Hence each subject assessed a total of 114 stimuli (57 color stimuli by two levels of display luminance), and it took about an hour.

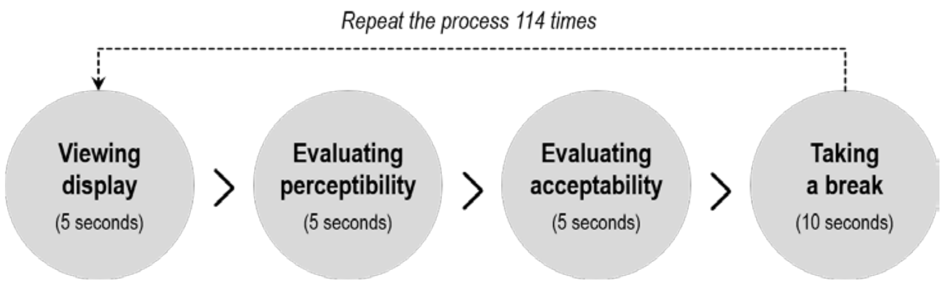


Figure 5-3. Experimental procedure for finding the optimal display chromaticity on a text-based content

5.1.3. Results and Analysis

Prior to analysis of the experimental results, responses of the subjects were converted into scores: the answer “yes” was scored one point and “no” did not receive a point. Next, all points were added up and positioned on two dimensional graphs represented by the level of RGB values in a horizontal axis and the accumulated points in a vertical axis.

The result of the display luminance of 10 cd/m^2 indicated that the points noticeably decreased both in perceptibility and acceptability as the level of the RGB values dropped. In the case of perceptibility, most subjects easily recognized that the display color is not a perfect white despite of small change in chromaticity, and there were little differences in the tendency among six hue categories, except a neutral color (see Figure 5-4 above). In regard of acceptability, however, high score was reported at the high levels of RGB values, but the score rapidly declined when the RGB level reached 240 or below. The remarkable discovery from the result was that the scores in acceptability were considerably higher in yellow than other hue categories (see Figure 5-4 below). The scores of yellow below the RGB level of 230 are about twice as likely to be the score compared to other hues. Paired sample t-test using an alpha level of 0.05 confirmed the significant difference in the scores between perceptibility and acceptability, $t(56) = -17.11$, $p < 0.05$. Nearly the same results were observed in the experiment on the display luminance of 40 cd/m^2, as shown in Figure 5-5. The mean scores were significantly lower in perceptibility than in acceptability, $t(56) = -16.54$, $p < 0.05$.

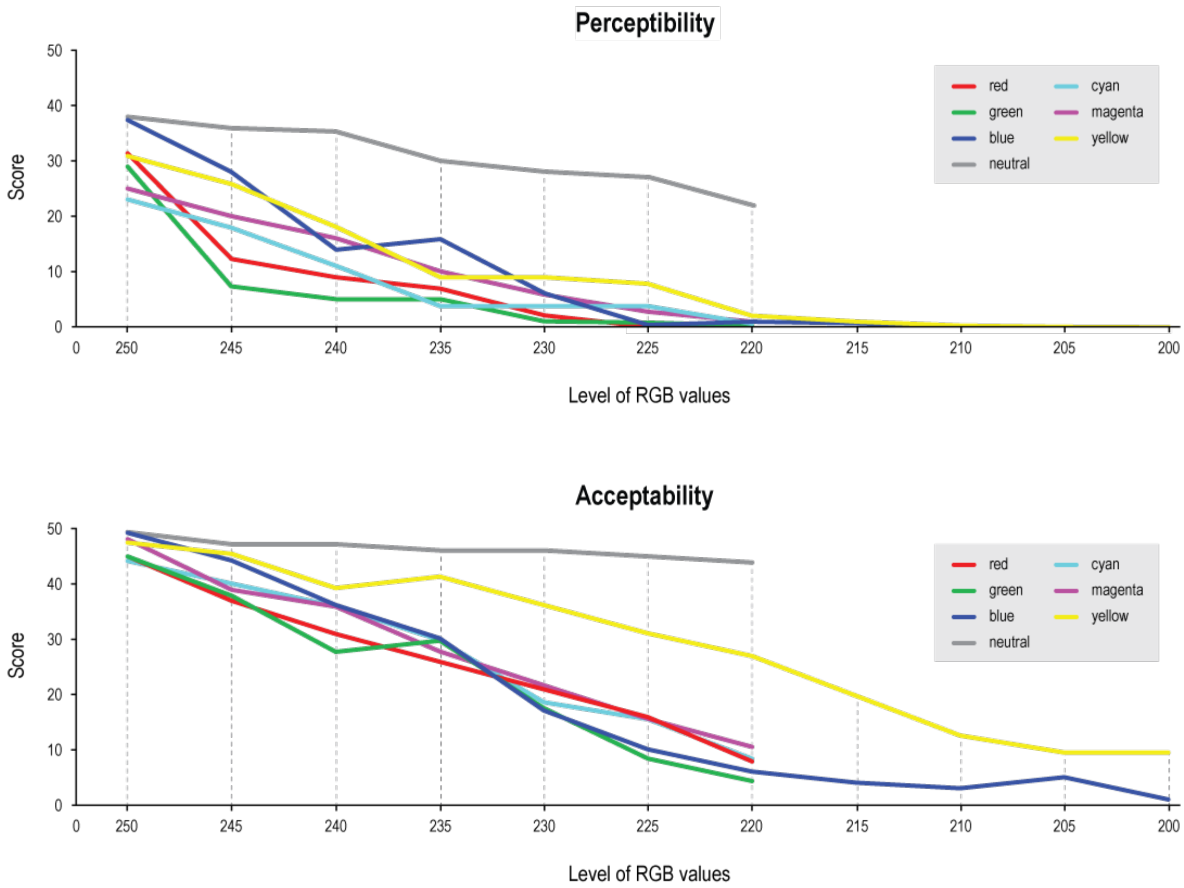


Figure 5-4. Perceptilibity (above) and acceptability (below) of display chromaticity on a text-based content with the display luminance of 10 cd/m^2

A paired sample t-test was performed to examine the effect of display luminance on a threshold evaluation, and the analysis indicated that the effect was non-significant both in perceptibility, $t(56) = -0.86$, $p = 0.39$, and in acceptability, $t(56) = -1.43$, $p = 0.26$. To put it differently, perceptibility or acceptability of display chromaticity is not influenced by display luminance.

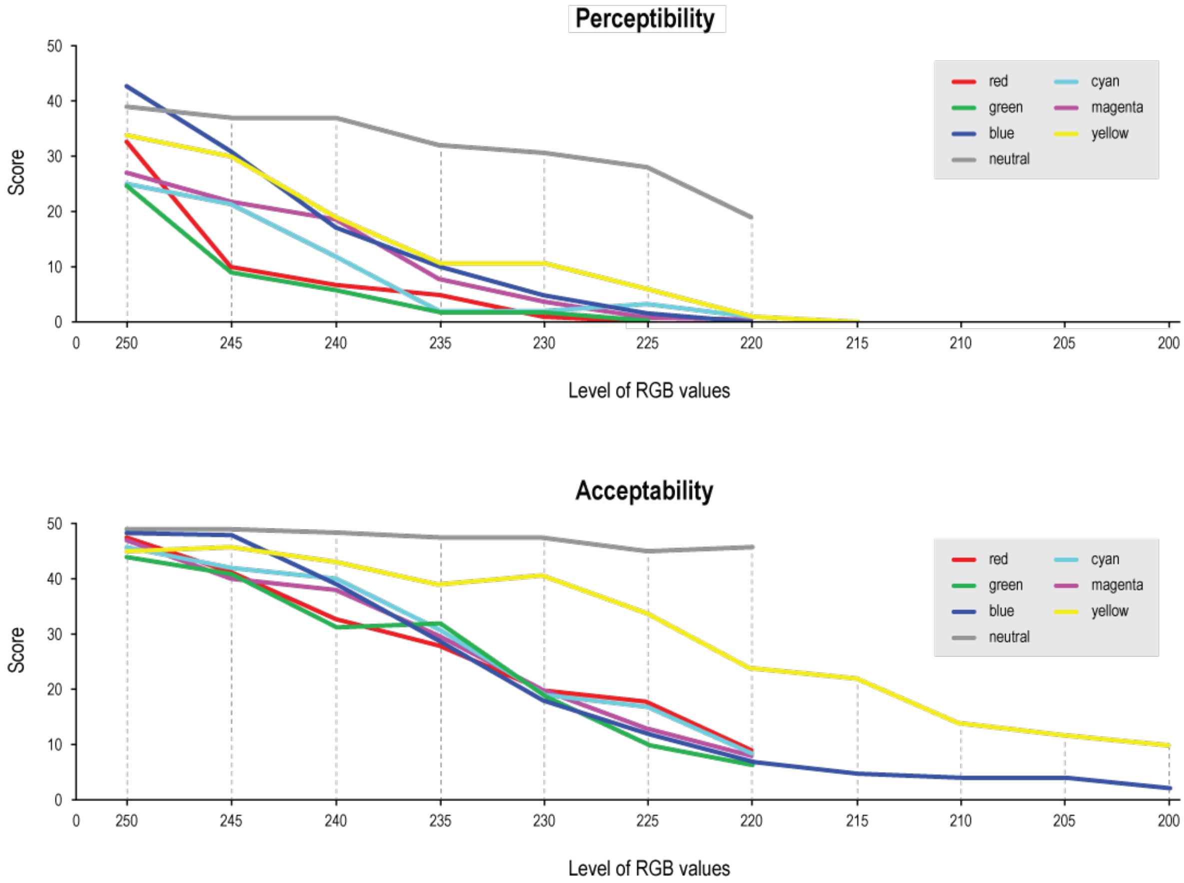


Figure 5-5. Perceptilibity (above) and acceptability (below) of display chromaticity on a text-based content with the display luminance of 40 cd/m^2

Next, the perceptible threshold and the acceptable threshold were defined as an agreement with more than 70 % of the subjects (a score of 35 or above), to establish the specific values of the optimal display chromaticity, following the criterion insisted by Suen and Lee (1985).

The results of two display luminance were completely the same. Perceptible thresholds of white display were similar across all the hue categories, and it was quite high. The subjects did not perceived the displayed color as white unless it is pure white which has the RGB values of 255, 255, and 255 in most of hue categories, except for blue and a neutral color. Perceptible threshold of blue was the RGB level of 250, which corresponds to the RGB values of 250, 250, and 255, and that of neutral color was the RGB values of 240, 240, and 240. The reason for observing relatively low perceptible threshold in blue is assumed to be the fact that the majority of smartphones on the Korean market have a display with a high color temperature that is shown as a white tinged with blue, for example, Samsung's Galaxy S series (Soneira, 2012).

On the contrary, there were large differences in acceptable threshold depending on the hue categories. Likewise with perceptual threshold, neutral color has the lowest level of acceptable threshold (RGB values of 220, 220, and 220). Among the six hue categories, acceptable threshold of yellow was the lowest, corresponding to the RGB values of 255, 255, and 230, whereas red and green had the highest threshold (RGB level of 245). Blue, cyan and magenta had the same level of threshold, the RGB level of 240. Acceptable threshold of each hue category was marked on the CIE xy chromaticity diagram as illustrated in Figure 5-6.

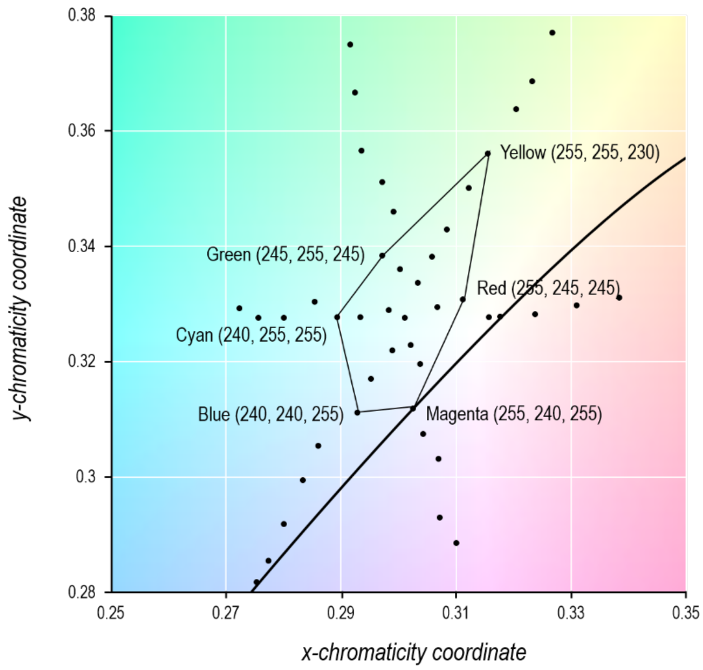


Figure 5-6. Acceptable threshold of the six hue categories on a text-based content (same results were reported on a display luminance of 10 cd/m^2 and those of 40 cd/m^2, and each dot indicates a color stimulus)

5.1.4. Findings

The analysis results showed that yellow not only received the highest scores in acceptability but also had the lowest acceptable threshold among the six hue categories. This means that the subjects feel less resistance when they use a smartphone display of white tinged with yellow in comparison with other colors.

The display also emits less blue light, which involves the adverse effect on the physiological system, than a white display. Thus it can be interpreted that the yellowish white with the RGB values of 255, 255, and 230 is the optimal display chromaticity for a text-based content consisting of only black and white components in terms of users' physiological comfort and psychological satisfaction. Although a neutral color had the lowest threshold both in perceptibility and acceptability, it is improper for display due to a significant decrease in display luminance.

A display which is applied to the discovered optimal chromaticity is seen in Figure 5-7. While the display in the figure looks somewhat saturated yellow, the display looks much less saturated on an actual display under low illuminance.

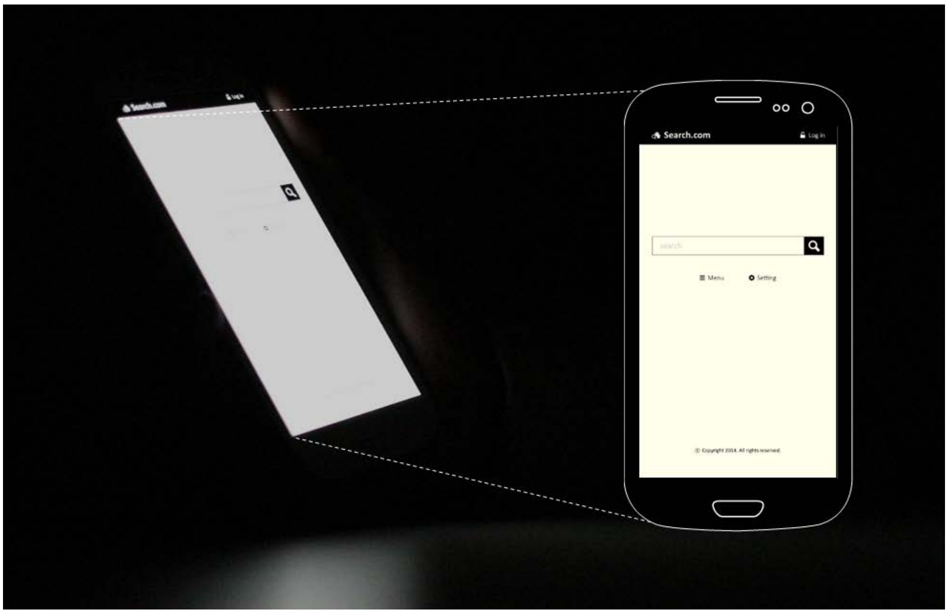


Figure 5-7. Optimal display chromaticity for text-based content: a white display tinged with yellow and with the RGB values of 255, 255, and 230

Including the white display tinged with yellow that was determined to be the optimal display chromaticity in this experiment, in addition, acceptable threshold was always lower than the perceptible threshold in all hue categories. That is, the subjects have willingness to use the color for their smartphone display even though it is not perceived as a pure white on the premise that the display has some positive effects on physiological system such as restful sleep or visual comfort.

Aforementioned results confirmed that display luminance does not affect the judgment of perceptibility and acceptability of the display chromaticity, so the experiments in next section are focused only on the luminance of 40 cd/m^2, referred to as the optimal display luminance for viewing mobile displays long hours.

5.2. Experiment on Text and Image-based Content

5.2.1. Objective

The purpose of the experiment is to identify the optimal display chromaticity for a text and image-based content which is composed of black texts and a colorful image on a white background, and to compare the experimental results with that of the previous experiment.

5.2.2. Method

Subjects

A total of 50 people made up of 26 males and 24 females were recruited. The subjects ranged in age from 19 to 31 years, with the mean age of 21.48 years with a standard deviation of 2.81 years. All of them were tested for color deficiency using the Ishihara's test for color blindness, and no significant color deficiencies were observed. People who were participated in the previous experiment were ruled out as the subject in this experiment.

Stimuli

Fifty-seven display color stimuli were produced in the same way as the experiment in section 5.1: Seven levels of RGB values (250, 245, 240, 235, 230, 225, and 220) for four hue categories (red, green, cyan, and magenta) and a neutral color, as well as 11 levels of RGB values (250, 245, 240, 235, 230, 225, 220, 215, 210, 205, and 200) for blue and yellow hue categories, as listed in Table 5-1. Therefore the respective hue category has either seven or 11 different intensities. RGB level indicates the intensity of the color, for instance, the RGB level of 220 in yellow hue represents the yellowish white with the RGB values of 255, 255, and 220.

The stimuli were reproductions of a news webpage, corresponding to a text and image-based content. It displays a typical content page with black texts, different shades of a white background and a colorful image to discover the influence of the content color on the judgment of perceptibility and acceptability. White balance of the image was adjusted in line with the background shade using MATLAB version 8.1 to avoid the perceptual color difference between the background and the image. For example, if the RGB values of the display background was 255, 240, and 240, white balance of the image was corrected on the basis of the values.

Next, two sets of display stimuli, which feature different images, were created to confirm the effect of the dominant color of the displayed image on the evaluation: Set 1 includes a photograph of green salad, and set 2 contains a photograph of people, as depicted in Figure 5-8. There are two reasons for choosing the images. First, the images representing people or food have relatively small color tolerance compared to other images, as well as those images account for a large percentage of the photograph on general webpages (Guan and Hung, 2010). Therefore it could be concluded that the content colors do not exert an influence on the decision of the optimal display chromaticity regardless of the displayed images if the effect of content color is not observed in the two images. Second, each of the two images has a dominant color, green for set 1 and red for set 2.

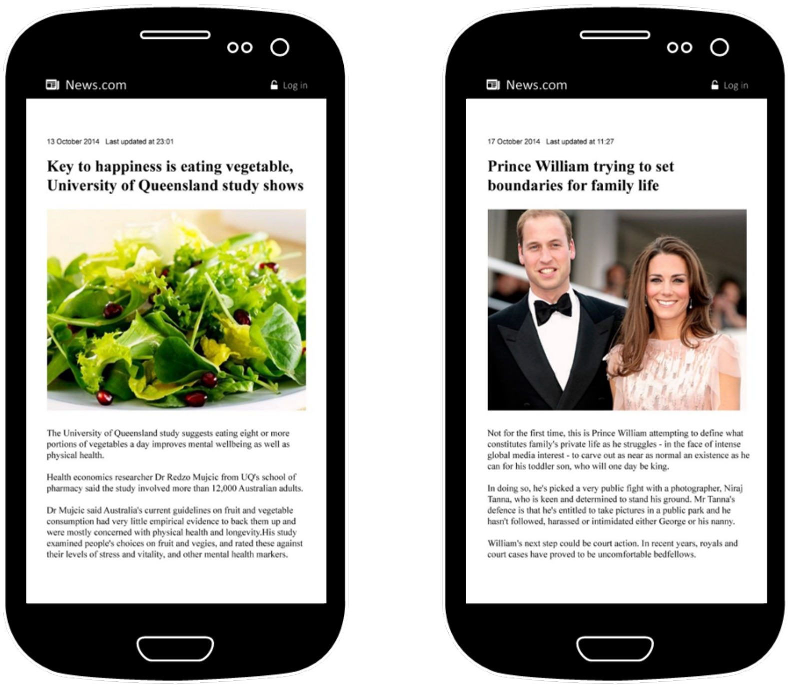


Figure 5-8. Text and image-based contents which display black texts, different shades of white background and a colorful image. Set 1 includes a photograph of green salad (left) and set 2 contains a photograph of people (right)

The stimuli were displayed on the same smartphone display used in previous experiment. The display luminance was set at 40 cd/m^2, since earlier experiment revealed that the luminance has no direct effect on the evaluation.

Procedure

The experiment was carried out in the same procedure with the former experiment (see Figure 5-9) under the identical condition. The subjects were permitted to watch the display stimuli with one of the two stimuli set and they answered the two questions below with either "yes" or "no", and an assistant sitting in a corner of the experimental room wrote down their answers on a laptop immediately.

Question 1. Does the display color look normal? In other words, do you feel the display presents a white background and an original image with no change in color? (perceptibility)

Question 2. Do you intend to apply the display color to your smartphone if it supports your body comfortably? (acceptability)

The subjects took a two-minute break with their eyes closed before turning to the next stimuli set. In total, 114 stimuli were evaluated in this experiment.

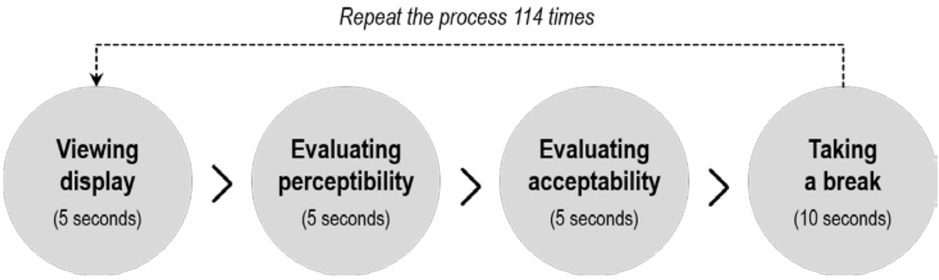


Figure 5-9. Experimental procedure for finding the optimal display chromaticity on a text and image-based content

5.2.3. Results and Analysis

Likewise with the former experiment, the responses of the subjects were changed into scores and schematized as two-dimensional graphs that the level of RGB values is plotted on the horizontal axis and the accumulated points on the vertical axis.

The analysis results closely paralleled to the results of the previous experiment. Both the scores in perceptibility and acceptability dropped sharply as the display chromaticity became saturated. That is, the more subjects recognized the color as not white, the less intention was observed to use the color for their smartphone display. In regard to set 1, a text and image-based content with a photograph of green salad, the scores in perceptibility began to fall noticeably when the RGB level reached 245 or below with the exception of a neutral color, and this trend was particularly drastic in red and green, as seen in Figure 5-10 above. Acceptability was rated with relatively higher scores than perceptibility in all the hue categories, but the scores started to decline remarkably at the RGB level of 240 or below, as described in Figure 5-10 below.

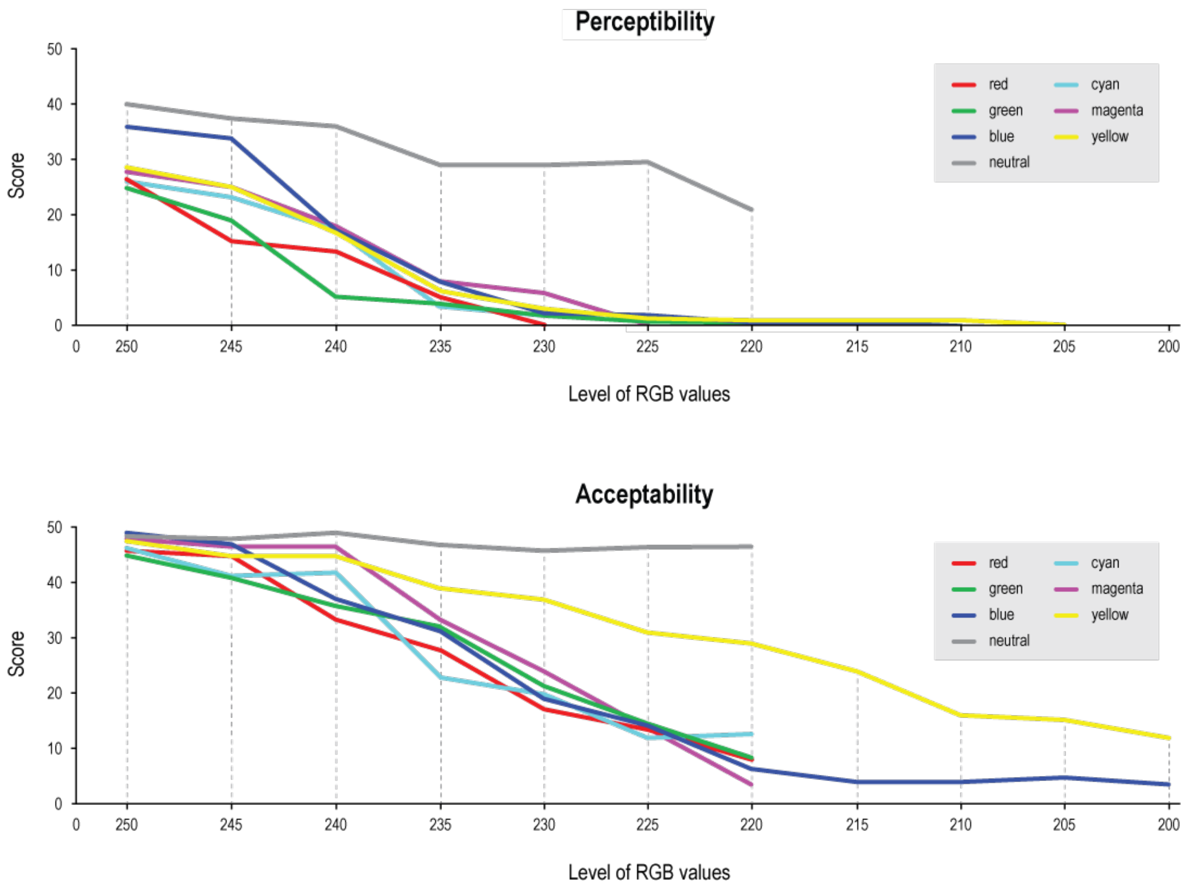


Figure 5-10. Perceptilibity (above) and acceptability (below) of display chromaticity on a text and image-based content with a photograph of green salad (set 1)

There were few changes in the acceptability scores for a neutral color at all RGB levels. The highest scores on average and the smallest percentage decline in the scores were observed in yellow compared with other hue categories, and the difference between the scores in yellow and other hues increased as the RGB level of the stimuli dropped. A paired sample t-test yielded statistical significant at an alpha level of 0.05 reported that perceptibility had higher scores in average than the scores of acceptability, $t(56) = -16.85$, $p < 0.05$. The results of set 2 (a text and image-based content with a photograph of people) were virtually the same as those of set 1 as shown in Figure 5-11. There was a significant difference in the scores between perceptibility and acceptability, $t(56) = -16.78$, $p < 0.05$.

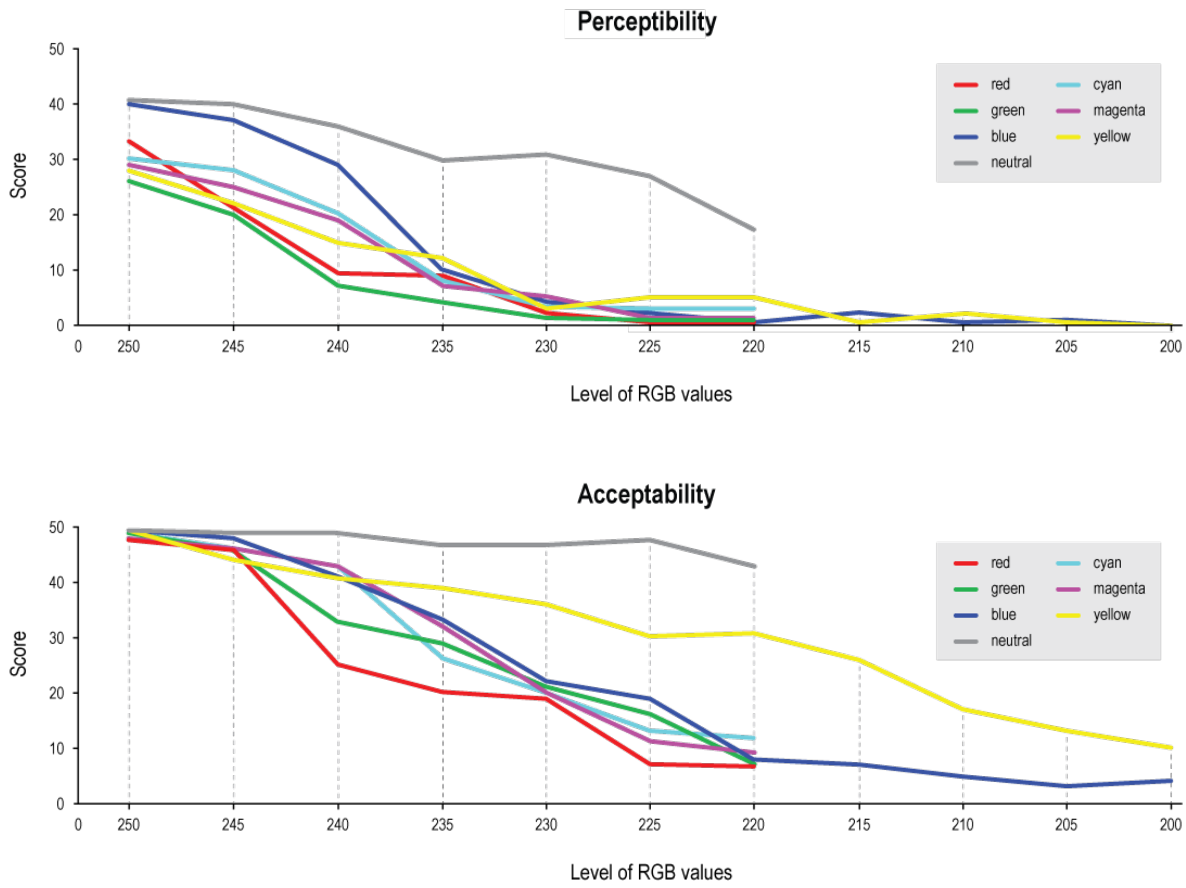


Figure 5-11. Perceptilibity (above) and acceptability (below) of display chromaticity on a text and image-based content with a photograph of people (set 2)

No significant difference was observed between the results of set 1 and those of set 2 both in perceptibility, $t(56) = -1.77$, $p = 0.21$, and acceptability, $t(56) = -0.26$, $p = 0.86$. In other words, content colors do not affect perceptibility and acceptability of display chromaticity on a text and image-based content.

Subsequently perceptible threshold and acceptable threshold were defined as a score of 35 or above, which means when more than 70 % of the subjects answering “yes” to the display stimuli, as previously stated. A similar tendency was obtained with the experiment in section 5.1 in all the hue categories. Perceptible threshold of red, green, cyan, magenta and yellow were perfect white, corresponding to the RGB values of 255, 255, and 255, whereas that of a neutral color was the RGB values of 240, 240, and 240.

Acceptable thresholds of the six hue categories in respective set were plotted on the CIE xy chromaticity diagram as depicted in Figure 5-12, and the results of two sets were almost identical. The only difference between them was that the acceptable threshold of green in set 1 was one level below than those in set 2. Levels of acceptable threshold in two sets were the RGB values for 240, 255, and 240 in set 1, and those for 245, 255, and 245 in set 2. Perhaps the subjects felt a greenish display is relatively well matched with the image of green salad since it mainly composed with the shades of green. As expected, yellow had the lowest acceptable threshold both in two sets, corresponding to the RGB values of 255, 255, and 230.

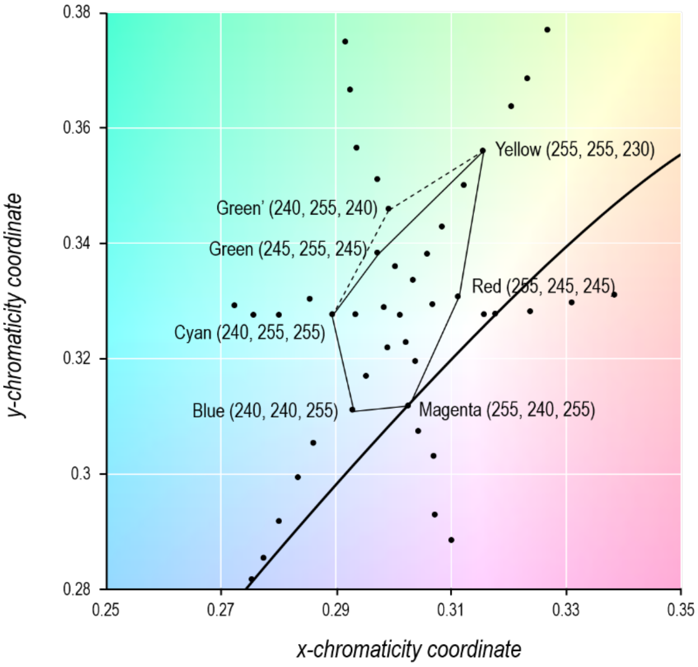


Figure 5-12. Acceptable threshold of the six hue categories on a text and image-based content (set 1 (dotted line), set 2 (solid line), and each dot indicates a color stimulus)

5.2.4. Findings

The experimental results clearly presented that the lowest acceptable threshold was observed in yellow among the six hue categories. Thus the adequacy of using the white with a yellow shade, which has the RGB values of 255, 255, and 230 (see Figure 5-13), was demonstrated as the optimal display chromaticity for viewing smartphones under low illuminance on a text and image-based content. The results were very consistent in the two sets, exclusive of the minor difference in acceptable threshold of green. Consequently it was revealed that the color composition of the image on a text and image-based content does not have a seriously effect on the decision of the optimal display chromaticity. In addition, perceptibility in blue is relatively lower than other hue categories, to put it another way, people recognize a white with blue shade as a pure white on displays, but no difference was found in acceptable threshold of blue.

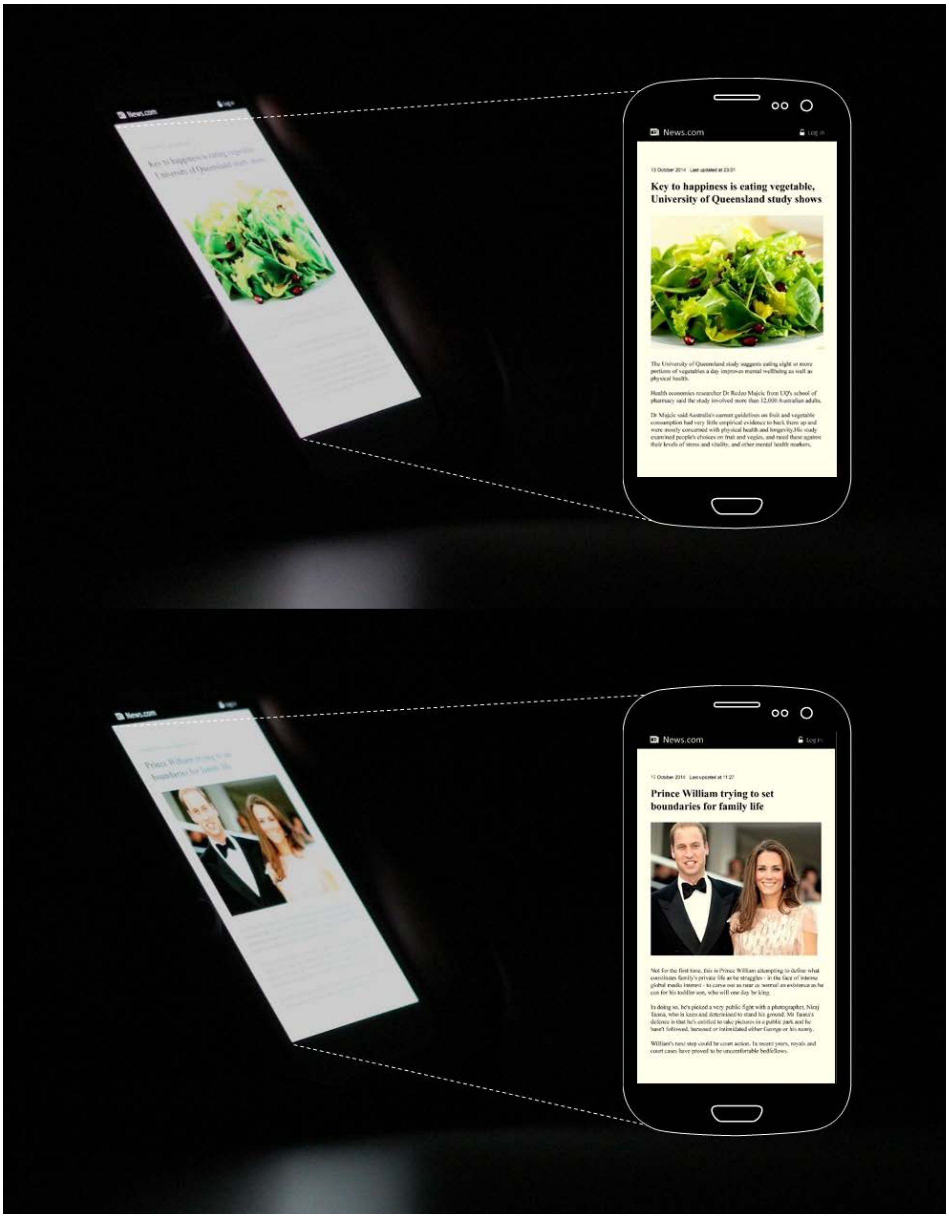


Figure 5-13. Optimal display chromaticity for a text and image-based content: a white display tinged with yellow and with the RGB values of 255, 255, and 230

5.3. Experiment on Video-based Content

5.3.1. Objective

The experiment aims at investigating the optimal display chromaticity for a video-based content which displays multicolored moving images while people use their smartphones in conditions of low illuminance. Moreover, it attempts to establish the optimal display chromaticity for nighttime smartphone users based on the interpretation of the three experiments in this chapter.

5.3.2. Method

Subjects

Thirty subjects including 18 males and 12 females volunteered to participate in the experiment. Their mean age was 22.84 years with a standard deviation of 3.11 years, and individuals were excluded from participation if they have a color deficiency or already joined in the previous experiments.

Stimuli

A total of 35 display stimuli comprising of one neutral color and six hue categories (red, green, blue, cyan, magenta, and yellow) with five levels of RGB values (225, 195, 165, 135, and 105) were created for the experiment, as listed in Table 5-3. In the experiment, RGB distance between the stimuli was relatively larger than that in the previous experiments, because color discrimination is more difficult in full-color displays having no standard white point. Appropriacy of the RGB distance of 30 was verified through the pilot test. Colorimetric values of the stimuli were plotted on the CIE xy chromaticity diagram as shown in Figure 5-14 (Five stimuli in neutral color category are overlapped in a single point since the stimuli have identical chromaticity).

Table 5-3. Hue category and colorimetric values of the 35 color stimuli

Stimuli	Hue category	Colorimetric values						
		Red	Green	Blue	x	y	CCT (K)	Luminance (cd/m²)
	Red	255	225	225	0.3310	0.3297	5564	39.48
	Red	255	195	195	0.3588	0.3284	3562	36.77
	Red	255	165	165	0.3860	0.3272	-	34.02
	Red	255	135	135	0.4002	0.3287	-	32.56
	Red	255	105	105	0.4178	0.3292	-	28.89
	Green	225	255	225	0.2924	0.3666	7169	39.67
	Green	195	255	195	0.2916	0.4024	6350	37.75
	Green	165	255	165	0.2897	0.4424	-	36.09
	Green	135	255	135	0.2875	0.4875	-	34.46
	Green	105	255	105	0.2858	0.5266	-	33.01
	Blue	225	225	255	0.2801	0.2918	9862	38.52
	Blue	195	195	255	0.2674	0.2703	-	35.26
	Blue	165	165	255	0.2493	0.2434	-	31.01
	Blue	135	135	255	0.2367	0.2172	-	27.85
	Blue	105	105	255	0.2196	0.189	-	23.22
	Cyan	225	255	255	0.2756	0.3276	8836	39.59
	Cyan	195	255	255	0.2588	0.3276	10028	38.20
	Cyan	165	255	255	0.2438	0.3276	-	36.59
	Cyan	135	255	255	0.2311	0.3275	-	35.85
	Cyan	105	255	255	0.2209	0.3275	-	34.87
	Magenta	255	225	255	0.3072	0.2930	7315	39.51
	Magenta	255	195	255	0.3085	0.2633	8022	36.92
	Magenta	255	165	255	0.3098	0.2342	-	34.12
	Magenta	255	135	255	0.3111	0.2074	-	31.77
	Magenta	255	105	255	0.3122	0.1844	-	29.04
	Yellow	255	255	225	0.3205	0.3638	5858	39.58
	Yellow	255	255	195	0.3384	0.3965	3884	39.11
	Yellow	255	255	165	0.3561	0.4267	-	38.51

Stimuli	Hue category	Colorimetric values						
		Red	Green	Blue	x	y	CCT (K)	Luminance (cd/m²)
	Yellow	255	255	135	0.3724	0.4538	-	37.33
	Yellow	255	255	105	0.3865	0.4850	-	35.87
	Neutral	225	225	225	0.3008	0.3287	7179	39.45
	Neutral	195	195	195	0.3008	0.3288	7179	35.29
	Neutral	165	165	165	0.3009	0.3290	7180	31.14
	Neutral	135	135	135	0.3010	0.3290	7180	26.55
	Neutral	105	105	105	0.3010	0.3292	7179	21.72

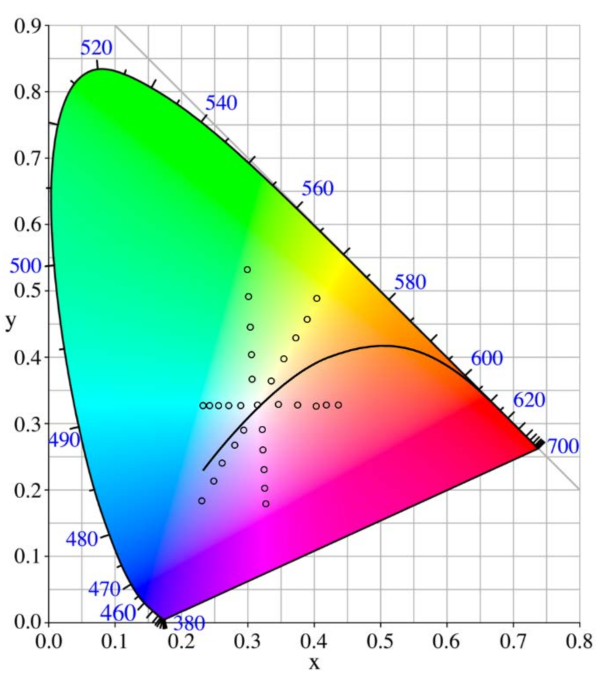


Figure 5-14. Colorimetric values of the 35 color stimuli on CIE xy chromaticity diagram (a solid line represents black body locus)

The stimuli were displayed in the form of a video-based content in 30 seconds long, and full-color moving images with three different themes – multicolored foods, people, and blue ocean – were shown for 10 seconds each, as illustrated in Figure 5-15. Foods and people were selected as the displayed images because they have a small color tolerance and hold a higher proportion in general video contents, and blue ocean was added to identify the sensitivity in blue since the previous experiments argued the reduction in blue light for achieving the optimal display chromaticity. White balance of the each stimulus was adjusted based on the 35 color stimuli using MATLAB version 8.1, and display luminance was set at 40 cd/m^2.

Figure 5-15. A 30 seconds long video-based content which displays full-color moving images. Three themes including multicolored foods (top), people (middle), and blue ocean (bottom) were shown for 10 seconds each.

Procedure

The experiment was conducted in the same way as the previous experiments as depicted in Figure 5-16. The subjects watched the 35 display stimuli in a random order, and they answered “yes” or “no” to the two questions below.

Question 1. Does the display color look normal? In other words, do you feel the display presents original videos with no change in color? (perceptibility)

Question 2. Do you intend to apply the display color to your smartphone if it supports your body comfortably? (acceptability)

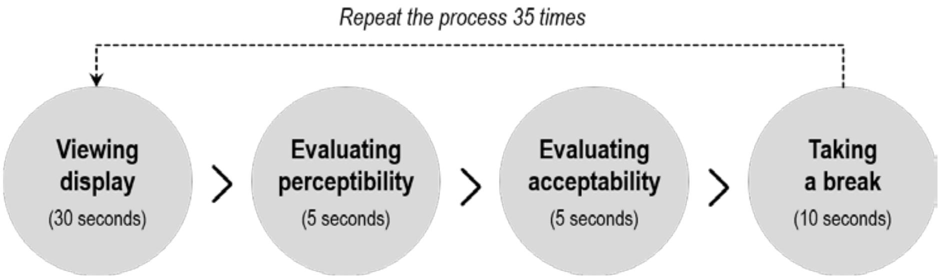


Figure 5-16. Experimental procedure for finding the optimal display chromaticity on a video-based content

5.3.3. Results and Analysis

At the RGB level of 225, more than half of the subjects perceived that the display presents a video with original colors across all hue categories, as shown in Figure 5-17 above, whereas hardly anyone recognized the display color as a white at the same RGB level in the previous two experiments. To put it plainly, perceptibility in a video-based content was relatively higher than that in a text-based content or a text and image-based content, and the reason is presumed that full-color displays have no standard white point which plays a point of reference. Also the scores in perceptibility became close to zero when the RGB level reached 195 or below, except yellow and a neutral color.

Acceptability was received higher scores than perceptibility in all the hue categories. It recorded considerably high scores at or over the RGB level of 195, but the scores rapidly decreased below the level, as described in Figure 5-17 below. Among the six hue categories, yellow rated the highest average scores and the smallest percentage decline in the scores. Moreover, the percentage decline was relatively small in blue and cyan, and it might be because those hues are harmonious with the blue ocean in the video. A paired sample t-test indicated a significantly higher scores in acceptability than perceptibility, $t(56) = -16.78$, $p < 0.05$.

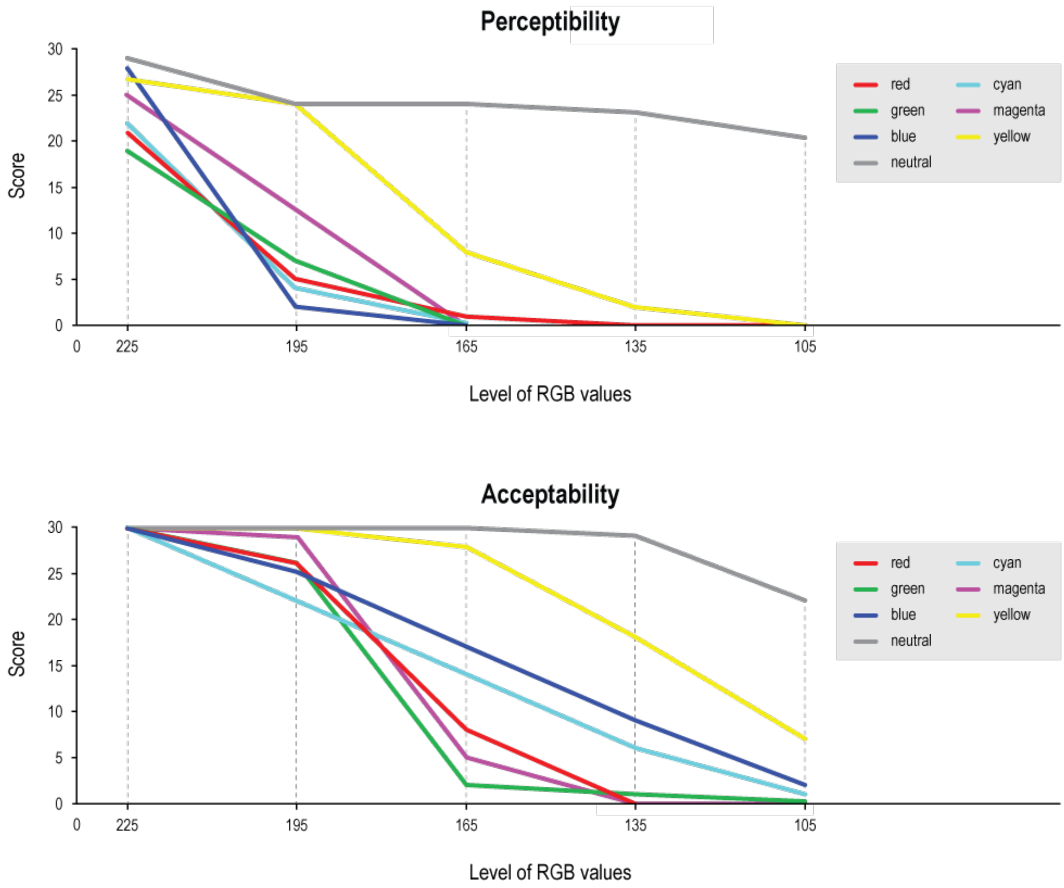


Figure 5-17. Perceptilibity (above) and acceptability (below) of display chromaticity on a video-based content

Acceptable threshold of the six hues, which was defined as an agreement with more than 70 % of the subject (a score of 21 or above), were plotted on Figure 5-18. Yellow had the lowest threshold which corresponds to the RGB vales of 255, 255, and 165, and other five hue categories had the same threshold level, the RGB level of 195.

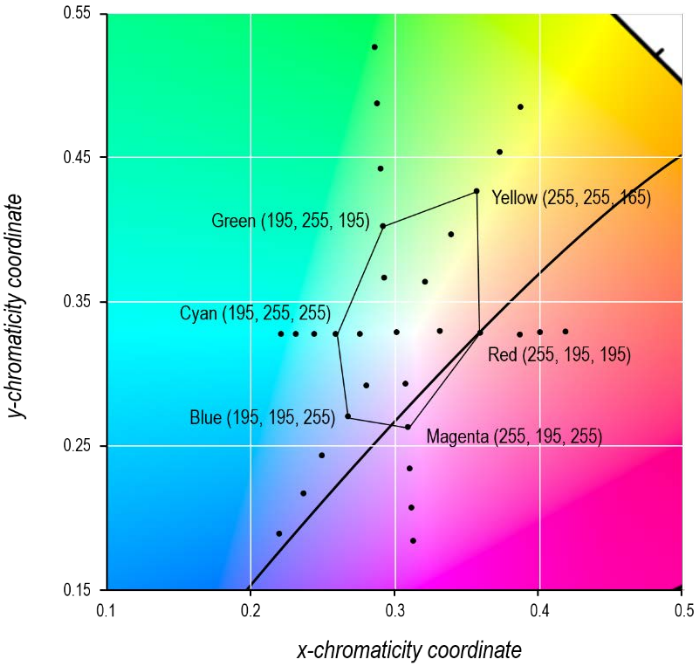


Figure 5-18. Acceptable threshold of the six hue categories on a video-based content

5.3.4. Findings

The lowest acceptable threshold was reported in yellow, and the RGB values of 255, 255, and 165 was determined as the optimal display chromaticity on a video-based content. The values look quite yellowish on a white display, but not that much on a full-color display. The subjects hardly noticed the change in white balance on a full-color display, because it is already full of colorful images as well as there is no white point on the screen. Thus, a relatively large variation in display chromaticity is allowed when people view a video-based content on smartphones. Figure 5-19 shows the smartphone that applied the proposed display chromaticity in a dark environment.

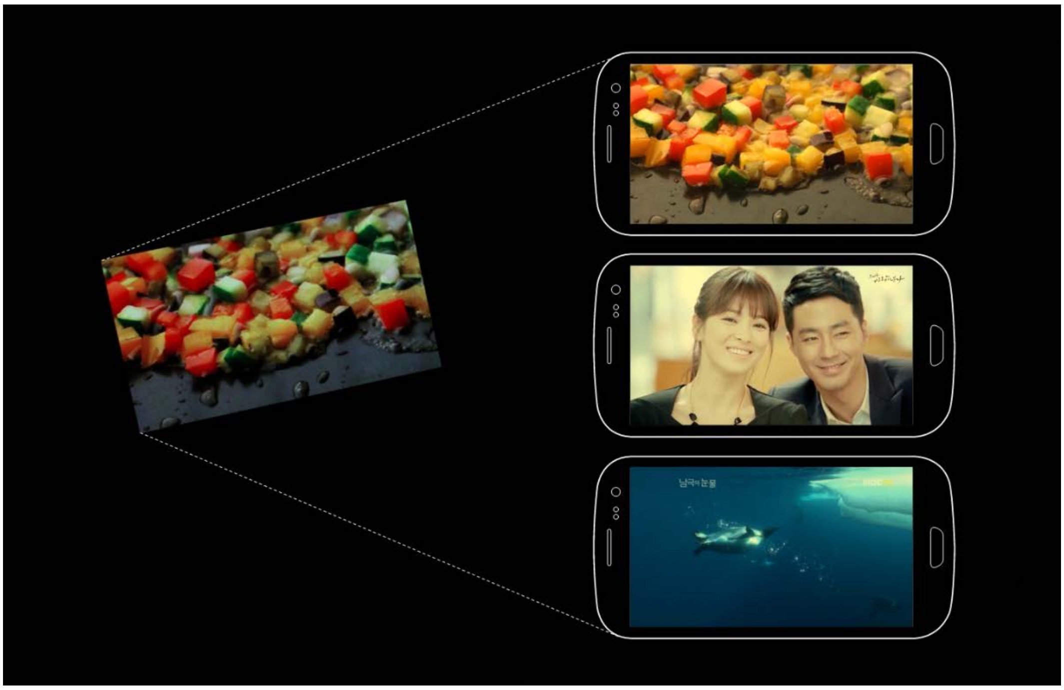


Figure 5-19. Optimal display chromaticity for a video-based content: a white display tinged with yellow and with the RGB values of 255, 255, and 165

5.4. Summary

This chapter investigated the optimal display chromaticity for viewing smartphones under low illuminance by reducing blue light, while not distorting the perceived quality of displays. Three experiments were conducted on a text-based content consisting of black texts and a white background, on a text and image-based content which contains black texts, a white background and a colorful image, and on a video-based content with full-color moving images. The subjects judged on perceptibility and acceptability of the displays with various chromaticity.

As a result, it was discovered that a white tinged with yellow had the highest acceptability in all three experiments. The optimal display chromaticity on a text-based content was identical with that on a text and image-based content, corresponding to the RGB values of 255, 255, and 230. By contrast, a video-based content took lower RGB levels as the optimal display chromaticity, which has the RGB values of 255, 255, and 165.

This result implies that reducing blue light on displays supports not only physiological comfort but also psychological satisfaction to nighttime smartphone users, as well as the optimal display chromaticity changes depending on color composition of the displayed content. A slight reduction in blue light is recommended if a white covers a majority of the display, whereas a large reduction is permitted on a full-color display which has no white point. Thus it could be a better solution if display chromaticity changes according to the displayed content on the smartphone.

In Chapter 6, as the next step of the study, a validation test is carried out to verify the effect of the optimal display luminance and chromaticity in real-life situation.

6

Validation of Optimal Display

6. Validation of Optimal Display

This chapter validates the effect of the optimal display in real-life situation. Section 6.1 introduces the importance of physiological evaluation for validating the effect of optimal display. Section 6.2 verifies the superiority of the proposed optimal display luminance and chromaticity compared to the current smartphone display in real-life situation.

6.1. Need for Physiological Validation in Real-life Situation

The optimal display luminance and chromaticity were identified in Chapter 4 and 5, respectively, by conducting diverse kinds of physiological and psychological assessments. In this chapter, overall superiority of the optimal display is validated through physiological evaluation in real-life situation for the following reason.

The evaluation methodologies used in the previous experiments, such as eye blinks, facial expression, and brainwave analysis were concentrated on discovering an instantaneous physiological effect. The methodologies have the advantage of being able to detect the users' immediate responses, but they cannot examine the circadian effect of smartphone use. By contrast, the prolonged evaluation allows researchers to observe the users' physiological responses over time, and ultimately it facilitates a more reliable and accurate investigation on the effect. It also closely connected to psychological response. Use of a physiologically uncomfortable display for a long time leads to a decrease in psychological satisfaction, whereas a comfortable display enhances the satisfaction.

In this regard, the study intends to measure the melatonin concentrations of subjects for validating physiological superiority of the optimal display to the current display. This method can report not only a physiological response right after the use of displays, but also the effect of displays on the subjects' circadian rhythm. Moreover, it allows the subjects to move without restriction and needs no experimenter during the experiment, contrary to brainwave analysis. The experiment is carried out in a form of a field experiment in real-life situation to achieve more practical responses.

Consequently a validation of the optimal display is conducted by measuring melatonin concentration, and a full description of the experiment is explained in the next section.

6.2. Validation of Optimal Display Luminance and Chromaticity

6.2.1. Objective

This section aims at validating the benefits of the optimal display luminance and chromaticity through the experiment in real-life situation. It attempts to investigate the effect of smartphone use at night on users' circadian rhythm when the display luminance and chromaticity are differently articulated, and to verify the superiority of the optimal display compared to the current display.

6.2.2. Method

Subjects

A group of eight people comprised of four males and four females completed the experiment. The mean age of the subjects was 21.88 years with a standard deviation of 2.71 years, and all of them had normal vision or corrected-to-normal vision. Individuals with any major health problems, sleep disorders, or those taking medicine regularly were excluded from participation. None of the subjects was either an extreme morning type or an extreme evening type.

Stimuli

Two levels of display luminance and two types of display chromaticity were employed to prepare the stimuli. Firstly, for the display luminance variations, the high luminance was set at 400 cd/m^2, as this is the maximum luminance of the latest smartphone (Samsung Galaxy S6). For low luminance, 40 cd/m^2 was applied, since it was the optimal display luminance for prolonged use of smartphones in conditions of low illuminance. With regard to the display chromaticity, it varied between a pure white and a white tinged with yellow. A pure white was reproduced when the all RGB channels were set at maximum, corresponding to the RGB values of 255, 255, and 255. The alternative white tinged with yellow was set with the RGB values of 255, 255, and 200, which is the intermediate RGB values between the optimal chromaticity for text-based and text and image-based content (255, 255, and 230), and that for video-based content (255, 255, and 165). In total, four types of display stimuli (two levels of luminance by two types of chromaticity) were created and labeled as follows (see Table 6-1): high luminance and pure white (HW) which corresponds to the current display, high luminance and white tinged with yellow (HY), low luminance and pure white (LW), and low luminance and white tinged with yellow (LY) which is equivalent to the optimal display.

Table 6-1. Four display stimuli consisting of two levels of luminance and two types of chromaticity

Stimuli		Luminance (cd/m^2)	Chromaticity (RGB values)
	HW (High luminance and pure White)	400	255, 255, 255
	HY (High luminance and white tinged with Yellow)	400	255, 255, 200
	LW (Low luminance and pure White)	40	255, 255, 255
	LY (Low luminance and white tinged with Yellow)	40	255, 255, 200

Evaluation Methodology

A total of three evaluation methods are carried out in this validation experiment for assessing physiological response as below.

Salivary melatonin concentration

Melatonin, chemically N-acetyl-5-methoxytryptamine, is a hormone produced from the pineal gland which plays a role in the regulation of human circadian rhythm (Dubocovich, 1983; Altun and Ugur-Altun, 2007). It is secreted the most at night, and is can be detected in blood, saliva or urine. Among them, measurement of blood melatonin concentration is the most accurate method, but it requires blood collection by venipuncture. Thus measurement of salivary melatonin has been widely used since the procedure for collecting sample is simple, safe and painless, as well as blood melatonin concentration is paralleled by corresponding variations in saliva where the saliva melatonin concentrations are about 30 % of that found in blood (Nowak et al., 1987; Voultsios et al., 1997).

In this experimental process, saliva samples were collected and analyzed by enzyme immunoassay using commercially available ELISA kits (The Salimetrics™ Salivary Melatonin Assay Kit) as shown in Figure 6-1. The inter- and intra-assay coefficients of variation were 7.4 % and 2.6 %, respectively, and the kit sensitivity was 1.37 pg/ml. Table 6-2 gives a full description of the procedure for melatonin collection in saliva.

Figure 6-1. Salivary melatonin assay kit (Salimetrics, State College, PA, USA)

Table 6-2. Procedure for saliva collection

Order	Description
1	Before starting collection, label the tubes (name, given stimulus, collection date and time)
2	Five minutes before each saliva sample, rinse the mouth thoroughly with water
3	Put a cotton into the mouth straight from the top without touching it with fingers
4	Put the cotton between the teeth and cheek and move it around with tongue for 1-2 minutes, until the cotton is thoroughly soaked with saliva
5	Put the cotton from the mouth straight into the tube, without touching it with fingers

The collected saliva samples were stored in a refrigerator with the temperature below 2 degrees to prevent the sample from spoiling, and then the samples were analyzed after the end of the experiment.

Body temperature and heart rate

In the experiment, body temperature was measured before and after each experiment since they have been used as a marker of circadian rhythm (Czeisler et al., 1980). Heart rate was also recorded to observe the activity levels of the central nervous system (Waldeck and Lambert, 2003).

Procedure

All subjects were given an instruction of the experimental procedure and the possible side effects from the experimenter, and they signed an informed consent form prior to the experiment. The subjects were instructed to maintain regular sleep-wake cycles for a week before the experiment. They were required to go to bed between 23:00 and 00:00 and to wake up between 07:00 and 08:00, and to send text messages at both bedtime and wake time every day in order for the experimenter to monitor their sleep schedule. Moreover, the subjects were asked to avoid consuming medicines, alcohol, nicotine, and any foods or drinks containing caffeine during this period.

Since melatonin secretion is especially activated after 22:00 (Lewy et al., 1995), each experimental session was carried out from 23:00 to 01:00. The subjects were requested to refrain from using personal VDTs, including smartphones, laptops, and tablet PCs, for two hours before the experiment and to sleep immediately after the end of experiment to eliminate the influence of other displays. During the experiment, they were required to engage in the given tasks, including watching videos, reading books, and web browsing on the smartphone. The experiment was conducted in the subject's bedroom, and the measured illuminance was less than 1 lx. Viewing position was not strictly controlled, but they were advised to view the smartphone from about 30 cm away, a typical viewing distance of a smartphone display.

Saliva samples were collected at 23:00 (before the experiment), 01:00 (after the experiment), and 09:00 the next day. Body temperature and heart rate were also measured by infrared ear thermometer and sphygmomanometer, respectively. As there were four types of display stimuli, a total of four experimental sessions were arranged for each subject. The experiment lasted for two weeks, and the interval between sessions was at least three days to give the subjects' body a chance to recover a regular circadian rhythm. All eight subjects participated in four sessions, and the four types of display stimuli were provided in random order. Figure 6-2 summarizes the experimental procedure.

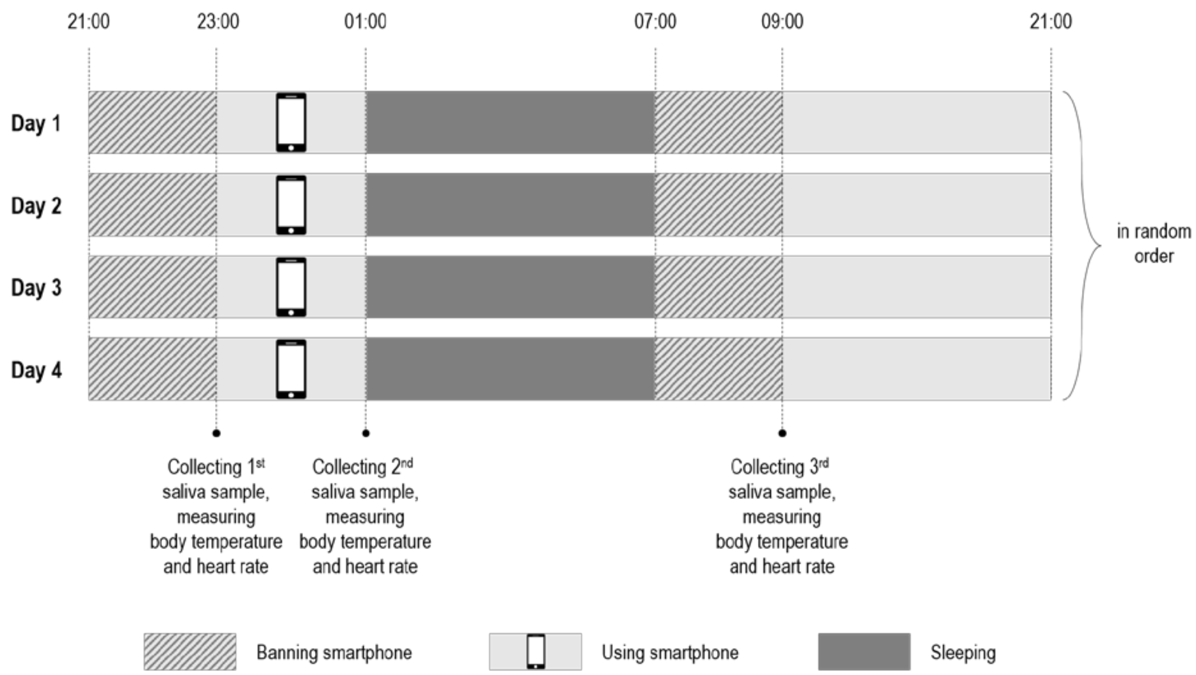


Figure 6-2. Experimental procedure for validating optimal display

6.2.3. Results and Analysis

Data obtained from three subjects were excluded from melatonin analysis because they showed higher salivary melatonin concentration at 09:00 the next day than at 01:00, which was considered to be an obscure pattern.

Figure 6-3 shows the mean difference in melatonin concentration between 01:00 and 23:00 across the four display stimuli. In general, the melatonin concentration increased at 01:00 in all stimuli. A Mann-Whitney U test was performed using an alpha level of 0.05 to examine the effect of display luminance on the difference in melatonin concentration, and the results indicated that the displays with high luminance suppressed nocturnal melatonin secretion. The difference in melatonin concentration was significantly lower in HW (mean ± SD = 4.84 ± 3.79 pg/mL) than in LW (12.57 ± 8.31 pg/mL), $U = 4$, $p < 0.05$. The difference in melatonin concentration in HY (10.55 ± 7.11 pg/mL) was also lower than in LY (12.38 ± 12.68 pg/mL), but no significant difference was found between the two stimuli, $U = 7$, $p = 0.44$.

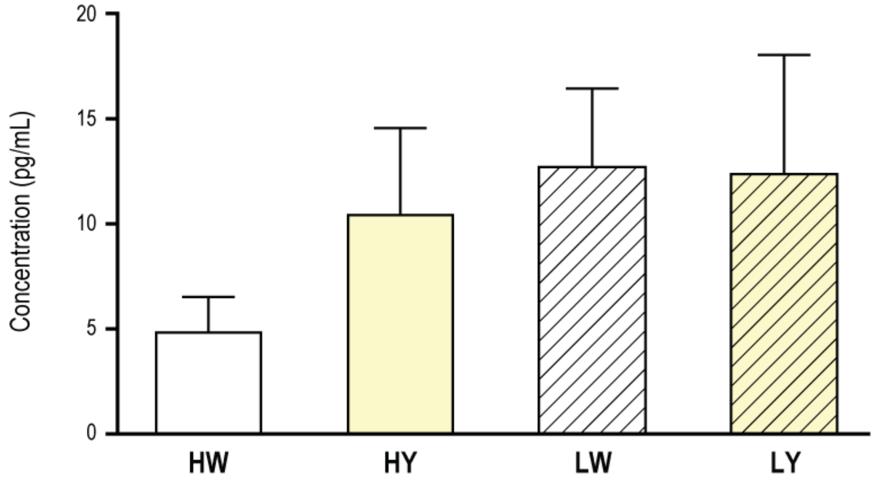


Figure 6-3. The mean difference in melatonin concentration between 01:00 and 23:00 for the four display stimuli (the error bars indicate standard deviation)

When comparing the difference in melatonin concentration according to display chromaticity, there was no significant difference between the mean values in HW and in HY (4.84 ± 3.79 pg/mL vs. 10.55 ± 7.11 pg/mL), $U = 2$, $p = 0.07$, although the difference in melatonin concentration was considerably lower in HW. Additionally, no significant difference was reported between LW and LY (12.57 ± 8.31 pg/mL vs. 12.38 ± 12.68

pg/mL), $U = 11$, $p = 0.42$. However, the insignificance of the statistical result might have been caused due to the small sample size. Particularly, only three samples were involved in the analysis for HY due to insufficiency of salivary samples. Hence, it is too early to conclude whether or not the display chromaticity affect nocturnal melatonin recreation.

Figure 6-4 provides an additional information for analyzing the results. It displays the difference in melatonin concentration between 09:00 the next day and 23:00. Higher melatonin concentration at 23:00 was reported in the displays with high luminance (HW and HY), whereas higher melatonin concentration at 09:00 the next day was observed in the displays with low luminance (LW and LY). Together with the result of Figure 6-3, the results imply that the overnight melatonin secretion of low-luminance subjects was greater compared to high-luminance subjects, suggesting an upward shift of the melatonin secretion. Besides, LY showed much more melatonin concentration compared with LW. To put the point another way, the difference in melatonin concentration between the two stimuli was hardly observed right after the use of the displays, but the difference became conspicuous in the morning after the night before. The result can be interpreted that the subjects have a more comfortable night after using LY, which corresponds to the optimal display luminance and chromaticity, in consideration of time delays in the secretion of salivary melatonin (Laakso et al., 1989). However it was not significant ($p = 0.21$), probably due to the wide individual variation (Burgess and Fogg, 2008).

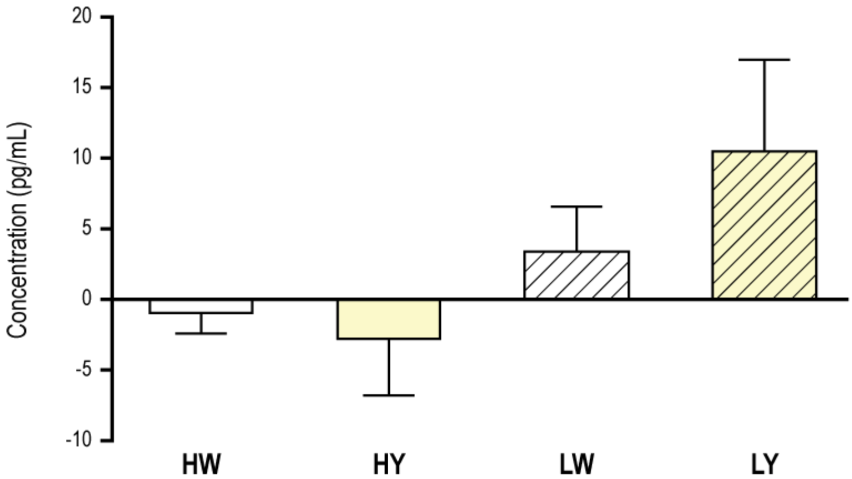


Figure 6-4. The mean difference in melatonin concentration between 09:00 the next day and 23:00 for the four display stimuli (the error bars indicate standard deviation)

Data collected from all eight subjects were used for analyzing body temperature. The mean body temperatures measured at 23:00, 01:00, and 09:00 the next day are shown in the left side of Figure 6-5, and an analysis of variance with repeated measurements confirmed the significant effects of time course, $F(2, 93) = 6.95$, $p < 0.05$, and display stimuli, $F(3, 92) = 2.92$, $p < 0.05$. The body temperature at 01:00 was low in comparison with 23:00 in every stimulus, and a larger decrease in body temperature was observed while using the displays with low luminance (LW: 0.7 degrees; LY: 0.8 degrees) than the displays with high luminance (HW: 0.1 degrees; HY: 0.2 degrees). The Wilcoxon signed-rank test confirmed the statistically significant decrease in body temperature both in LW, $Z = -2.51$, $p < 0.05$, and LY, $Z = -2.53$, $p < 0.05$, whereas no significant difference was observed in HW, $Z = -1.19$, $p = 0.12$, and HY, $Z = -0.74$, $p = 0.23$. The results indicated that the body temperature was not influenced by display chromaticity, although a slightly larger decrease in the body temperature was reported when using the displays tinged with yellow (HY and LY) than the pure white displays (HW and LW).

Regarding heart rate, there was a significant difference according to time course, $F(2, 93) = 2.24$, $p < 0.05$. In all conditions, the heart rate decreased after the experiment (01:00) and returned to normal after waking (09:00 the next day), as shown in the right side of Figure 6-5. There was no significant difference with regard to display stimuli, $F(3, 92) = 1.20$, $p = 0.32$.

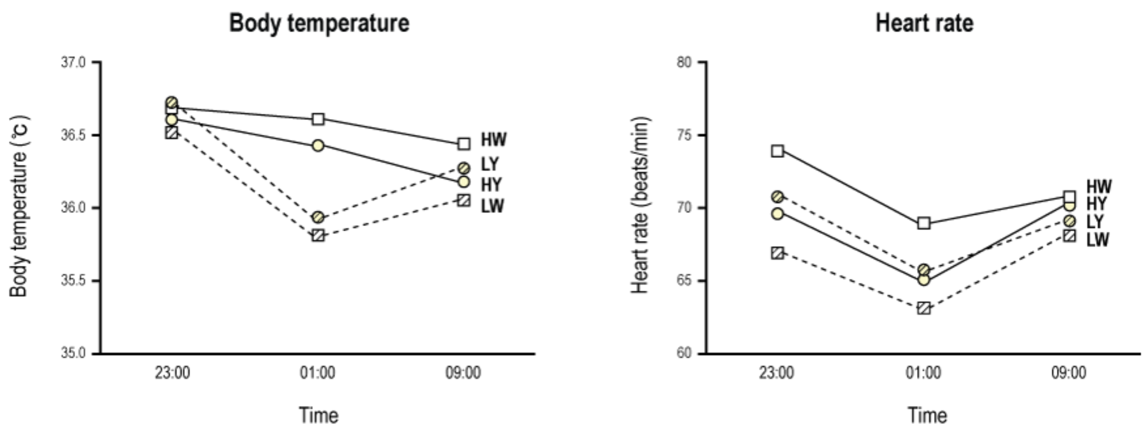


Figure 6-5. The mean body temperature at 23:00, 01:00, and 09:00 the next day for the four display stimuli (left) and the mean heart rate at 23:00, 01:00, and 09:00 the next day for the four display stimuli (right)

6.2.4. Findings

The study examined the effect of nighttime smartphone use on the users' circadian rhythm. Display luminance has a decisive influence on nocturnal melatonin secretion and body temperature. Using the displays with high luminance induces melatonin suppression, resulting in trouble falling asleep. On the contrary, when using the displays with low luminance, it was observed relatively higher melatonin concentrations and larger decreases in body temperature, which reflect the regular circadian rhythm at night (Colquhoun, 1971; Monk et al., 1997; Lack et al., 2008). The result was consistent with the previous studies in that the task performance with a bright display suppresses the nocturnal melatonin concentration and other physiological indicators of human circadian rhythm (Higuchi et al., 2003; Wood et al., 2013). In other words, the displays with low luminance interfere less with one's nighttime sleep and did not produce a harmful effect on circadian rhythm.

The effect of display chromaticity on the users' circadian rhythm was also found. Comparatively higher melatonin concentration was reported after using the display tinged with yellow, which filtered more blue light than the white display. This tendency was more likely in the high-luminance displays than in the low-luminance displays, and it was probably due to the difference in color sensitivity according to luminance levels. A decrease in display luminance causes a decrease in color sensitivity (Kelly, 1961; Melgosa et al., 1999), and therefore, the effect of chromaticity might less appears on low-luminance displays.

As a consequence, the experimental results confirmed the benefits of the display with low luminance and tinged with yellow. It indicates the superiority of the proposed optimal display among the four stimuli for comfortable use of smartphones under low illuminance.

6.3. Summary

This chapter verified the effect of the optimal display by conducting physiological evaluation in real-life situation.

Firstly, the importance and necessity of a physiological validation was investigated, and three evaluation methodologies, including measuring melatonin concentration, body temperature, and hear rate, were selected for the validation. Next, the validation experiment was carried out in the subjects' private room during a two week period.

The experimental result showed that both display luminance and chromaticity affect users' circadian rhythm. The displays with high luminance suppress nocturnal melatonin secretion and disrupt the decrease in body temperature while sleeping more so than do displays with low luminance, as well as higher melatonin suppression was observed after using the white display than the display tinged with yellow. These results confirmed the overall superiority of the optimal display compared to the current display.

7

Conclusion

7.1. Summary of Major Findings

7.2. Contributions

7.3. Suggestions for Future Research

7. Conclusion

This chapter concludes the dissertation by integrating findings and implications of the previous chapters into concise and reliable body of knowledge. A summary of the major findings is presented in section 7.1 according to research aims and objectives. Section 7.2 describes overall contributions and the core values of the dissertation. Lastly, section 7.3 discusses limitations and possible future directions of the research.

7.1. Summary of Major Findings

In short, this dissertation presents the optimal display luminance and chromaticity for viewing mobile displays under low illuminance by balancing physiological comfort and psychological satisfaction. While many other findings are included in the body of the dissertation, those presented below represent what are believed to be the most important and valuable achievements.

- ***Current smartphone displays do not offer optimal luminance and chromaticity in conditions of low illuminance, and inappropriate display settings exert a harmful effect on users.***

Despite an increase in the use of smartphones at night under low illuminance, existing smartphones do not provide appropriate display luminance and chromaticity to nighttime smartphone users. Bright blue light emitted from displays leads to visual discomfort as well as decrease in visual performance, and in severe cases, it disrupts the body’s circadian rhythm by involving physiological systems. Some applications, such as an auto-bright function or a blue light filter, were suggested to reduce the problems, but most users have still expressed dissatisfaction with the display setting of their smartphones. It implies a need to investigate a display that supports optimal luminance and chromaticity in conditions of low illuminance.

· ***Physiological comfort and psychological satisfaction should be kept in balance to achieve the optimal display luminance and chromaticity.***

Physiological comfort indicates how comfortable the body is, and psychological satisfaction refers to how pleasant the thing is. These are two of the most important factors to evaluate the perceived quality of displays, and the optimal display could be achieved if both factors are satisfied. A display only concentrated on improving physiological comfort might fail to meet the user's psychological satisfaction, and a display that supports psychological satisfaction but lacks physiological comfort cannot be a good solution either. To achieve the optimal display luminance and chromaticity, thus, a display must strike a balance between physiological comfort and psychological satisfaction.

· ***Optimal display luminance changes with the passage of time spent watching on the basis of visual adaptation.***

Optimal luminance changes depending on the adaptation process of human visual system. The luminance which was perceived to be bright at first becomes dark after a time due to light adaptation. In other words, the optimal display luminance for the first sight of a display (*initial viewing*) and that for continuous display watching (*continuous viewing*) are different from each other, and thus display luminance should be changed over time to keep the optimal value consistently. In this regard, an adaptive luminance model was developed to provide optimal display luminance for prolonged use of smartphones under low illuminance. In the model, display luminance begins with a luminance of 10 cd/m^2. After 10 seconds, the luminance increases for 20 seconds in accordance with the pace of visual adaptation, and becomes constant when it reaches 40 cd/m^2. That is to say, in the beginning, it offers a fairly low luminance to make users feel comfortable, and the luminance gradually increases as they visually adapt to the display in order to enhance user satisfaction. Furthermore, the change in display luminance from *initial viewing* to *continuous viewing* occurs very slowly to avoid disturbing users.

· ***Optimal display chromaticity reduces emissions of blue light from displays and does not distort the perceived quality of displays.***

Blue light emitted from displays has adverse influences on users' physiological system. Hence the optimal display chromaticity has to reduce blue light as much as possible within the range of acceptable threshold. The display tinged with yellow satisfies these requirements. It emits less blue light since the intensity of blue is lower than that of red and green in yellow shade, and it has a relatively large acceptability; users feel less resistance when they use a smartphone display of white tinged with yellow in comparison with other colored displays. However, there is little difference in optimal display chromaticity regarding the color composition of the displayed content. A slight reduction in blue light (RGB values of 255, 255, and 230) is recommended when a white color covers a majority of the display, such as on internet webpages, whereas a large reduction (RGB values of 255 ,255, and 165) is permitted on a full-color display that has no standard white point, for instance, movies or other video clips. The results suggest a change in display chromaticity according to the displayed content or individual preference, within the specific chromaticity range that supports users' physiological comfort.

- ***The optimal display is superior to the current display for using smartphones under low illuminance in respect of physiological comfort and psychological satisfaction.***

The optimal display suggested in the dissertation has low luminance and is tinged with yellow. It enables users to feel visually comfortable and to keep high satisfaction level while using smartphones in conditions of low illuminance. Moreover, the display interferes less with the secretion of the hormone that promotes sleep in humans, and thus it does not have a harmful influence on users' circadian rhythm in spite of prolonged use of smartphones at night. As a consequence, the superiority of the optimal display to the current display is validated in terms of physiological comfort and psychological satisfaction.

- ***The optimal display requires lower power consumption than the current display.***

From the viewpoint of energy efficiency, the optimal display consumes less electric power than the current display because it has a lower level of display luminance and emits less blue light, which is known to be the most power-consuming among red, green, and blue colored LEDs. According to power measurements of the smartphone used in the study, the power consumption for web browsing on the current display was measured at 0.20 watts (total power consumption: 0.79 watts), whereas the optimal display required 0.15 watts (total power consumption: 0.74 watts), as presented in Figure 7-1. In other words, the optimal display is able to reduce display power consumption by 25 %. Although previous studies have achieved significant power savings by changing the brightness or color of displays, the researchers rarely paused in their studies to consider user acceptance. In this respect, this study is remarkable for maintaining user satisfaction and reducing power consumption at the same time.

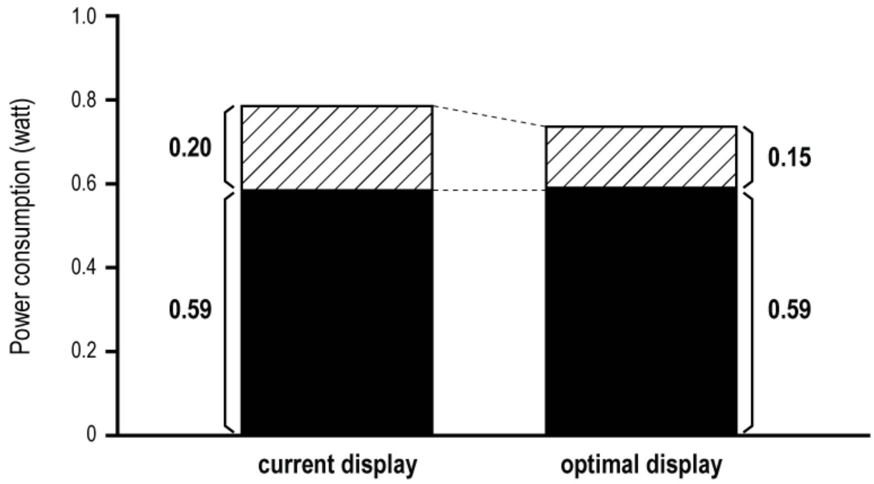


Figure 7-1. The power consumption for web browsing on the current smartphone display and on the optimal display (the slashed areas indicate display power consumption, and the black-colored areas indicate system power consumption). The optimal display saves display power consumption by 25 %.

7.2. Contributions

The findings of this dissertation are expected to provide useful knowledge, not only in the academic fields of design and engineering but also in the display industry. The contributions of the study are based on the findings and the process of the findings, and achieved a new discovery through designerly way of thinking, by integrating knowledge and insights from different disciplines.

The dissertation has made a primary contribution to define the notion of the optimal display, and to identify the significant factors in achieving the optimal display as well as the relationship between the factors. A number of studies to improve display quality were focused on either technical or perceptual aspects, but there has been no attempt to address the topic in an integrated approach. This dissertation collected and analyzed the evaluation criteria of displays based on the existing studies and discovered that two factors, physiological comfort and psychological satisfaction, play a significant role in the perceived quality of displays, and that the optimal display could be achieved only if both factors are well-balanced. On the basis of the discovery, a notion of the optimal display was defined as "*the display luminance and chromaticity that support both physiological comfort and psychological satisfaction.*"

The discovery also establishes a basic knowledge framework that shows the relationship between physiological comfort and psychological satisfaction according to the intensity of display luminance and chromaticity. A potential for the framework was discussed in Chapter 3, and it was confirmed through the experiments in Chapter 4 and 5. Figure 7-2 conceptually presents the framework by representing intensity of luminance and chromaticity in the horizontal axis, and an achievement rate in the vertical axis. In the case of display luminance, the achievement of physiological comfort was highest at the luminance of 10 cd/m^2 and decreased as a luminance increased, whereas the achievement of psychological satisfaction was highest at the luminance of 40 cd/m^2. In other words, the best luminance for comfort is not the best for satisfaction, and vice versa. However, the luminance ranged between 10 cd/m^2 to 40 cd/m^2 yielded a considerably high achievement rate in both of two factors, hence it can be interpreted as the range of optimal display luminance. A similar tendency was observed in display chromaticity. Physiological comfort was highest when the red and green channels were set at maximum but the blue channel was set at minimum (i.e., R: G: B=1: 1: 0), and it gets reduced as the intensity of blue channel increased. On the other hand, in terms of psychological satisfaction, the highest achievement was recorded when the all RGB channels were set at maximum (i.e., R: G: B=1: 1: 1). Furthermore, an RGB ratio between 1: 1: 0.7 and 1: 1: 0.9 was determined to be the optimal display chromaticity because it is above the users' acceptable threshold. Simply put, the range that has fairly high achievement both in comfort and satisfaction is better than the best point of respective aspects. Hence, to provide uses with the optimal solution, it is important to find the specific range that attains high levels of physiological comfort and psychological satisfaction at the same time, and this could be defined by considering users' acceptable threshold. In this respect, the suggested framework serves as a useful guide to the researchers who are in the process of designing user evaluation methods for their study.

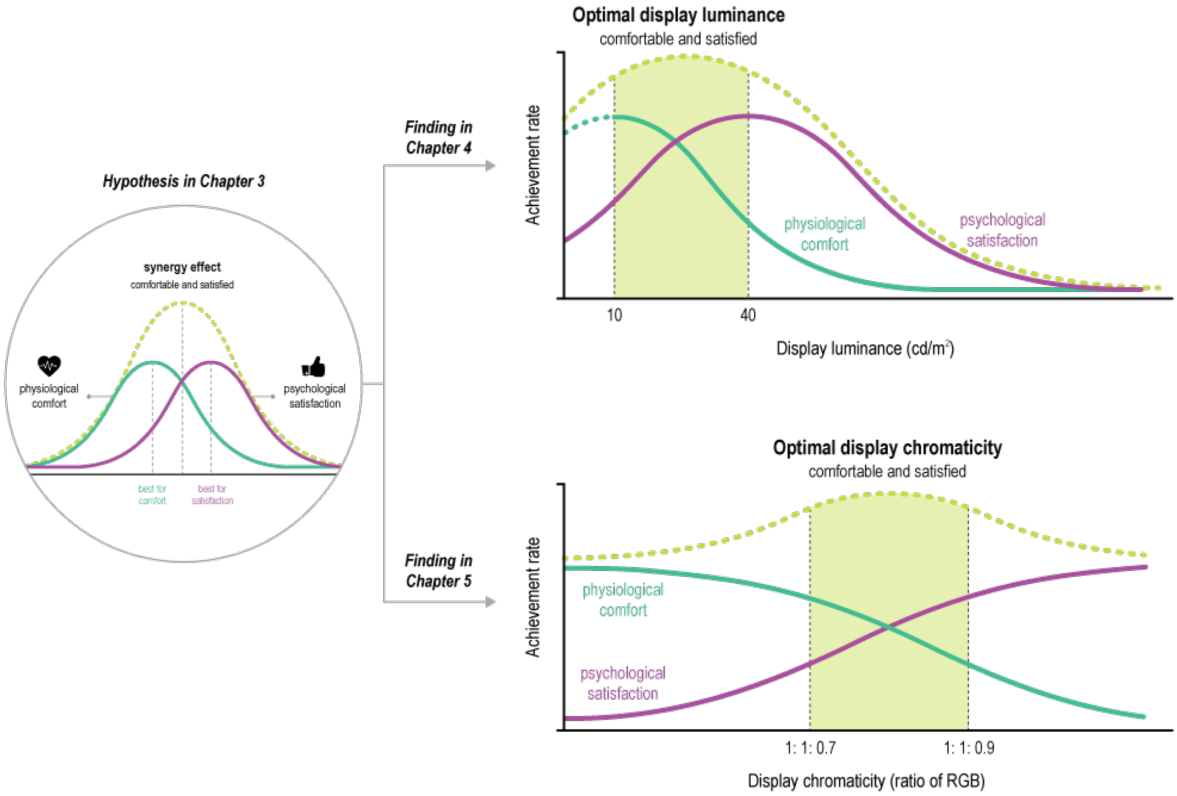


Figure 7-2. Relationship between physiological comfort and psychological satisfaction according to an intensity of display luminance and chromaticity

In addition, this study opens up a possibility that an evaluation result of an object might be changed depending on situations. Users adapt to the given stimulus or the environments as time goes on, and this may change the importance of physiological and psychological aspects of the object, resulting in a difference in evaluation results. Thus, researchers should take into account the possibility of assessing preference or usability on the object intended for prolonged use.

7.3. Suggestions for Future Research

The study has achieved its aim of investigating the optimal display luminance and chromaticity for viewing mobile displays under low illuminance. It is expected that the findings of this study contribute to a pleasing and comfortable use of mobile displays by applying to diverse types of VDTs. Besides, we hope that the optimal display plays a decisive role in the electronics industry for increasing the design competitiveness of the products.

The findings from this study provide some opportunities for future research. Above all, supplementary research should be carried out for different age groups. According to the previous studies, user’s age is one of the critical factor in VDT research because of the phenomenon of presbyopia for people over 40 years of age (Yeow and Taylor, 1990; Charness and Dijkstra, 1999). Therefore, it can be possible to suggest different versions of optimal display model fitting each age group by comparing the optimal display settings between the young and the old.

It might also be meaningful to examine the relationship between optimal display settings and ambient illuminance, because the major visual functions, including visual adaptation and color discrimination, are sensitive to ambient illuminance (Menozzi et al., 2001), as well as the earlier studies discovered that ambient illuminance has an influence on visual perception and preference of displays (Devlin et al., 2006; Rempel et al., 2009; Choi et al., 2010).

Last but not least, an exploration of the effect of display size on the optimal display setting will make the study more worthy. This study conducted the experiments focusing on the small-sized display using smartphones, but the larger-sized displays such as tablet PCs and televisions are also frequently used in the conditions of low illuminance. Hence, it should be revealed whether or not the results of this study are relevant to display size.

Such additional research will not only improve the overall value of the study but will also offer practical assistance for implementing the results on smartphones.

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Summary in Korean

저조도 환경에 적합한 디스플레이 휘도 및 색도

디스플레이 기술이 발전하고 다양한 종류의 VDT (Visual Display Terminal)가 일상 생활에 널리 보급됨에 따라 사용자들이 디스플레이를 사용하는 시간이 점차적으로 증가하고 있다. 최근 연구에 따르면 약 80 %의 사람들이 잠들기 전 불이 꺼진 어두운 방 안에서 스마트폰을 사용한다고 한다. 이러한 상황에서는 주변 밝기에 비해 스마트폰 디스플레이에서 나오는 빛의 휘도가 상대적으로 매우 높으며, 따라서 사용자는 눈부심으로 인한 시각적 피로감을 느끼게 된다. 또한 디스플레이에서 방출되는 청색광 (blue light)은 숙면을 돕는 호르몬의 분비를 저해하여 생체 리듬을 불규칙하게 만들며 심각한 경우 수면 장애를 유발하기도 한다.

이에 본 연구에서는 어두운 환경에서 사용하기 적합한 모바일 디스플레이의 휘도 및 색도를 탐색하고, 이 과정에서 사용자의 생리적인 편안함과 심리적인 만족도 간의 균형을 이루고자 하였다. 연구의 목적을 달성하기 위해 3 가지의 단계적 과정이 수행되었으며, 각 단계에 대한 상세한 내용은 다음과 같다.

첫째로, 다양한 밝기를 가진 디스플레이에 대한 사용자들의 생리 및 심리 반응을 평가하여 어두운 환경에서 시청하기 적합한 디스플레이 휘도를 찾아내었다. 그 결과 처음 디스플레이를 볼 때 적합한 휘도와 장시간 디스플레이를 사용할 때 적합한 휘도가 각기 다름을 밝혔으며, 이 둘을 모두 충족시키기 위해서는 휘도가 점차적으로 변화해야 함을 확인하였다. 또한 이를 바탕으로 시간에 따라 주변 밝기에 적응하는 인간의 시각 체계를 고려한 ‘순응형 휘도 모델 (adaptive luminance model)’을 제안하였다. 해당 모델은 사용자가 시각적 편안함을 유지할 수 있도록 10 cd/m^{2}의 낮은 디스플레이 휘도를 제시하며 이를 10 초 동안 유지한다. 그 후 시각 순응 과정에 맞추어 20 초 간 점차적으로 휘도가 증가하고, 40 cd/m^{2}에 도달하게 되면 변화를 중지하고 그 밝기를 유지한다.

다음으로, 디스플레이 색도에 대한 사용자들의 심리적 허용 범위를 탐색하고 이를 바탕으로 최적 디스플레이 색도를 밝혀내었다. 실험 결과 노란 빛을 띠는 흰색 디스플레이에서의 허용 범위가 가장 크며, 또한 청색광을 가장 많이 줄일 수 있는 것으로 확인되었다. 그러나 이는 디스플레이 상에 제시된 콘텐츠의 색채 구성에 따라 약간의 차이가 존재했다. 흰색이 주를 이루는 디스플레이의 경우 작은 폭의 색도 변화가 권장되는 반면, 백색점이 존재하지 않는 풀컬러 디스플레이에서는 상대적으로 큰 폭의 색도 변화가 허용된다.

마지막으로, 검증 평가를 통해 앞서 찾아낸 디스플레이 휘도 및 색도의 실제적 효과를 확인하였다. 다양한 휘도와 색도의 디스플레이를 사용한 후 사용자의 멜라토닌 분비량, 체온, 심박수를 측정한 결과 노란빛을 띤 저휘도 디스플레이가 사용자의 생체 리듬에 가장 적은 영향을 미친다는 것이 밝혀졌으며, 이는 본 연구 결과 제안된 최적 디스플레이 (optimal display)의 우수성을 입증한다.

본 연구는 다학제적인 접근을 통해 어두운 환경에서 사용하기 적합한 스마트폰의 디스플레이 휘도 및 색도를 제안하였다. 스마트폰 사용이 사용자의 건강에 미치는 영향이 큰 화두가 되고 있는 지금, 본 연구는 보다 편안하고 만족스러운 디스플레이 사용에 큰 기여를 할 수 있을 것이라 생각되며, 또한 연구 결과를 실제 VDT 에 적용함으로써 제품의 디자인 경쟁력을 향상시키는 역할을 하게 되기를 기대한다.

핵심어: 최적 디스플레이, 디스플레이 휘도 및 색도, 저조도 환경, 시각 순응

Appendix

Appendix 1. Target luminance, ambient luminance and viewing appropriacy of the instances

No.	Instance	Luminance (cd/m^2)		Viewing appropriacy	
		Target	Ambient	*Initial viewing*	*Continuous viewing*
1	Using a smartphone at night (1)	40	1	inappropriate	appropriate
2	Using a smartphone at night (2)	140	1	inappropriate	inappropriate
3	A signboard on a dim street	801	8	inappropriate	inappropriate
4	A navigation system in a car	85	10	appropriate	appropriate
5	LEDs on electronics in a dim room	12	25	appropriate	inappropriate
6	Working on a laptop in an office (1)	204	117	appropriate	appropriate
7	Working on a laptop in an office (2)	186	93	appropriate	appropriate
8	Using a smartphone under sunlight	143	6240	inappropriate	inappropriate
9	Using a smartphone in a bright room	141	313	appropriate	appropriate
10	Watching TV in a dark room	503	13	appropriate	inappropriate
11	LEDs on electronics in dark room (1)	6	2	inappropriate	inappropriate
12	LEDs on electronics in dark room (2)	2	1	inappropriate	inappropriate
13	Sunlight entering through window (1)	3980	125	appropriate	inappropriate
14	Sunlight entering through window (2)	3750	14	inappropriate	inappropriate

No.	Instance	Luminance (cd/m^2)		Viewing appropriacy	
		Target	Ambient	*Initial viewing*	*Continuous viewing*
15	Lit desk lamp at night	279	6	appropriate	inappropriate
16	Light from refrigerator in the daytime	78	137	appropriate	appropriate
17	Light from refrigerator at night	78	2	inappropriate	inappropriate
18	Watching movie in a theater	117	5	inappropriate	appropriate
19	Beam of an automobile headlight (1)	75	4	inappropriate	inappropriate
20	Beam of an automobile headlight (2)	130	4	inappropriate	inappropriate
21	Watching TV in a bright room	497	218	appropriate	appropriate
22	Neon sign at night (1)	557	3	inappropriate	inappropriate
23	Neon sign at night (2)	1803	6	inappropriate	inappropriate
24	Streetlamp on a dark road (1)	22	2	appropriate	inappropriate
25	Streetlamp on a dark road (2)	4	1	appropriate	inappropriate
26	Lit signboard at night	199	18	inappropriate	inappropriate
27	Traffic light at sunset	443	1650	appropriate	appropriate
28	Photoflood lamp	2500	1780	appropriate	inappropriate
29	Light from emergency exit at night	117	2	inappropriate	inappropriate
30	Dashboard of a car at night	5	3	appropriate	inappropriate
31	Dashboard of a car in the daytime	5	56	inappropriate	inappropriate
32	Taillight for an automobile	46	17	appropriate	appropriate

No.	Instance	Luminance (cd/m^2)		Viewing appropriacy	
		Target	Ambient	*Initial viewing*	*Continuous viewing*
33	Light in a tunnel	247	240	appropriate	appropriate
34	Lit electronic clock in a dark room	12	2	inappropriate	inappropriate
35	Lit desk lamp in a dim room	430	56	appropriate	appropriate
36	Watching TV in a dim room	489	112	appropriate	appropriate
37	Beam projector in a class room	51	7	appropriate	appropriate
38	Using tablet PC in a bus	165	58	appropriate	appropriate
39	Using laptop in a café	205	102	appropriate	appropriate
40	Using tablet PC in a room	398	363	appropriate	appropriate
41	Light from dishwasher at night	214	3	inappropriate	inappropriate
42	Sleep lamp at night	23	4	appropriate	inappropriate
43	LEDs on electronics in a dim room	12	25	appropriate	inappropriate
44	Using smartphone in an office	35	210	appropriate	inappropriate
45	Beam projector in a bright room	51	1320	inappropriate	inappropriate
46	Taillight of a car ahead	46	40	appropriate	appropriate
47	Using smartphone on a cloudy day	148	1570	appropriate	appropriate
48	Electronic signage at underpass	1000	43	inappropriate	inappropriate
49	Digital photo frame in a room	238	163	appropriate	appropriate
50	Digital signage on the road (1)	789	658	appropriate	appropriate

No.	Instance	Luminance (cd/m^2)		Viewing appropriacy	
		Target	Ambient	*Initial viewing*	*Continuous viewing*
51	Digital signage on the road (2)	1800	7850	appropriate	inappropriate
52	Bridge decorated with lights	26	1	appropriate	appropriate
53	Emergency light at underpass	237	23	appropriate	appropriate
54	Digital signage in residential areas	400	5	inappropriate	inappropriate
55	Digital signage in downtown	1000	25	inappropriate	inappropriate
56	Light from handrail at night	5	1	appropriate	inappropriate
57	Electronic signage in the daytime	557	342	appropriate	appropriate
58	Glowing lights on a Christmas tree	118	20	appropriate	appropriate
59	Viewing display in a dim room (1)	78	38	appropriate	appropriate
60	Viewing display in a dim room (2)	81	12	appropriate	appropriate

Appendix 2. The scores in perceptibility and acceptability on a text-based content with the display luminance of 10 cd/m^2 (N=50)

Level of RGB	Red		Green		Blue		Cyan		Magenta		Yellow		Neutral	
	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.
250	31	45	29	45	38	49	23	44	25	48	31	47	38	49
245	12	37	7	38	28	44	18	40	20	39	26	45	36	47
240	9	31	5	28	14	36	11	36	16	36	18	39	35	47
235	7	26	5	30	16	30	4	30	10	28	9	41	30	46
230	2	21	1	18	6	17	4	19	6	22	9	36	28	46
225	0	16	1	9	0	10	4	16	3	16	8	31	27	45
220	0	8	0	5	1	6	0	9	1	11	2	27	22	44
215					1	4					1	20		
210					0	3					0	13		
205					0	5					0	10		
200					0	1					0	10		

Appendix 3. The scores in perceptibility and acceptability on a text-based content with the display luminance of 40 cd/m^2 (N=50)

Level of RGB	Red		Green		Blue		Cyan		Magenta		Yellow		Neutral	
	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.
250	33	48	25	44	43	49	25	46	27	47	34	45	39	49
245	10	41	9	41	31	48	22	42	22	40	30	46	37	50
240	7	33	6	31	17	39	12	40	19	38	19	43	37	49
235	5	28	2	32	10	29	2	31	8	30	11	38	32	48
230	1	20	2	19	5	18	2	19	4	20	11	41	31	48
225	0	18	0	10	2	12	4	17	1	13	6	34	28	45
220	0	9	0	7	0	7	0	9	1	8	1	24	19	47
215					0	5					0	22		
210					0	4					0	14		
205					0	4					0	12		
200					0	2					0	10		

Appendix 4. The scores in perceptibility and acceptability on a text and image-based content with a photograph of green salad (N=50)

Level of RGB	Red		Green		Blue		Cyan		Magenta		Yellow		Neutral	
	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.
250	26	46	25	45	36	49	26	46	28	48	29	48	40	46
245	15	45	19	41	34	47	23	41	25	47	25	45	37	48
240	13	33	5	36	17	37	18	42	18	47	17	45	36	49
235	5	28	4	32	8	31	3	23	8	33	6	39	29	47
230	0	17	2	21	2	19	2	20	6	24	3	37	29	46
225	0	14	0	14	2	14	0	12	0	14	1	31	30	47
220	0	8	0	8	0	6	2	13	0	3	0	29	21	47
215					1	4					0	24		
210					0	4					1	16		
205					0	6					0	15		
200					0	4					0	12		

Appendix 5. The scores in perceptibility and acceptability on a text and image-based content with a photograph of people (N=50)

Level of RGB	Red		Green		Blue		Cyan		Magenta		Yellow		Neutral	
	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.
250	33	48	26	48	40	50	30	49	29	48	28	50	41	49
245	21	46	20	46	37	48	28	46	25	46	22	44	40	49
240	9	25	7	33	29	41	20	43	19	43	15	41	36	49
235	9	20	4	29	10	33	8	26	7	32	12	39	30	47
230	2	19	1	21	4	22	3	20	5	20	2	36	31	47
225	0	7	1	16	2	19	3	13	1	11	5	30	27	48
220	0	7	1	7	0	8	3	12	1	9	5	31	17	43
215					3	7					0	26		
210					0	5					2	17		
205					1	3					0	13		
200					0	4					0	10		

Appendix 6. **The scores in perceptibility and acceptability on a video-based content (N=30)**

Level of RGB	Red		Green		Blue		Cyan		Magenta		Yellow		Neutral	
	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.	Percept.	Accept.
225	21	30	19	30	28	30	22	30	25	30	27	30	29	30
195	5	26	7	26	2	25	4	22	12	28	24	30	24	30
165	1	8	0	2	0	17	0	14	0	5	8	28	24	30
135	0	0	0	1	0	9	0	6	0	0	2	18	23	29
105	0	0	0	0	0	2	0	1	0	0	0	7	20	22