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Adaptive luminance difference between text and background for comfortable reading on a smartphone

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ABSTRACT

This study proposes a model of adaptive luminance difference between text and background for comfortable reading on a smartphone display. The study is composed of two experiments. In Experiment I, the optimal luminance difference is identified in accordance with reading speed and preference. On the basis of the experimental results, the gradual decrease of luminance difference between text and background is developed. The change occurs while reading the text, and the model is applied to various illuminance levels. In Experiment II, the effect of adaptive luminance difference is validated in terms of reading speed, preference, and brainwave analysis using an electroencephalogram. Empirical evidence confirms that the developed model improves physiological comfort and psychological satisfaction, thereby it has a potential to be applied to the visual display industry.

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1. Introduction

With an increase in various types of visual display terminals (VDTs), many daily activities are now done digitally, such as reading books. Electronic books, or e-book have been quickly becoming more popular than paper books, and subsequently a number of studies have been carried out to examine comfortable reading on displays. In particular, the relationship between display luminance and reading performance has been focused on in previous studies (Krupinski et al., 1999; Seetzen et al., 2006; Yoshida et al., 2006; Rempel et al., 2009). For example, Buchner and his colleagues (2009) determined that displays with higher luminance provide better reading performance. Similarly, Benedetto's research team (2014) argued that both visual performance and visual fatigue increase as the level of display luminance rises. However, inadequately high or low luminance leads to a decline in visual performance and visual fatigue (Hultgren and Knave, 1974; Swinkels et al., 2008; Chen et al., 2012). Moreover, some revealed that people prefer lower display luminance in the condition of low illuminance, whereas they prefer higher display luminance in bright conditions (Merrifield and Silverstein, 1988; Mantiuk et al., 2009). Meanwhile, a great effort has been made to examine the effect of luminance difference between text and background on a display. It is generally believed that higher luminance difference between text and background enhances legibility and reading speed (Legge and Rubin, 1986; Legge et al., 1990; Knoblauch et al., 1991; Ling and Van Schaik, 2002). On the contrary, some other studies claimed that excessively high luminance difference decreases visibility and visual comfort (Dixon and Di Lollo, 1991; Yang et al., 2014). Although the aforementioned studies attempted to find the optimal luminance for reading on a display, these suggestions lack careful consideration of the human visual system. Since human vision provides time-dependent adaptation to ambient environment (Adelson, 1982; Pattanaik et al., 2000; Ledda et al., 2004), it is relevant to change display luminance with the passage of time (Benya and Schwartz, 2001; Na et al., 2014), especially for long hours of reading on a display.

In this regard, this study intends to investigate optimal luminance difference between text and background for comfortable reading on smartphone displays in respect to reading time and ambient illuminance. Ultimately, the study aims at developing a model for adaptive luminance difference that gradually changes luminance difference with the lapse of time to improve users' physiological comfort and psychological satisfaction. In addition, the effect of the developed model is validated with multidimensional assessments.

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2. Experiment I: development of adaptive luminance difference

2.1. Objective

The goal of Experiment I was to identify the optimal luminance difference between text and background under two different levels of illuminance in terms of physiological comfort and psychological satisfaction. It also attempts to develop a model of adaptive luminance difference for comfortable reading on a smartphone display.

2.2. Method

2.2.1. Display stimuli

Three types of luminance difference were created as display stimuli for the experiment: The first set was *text change*—the text starts from black and it becomes brighter as luminance difference decreases, while the background is fixed as white; the second set was *background change*—the text remains black and the background shifts from white and it gets darker; and last set was *text-background change*—the text begins as black and it grows brighter whereas the background starts from white and becomes darker at the same rate. Thereafter, it was defined the maximum luminance difference between text and background as 100% and the minimum luminance difference as 0%, and each set was divided into 10 levels, as shown in Table 1.

Prior to the main experiment, 10 people were instructed to select the stimulus with the smallest but still acceptable luminance difference for each of the three sets. The results indicated that the minimum acceptable luminance difference for each set was found to be 40% (stimulus 3), 70% (stimulus 5), and 40% (stimulus 7), respectively (see Table 2). In addition to the three stimuli, 100% (stimulus 1) as well as an intermediate luminance difference between the 100% and the minimum acceptable luminance difference for each set—stimuli 2, 4, and 6 were inserted, hence a total of seven stimuli were finally determined for the experiment.

2.2.2. Experimental setup

The experiment was carried out under the two different levels of illuminance—in the bright condition (600 lx) and in the dim condition (50 lx), and the correlated color temperature of the two conditions was equal (approximately 6300 K). The two illuminance levels were selected since the illuminance of indoor working place and that of dark room are about 600 lx and 50 lx, respectively (Lehto and Landry, 2012).

The stimuli were displayed on a 4.8-inch diagonal screen smartphone, and the auto brightness function was operated. Subjects were instructed to view a smartphone from a distance of about 30 cm throughout the experiment, a typical viewing distance of a smartphone display (Spencer et al., 2013). They were involved in one of the two illuminance levels. Fifty people composed of 26 males and 24 females (Mean age = 23.18; SD = 1.99) participated in the experiment in the bright condition, whereas 30 people including 16 males and 14 females (Mean age = 22.00; SD = 2.82) took part in the experiment in the dim condition. All of the subjects were paid volunteers, and they had normal or corrected-to-normal vision.

2.2.3. Procedure

The subjects were asked to read a 10-page (approximately 800 words) article on a smartphone display with the seven display stimuli, and a 1-min break was allowed before moving on to the next reading sessions. Each article contained different but similar content in order to prevent the influence of reading content. The display stimuli and reading content were shown in a random order, and both physiological comfort and psychological satisfaction were evaluated. The subjects' reading speeds were measured for investigating physiological response because people read faster under visually comfortable conditions (Roufs and Boschman, 1997; Smith and Wilkins, 2007). Besides, the preference was assessed for examining psychological comfort regarding the seven stimuli with a 5-point Likert scale wherein a 1-point indicates not preferred whereas a 5-point means highly preferred as well as felt comfortable with the given stimulus.

2.3. Results and analysis

The reading speeds for each page were compared, and the results indicated that speed became faster over reading time. It gradually increased until the subject reached the 6th page, or about 150 s after they began reading, and then maintained the speed from the 7th page. The mean reading speed of the 7th to 10th page (237.78 word/min) was statistically significantly higher than that of the 1st to 6th page (215.06 word/min), $t(49) = -4.87$, $p < 0.05$. This implies that the subjects generally focus their attention on reading approximately 150 s after they start reading, hence luminance difference should be changed after that time to circumvent an interruption of concentration on reading content.

In regard to the bright condition, an analysis of variance showed that the effect of luminance difference on reading speed was significant, $F(6, 343) = 4.35$, $p < 0.05$. The highest reading speed was observed in stimuli 5 and 4 and followed closely by stimuli 7 and 6, whereas reading speed of stimulus 1 was the lowest as shown in Table 2. Contrary to reading speed, preference was significantly higher in stimulus 1 than in other stimuli, $F(6, 343) = 5.12$, $p < 0.05$, and stimuli 6 and 2 followed. The stimuli with relatively lower luminance difference between text and background (stimuli 3, 5, and 7) received low preference scores, which implies that the preference decreased as the luminance difference declines. Consequently, it is discovered that stimulus 1, the maximum luminance difference between text and background, has higher preference but leads to poorer reading performance, whereas two

Table 1
Three types of luminance difference: *text change*, *background change* and *text-background change*.

Luminance difference (%)	100	90	80	70	60	50	40	30	20	10
text change		A	A	A	A	A	A	A	A	A
background change	A	A	A	A	A	A	A	A	A	A
text-background change		A	A	A	A	A	A	A	A	A

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Table 2
The mean reading speed and preference for the seven display stimuli in Experiment I.

Stimuli (1–7)	*Default*	*Text change*		*Background change*		*Text-background change*	
	1	2	3	4	5	6	7
Background luminance (%)	100 (white)	100	100	80	70	85	70
Text luminance (%)	0 (black)	30	60	0	0	15	30
Luminance difference (%)	100	70	40	80	70	70	40
Example of stimuli	A	A	A	A	A	A	A
Bright condition (600 lx)							
Reading speed[a] (SD)	221.65(45.50)	256.38(76.80)	249.58(76.03)	264.87(72.77)	266.70(71.04)	261.21(68.54)	263.33(53.76)
Preference[b] (SD)	4.06(0.89)	3.14 (0.96)	1.58 (0.64)	2.80 (1.20)	2.30 (1.00)	3.40(0.96)	2.40(0.77)
Dim condition (50 lx)							
Reading speed[a] (SD)	286.89(57.88)	301.30(68.29)	296.67(75.75)	295.60(66.66)	292.77(59.47)	316.39(71.98)	291.72(68.63)
Preference[b] (SD)	3.70(1.20)	3.70(0.63)	2.90(1.12)	2.80(0.76)	2.67(0.99)	3.27(1.20)	3.27(1.14)

[a] Unit: words/minute.
[b] Scale: 1–5.

stimuli in the set of background change (stimuli 4 and 5) are high in reading performance and low in preference. Besides, both reading performance and preference are better in stimulus 6, the luminance difference of 70% in the set of *text-background change*. In terms of the dim lighting condition, stimulus 6 recorded the highest reading speed, and there was very little difference in the reading speed of other stimuli. The result of statistical analysis was non-significant, $F(6, 203) = 0.73$, $p > 0.05$. Also, stimuli 1 and 2 were the most preferred, followed by stimuli 6 and 7, $F(6, 203) = 5.38$, $p < 0.05$.

In summary, consistent tendency was observed in the bright condition and the dim condition. Stimulus 1 was outstandingly preferred in both of the two conditions, and stimulus 6 was examined as the most appropriate luminance difference in consideration of reading performance and preference.

2.4. *Model of adaptive luminance difference*

On the basis of the experimental results, a model of adaptive luminance difference for comfortable reading on a smartphone display was developed as illustrated in Fig. 1, and it gradually changes luminance difference between text and background with the passage of reading time. The model begins at a maximum luminance difference which corresponds to stimulus 1, because it has the highest level of preference. According to previous studies, however, overly high luminance difference reduces visual comfort and visual performance (Wang and Chen, 2000; Yang et al., 2014).

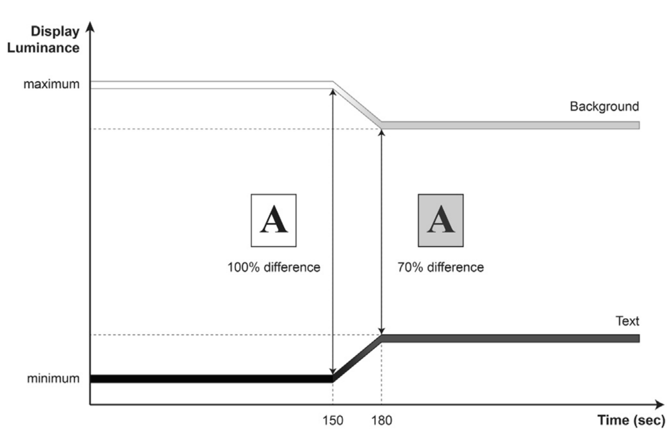

Fig. 1. Adaptive luminance difference: Luminance difference between text and background gradually decreases with the passage of reading time.

Thus the luminance difference starts to decrease 150 s after user begins to read, which is equivalent to the time taken to concentrate on reading content. It changes very slowly for 30 s, or at a rate of 1%/s, until the luminance difference reaches 70% of text-background change (85% of background and 15% of text, corresponding to stimulus 6) and keeps the difference continuously, since it is well balanced between physiological comfort and psychological satisfaction.

Next, the developed model was presented to the subjects who participated in Experiment I, and more than 90% of them did not notice the change of luminance difference in the model. Therefore, it provides users with higher preference and better reading performance by supporting human visual comfort.

3. Experiment II: validation of adaptive luminance difference

3.1. *Objective*

Experiment II aims at validating the superiority of adaptive luminance difference compared to existing smartphone display. The effect of the developed model is confirmed by conducting a series of physiological and psychological assessments.

3.2. *Method*

Ten students including 5 males and 5 females participated in the experiment, and their mean age was 22.90 years with a standard deviation of 2.95 years. The subjects took part both in the bright condition and the dim condition, and the experiment was carried out under the same experimental setup with Experiment I.

Two display stimuli were prepared for validation experiment: one was *adaptive luminance difference* which is developed from the study, and the other was *black text on white background* (stimulus 1 in Experiment I), which corresponds with existing smartphone displays and represents maximum luminance difference, as shown in Table 3. The subjects were instructed to read an article for 5 min on a smartphone with the two stimuli under two levels of illuminance, and the display stimuli, reading content and illuminance levels were provided in a random order.

In the experiment, reading speed, preference, and brainwave rhythm were recorded using an electroencephalogram (EEG) to evaluate physiological comfort and psychological satisfaction. For measuring the brainwave signals, four electrodes, Fp1, Fp2, ground potential, and the reference potential, were placed on the subjects' head, as depicted in Fig. 2. Brainwaves were measured for 5 min and 10 s, and the first 10 s of the signal were eliminated after the

Table 3
The mean ratio of high beta rhythm, reading speed and preference for the two stimuli in Experiment II.

Stimuli	*Black text on white background*	*Adaptive luminance difference*
Example of stimuli	A	A → A
Bright condition (600 lx)		
Ratio of high beta rhythm[a] (SD)	7.03 (4.33)	5.20 (2.56)
Reading speed[b] (SD)	223.86 (78.94)	246.44 (103.39)
Preference[c] (SD)	3.90 (1.10)	3.80 (0.92)
Dim condition (50 lx)		
Ratio of high beta rhythm[a] (SD)	7.12 (5.60)	6.33 (5.20)
Reading speed[b] (SD)	200.20 (80.60)	231.66 (110.14)
Preference[c] (SD)	3.50 (0.85)	3.50 (0.71)

[a] Unit: %.
[b] Unit: words/minute.
[c] Scale: 1–5.

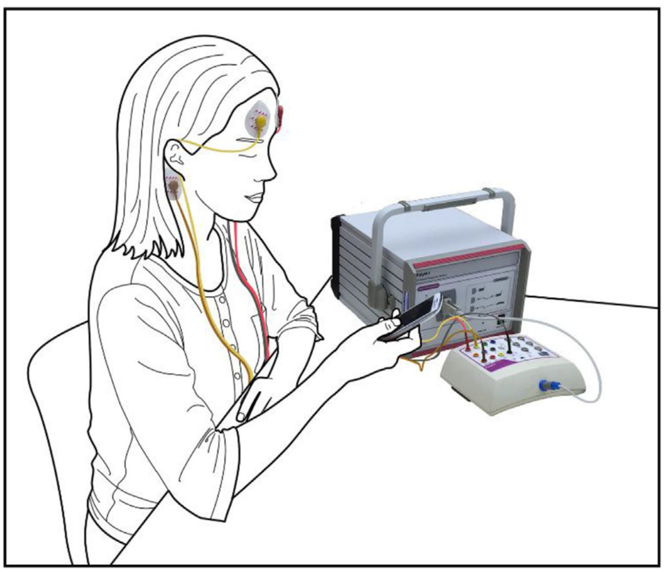

Fig. 2. Experimental setup for brainwave analysis.

measurement to attain higher accuracy of the results. The relative ratio of high beta rhythm to the entire range was then analyzed. High beta waves occur at a frequency of 21–30 cycles per second and they present stress and anxiety states (Yasui, 2009), so a low ratio of high beta rhythm signifies a relaxed state.

3.3. Results and analysis

Analyzing the experimental results, as shown in Table 3, compared the effect of the two stimuli. In the case of the bright condition, dependent t-test reported that the mean ratio of high beta rhythm in *adaptive luminance difference* was significantly lower than that in *black text on white background*, $t(9) = 2.19$, $p < 0.05$, one-tailed. It was even lower than typical emission of high beta rhythm while reading books (Lin and Hsu, 2012). A high ratio of high beta rhythm indicates stressful mental state; hence the result showed that the subjects stay relaxed when using smartphones with the developed model. Besides, the subjects read articles faster in *adaptive luminance difference* than in *black text on white background*, $t(9) = -2.19$, $p < 0.05$, one-tailed, which implies better reading performance in the adaptive model. However the result on preference was non-significant, $t(9) = 0.32$, $p > 0.05$, one-tailed, although a slightly higher preference was observed for *black text on white background* over *adaptive luminance difference*. Similar results were reported in the dim condition. Mean ratio of high beta rhythm was significantly lower in the developed model, $t(9) = 2.20$, $p < 0.05$, one-tailed, reading speed in the model was 15% higher than that in *black text on white background*, $t(9) = -2.10$, $p < 0.05$, one-tailed, and the preference scores of the two stimuli were equal to each other, $t(9) = 0.01$, $p > 0.05$, one-tailed.

In conclusion, the experiment validated that the adaptive model that gradually changes luminance difference between text and background is superior to existing smartphone displays in terms of physiological comfort and psychological satisfaction, regardless of ambient illuminance levels.

4. General discussion

This study carried out two experiments to develop a model of adaptive luminance difference which supports comfortable reading on a smartphone display and to verify the effect of the model in terms of physiological comfort and psychological satisfaction.

From Experiment I, it was revealed that the maximum luminance difference between text and background has the highest level of preference but it brings a decline in reading performance. On the other hand, luminance difference of 70% in the set of *text-background change* results in enhanced preference and better performance, which it is consistent with the researchers' previous study (Na and Suk, 2014). Also similar tendency was observed in experimental results regardless of ambient illuminance levels, thus a model of adaptive luminance difference was developed based on the empirical findings.

In Experiment II, the effect of the developed model and existing smartphone displays was compared, and the results showed that adaptive luminance difference allows users to read content in a comfortable state. It reduces visual stress and improves preference by keeping the balance between physiological comfort and psychological satisfaction.

From the viewpoint of practical application, this study could be evolved into a smartphone function that automatically runs when a user opens reading content on his or her smartphone. However, supplementary research is required for applying the function into a real life situation. Although the study found that there was little difference in the experimental results between bright condition and dim condition, additional experiments under various levels of illuminance such as very bright condition or dark condition should be conducted, because people use their smartphones with no bound to time and place (Chen et al., 2013) and ambient illuminance affects visual performance of displays (Merrifield and Silverstein, 1988; Rempel et al., 2009). It might also be

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worthwhile to find a solution for enhancing visual comfort and preference on a colorful display, not limited to black-and-white reading content. Such additional research will not only improve the overall value of the study but will also offer an opportunity for implementing the results on smartphones.

5. Conclusion

The study exploited the optimal luminance difference between text and background for comfortable reading on a smartphone display and established a model of adaptive luminance difference that is available in a large range of illuminance levels. In the model, luminance difference starts with the maximum and it gradually decreases with the passage of reading time. The benefits of the developed model in comparison with existing smartphone display were validated in terms of physiological comfort and psychological satisfaction. It is expected that this study will contribute to reading comfort on various types of display devices such as smartphones, tablet PCs, and e-books.

References

Adelson, E.H., 1982. Saturation and adaptation in the rod system. Vis. Res. 22, 1299–1312.

Benedetto, S., Carbone, A., Drai-Zerbib, V., Pedrotti, M., Baccino, T., 2014. Effects of luminance and illuminance on visual fatigue and arousal during digital reading. Comput. Hum. Behav. 41, 112–119.

Benya, J., Schwartz, P., 2001. Advanced Lighting Guidelines. New Buildings Institute.

Buchner, A., Mayr, S., Brandt, M., 2009. The advantage of positive text-background polarity is due to high display luminance. Ergonomics 52, 882–886.

Chen, J., Cranton, W., Fihn, M., 2012. Handbook of Visual Display Technology. Springer.

Chen, X., Chen, Y., Ma, Z., Fernandes, F.C., 2013. How is energy consumed in smartphone display applications?. In: Proceedings of the 14th Workshop on Mobile Computing Systems and Applications, 3.

Dixon, P., Di Lollo, V., 1991. Effects of display luminance, stimulus meaningfulness, and probe duration on visible and schematic persistence. Can. J. Psychol./Revue Can. de Psychol. 45, 54.

Hultgren, G.V., Knave, B., 1974. Discomfort glare and disturbances from light reflections in an office landscape with CRT display terminals. Appl. Ergon. 5, 2–8.

Knoblauch, K., Arditi, A., Szlyka, J., 1991. Effects of chromatic and luminance contrast on reading. JOSA A 8, 428–439.

Krupinski, E., Roehrig, H., Furukawa, T., 1999. Influence of Film and Monitor Display Luminance on Observer Performance and Visual Search. In: Academic Radiology, 6, pp. 411–418.

Ledda, P., Santos, L.P., Chalmers, A., 2004. A local model of eye adaptation for high dynamic range images. In: Proceedings of the 3rd International Conference on Computer Graphics, Virtual Reality, Visualisation and Interaction in Africa, pp. 151–160.

Legge, G.E., Parish, D.H., Luebker, A., Wurm, L.H., 1990. Psychophysics of reading. XI. Comparing color contrast and luminance contrast. JOSA A 7, 2002–2010.

Legge, G.E., Rubin, G.S., 1986. Psychophysics of reading. IV. Wavelength effects in normal and low vision. JOSA A 3, 40–51.

Lehto, M.R., Landry, S.J., 2012. Introduction to Human Factors and Ergonomics for Engineers. Crc Press.

Lin, H.W., Hsu, M.H., 2012. Exploring the Mystery of Literary Reading: a Psychophysiological Perspective.

Ling, J., Van Schaik, P., 2002. The effect of text and background colour on visual search of web pages. Displays 23, 223–230.

Mantiuk, R., Rempel, A.G., Heidrich, W., 2009. Display considerations for night and low-illumination viewing. In: Proceedings of the 6th Symposium on Applied Perception in Graphics and Visualization, pp. 53–58.

Merrifield, R., Silverstein, L.D., 1988. The ABC's of Automatic Brightness Control.

Na, N., Jang, J., Suk, H.J., 2014. Dynamics of Backlight Luminance for Using Smartphone in Dark Environment. IS&T/SPIE Electronic Imaging. 90140I-90140I-90146.

Na, N., Suk, H.-J., 2014. Adaptive luminance contrast for enhancing reading performance and visual comfort on smartphone displays. Opt. Eng. 53, 113102–113102.

Pattanaik, S.N., Tumblin, J., Yee, H., Greenberg, D.P., 2000. Time-dependent visual adaptation for fast realistic image display. In: Proceedings of the 27th Annual Conference on Computer Graphics and Interactive Techniques, pp. 47–54.

Rempel, A.G., Heidrich, W., Li, H., Mantiuk, R., 2009. Video viewing preferences for HDR displays under varying ambient illumination. In: Proceedings of the 6th Symposium on Applied Perception in Graphics and Visualization, pp. 45–52.

Roufs, J.A., Boschman, M.C., 1997. Text quality metrics for visual display units: I. Methodological aspects. Displays 18, 37–43.

Seetzen, H., Li, H., Ye, L., Heidrich, W., Whitehead, L., Ward, G., 2006. 25.3: Observations of luminance, contrast and amplitude resolution of displays. In: SID Symposium Digest of Technical Papers, 37, pp. 1229–1233.

Smith, L., Wilkins, A., 2007. How many colours are necessary to increase the reading speed of children with visual stress? A comparison of two systems. J. Res. Read. 30, 332–343.

Spencer, L., Iacoponi, J., Shah, S., Cairns, G., 2013. P. 134L: late news poster: resolution limits for smartphones—video playback. In: SID Symposium Digest of Technical Papers, 44, pp. 1099–1102.

Swinkels, S., Heynderickx, I., Yeates, D., Essers, M., 2008. 66.1: ambient light control for mobile displays. In: SID Symposium Digest of Technical Papers, 39, pp. 1006–1009.

Wang, A.-H., Chen, M.-T., 2000. Effects of polarity and luminance contrast on visual performance and VDT display quality. Int. J. Ind. Ergon. 25, 415–421.

Yang, S., Shuguang, K., Weixi, Z., Sheng, P., Mi, T., Kangjun, L., Xingtao, Z., 2014. Study of preferred background luminance in watching computer screen in children. Chin. Med. J. 127, 2073–2077.

Yasui, Y., 2009. A brainwave signal measurement and data processing technique for daily life applications. J. Physiol. Anthropol. 28, 145–150.

Yoshida, A., Mantiuk, R., Myszkowski, K., Seidel, H.P., 2006. Analysis of reproducing Real-world appearance on displays of varying dynamic range. Comput. Graph. Forum 25, 415–426.

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