

# Modeling for Display Brightness Perception Based on Retina Imaging

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## Abstract

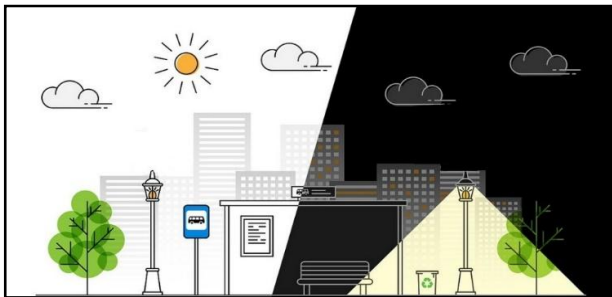
*Quantitative assessment of perceived display brightness has been challenging. Our preliminary work, through analyzing subjective brightness and the visual system, identified physical luminance and pupil size as critical indicators affecting perceived brightness. This paper establishes a general form of perceptual display brightness model based on retinal imaging. This model can assist in optimizing real-time brightness adjustment of display devices to meet people's requirements for comfortable display brightness.*

## Author Keywords

Perceived brightness; human visual system; physical luminance; pupil size; visual comfort.

## 1. Introduction

In the wake of rapid advancements in display technology, coupled with an increase in consumer capacity and shifts in lifestyle, dependence on various display devices continues to escalate. The eye's significance in the human visual system (HVS) is paramount; external light passes sequentially through structures such as the pupil, lens, and vitreous body, ultimately forming an image on the retina. Retinal cells play a critical role in human light perception. For instance, retinal cone cells primarily detect light intensity and color and are predominantly active in bright light conditions. Meanwhile, retinal rod cells, which can only detect light intensity and not color, are principally active in low-light conditions [1,2]. The range of brightness perceivable by the human eye is vast. This is mainly due to the regulatory functions of elements such as the pupil, photoreceptor cells, and neurons. The pupil adjusts its size based on the intensity of external light, ensuring that the light projected onto the retina is neither too weak nor too strong [3]. Therefore, resolving the key technical issue of mismatch between the physical luminance and the perceived brightness of displays is essential.



**Figure 1.** Perception of brightness from a picture of identical luminance varies in different environments.

Figure 1 shows the perceived difference in brightness in different environments. The brightness stimulus the human eye perceives changes with the environmental light conditions. Although the physical luminance of display devices can be measured with corresponding instruments, perceived brightness is a subjective experience that cannot be measured directly [3]. Research

combining the assessment of perceived brightness with human perception is scant, and existing measurement instruments and methods fail to reflect the human eye's perception of brightness accurately and objectively in spatial environments. Consequently, evaluating the actual display performance should go beyond necessary physical measurements and thoroughly consider the viewer's experience during observation.

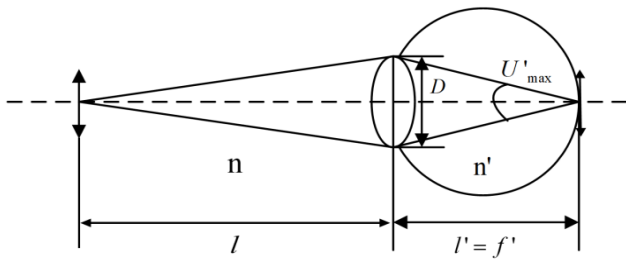
Dating back to the 19th century, Weber's Law posited that perceived brightness does not depend on absolute luminance but on relative luminance [4]. Fechner later applied this to sensory experience, discovering that the intensity of human sensations is directly proportional to the logarithm of the external stimulus intensity [5]. In the 20th century, Stevens' Law validated the relationship between brightness levels and background adaptation levels through a simple exponential function. Together with Seim et al., they combined cone responses and adaptive changes to describe brightness threshold and scaling data response equations [6]. Moving into the 21st century, Lim K et al. investigated the influence of peripheral visual luminance (PVL) and field of view (FOV) on the perceived display brightness by observers [7]. More recently, L. Yang et al. measured LCD and AR display systems under different environmental illuminances, employing the "Feu" to consider luminance distribution for obtaining subjective brightness [8]. Their research found that pupil diameter significantly affects perceived brightness [9]. By computing retinal illuminance, we provided a relationship equation between perceived brightness, pupil diameter, and display luminance. And we also offered an estimation equation for pupil diameter [11].

## 2. Theoretical research

As an extension of our previous work, in this paper, we design subjective evaluation experiments using smartphones and computer monitors, two of the most commonly used display devices. Through these experiments, participants' subjective evaluation values and real-time pupil sizes can be obtained under various lighting environments based on predefined perceived brightness levels. Based on a quantitative analysis of factors affecting perceived brightness level ratings and incorporating the physical imaging process of external objects on the retina, the experimental data will be modeled to establish an optimized model for perceived brightness.

Perceived brightness differs from physical luminance, reflecting the actual luminance perception of the human eye, influenced by the surrounding environmental and psychological factors and the inherent characteristics of the HVS itself [12,13]. Considering the imaging process of objects on the retina, we explore its correlation with perceived brightness. External objects image on the retina through the eye, stimulating the photoreceptor cells and evoking vision, with the intensity of the stimulus creating sensations of light and dark. When the viewing angle of the eye towards an object is large, the image area of the object on the retina is also larger. The strength of the light-emitting surface's stimulation of the photoreceptor cells depends on the luminous flux received per unit area of the retina, the illuminance [14]. As

shown in Fig. 2, the imaging process of a light-emitting surface on the retina can approximate a lens imaging system.



**Figure 2.** The imaging process of a light-emitting surface on the retina.

It can be seen from Fig. 2 that the size of the light stimulus on the retina determines the perception of light. Thus, perceived brightness is closely related to retinal imaging illuminance. According to the equation for imaging illuminance, the retinal imaging illuminance can be expressed as Equation (1):

$$E' = \tau\pi L \left(\frac{n'}{n}\right)^2 \sin^2 U'_{max} \quad (1)$$

In air, since the object distance is much greater than the image distance and the image-side focal length, the image distance is approximately equal to the image-side focal length. Also, based on trigonometric relationships, Equation (2) holds true:

$$\sin U'_{max} \approx \frac{D}{2f'} \quad (2)$$

Where  $L$  refers to the physical luminance measured by nits,  $D$  refers to the pupil diameter measured by mm,  $\tau$  is the transmittance of the eyeball,  $n$  is the refractive index in air,  $n'$  is the refractive index of the image space medium, and  $f'$  is the focal length of the eyeball. Therefore,  $\tau$ ,  $n'$ , and  $f'$  are constants under specific conditions. For instance, for objects in air,  $n = 1$ ,  $n'$  is approximately 1.336 [15], similar to the refractive index of the vitreous body in the human eye, allowing Equation (1) to be further transformed and simplified into Equation (3).

$$E' = 1.4\tau L \left(\frac{D}{f'}\right)^2 = a \cdot LD^2 \quad (3)$$

Where  $a$  is determined by the properties of the above factors.

Analyzing the eye's imaging rules shows that an object's luminance and pupil diameter play key roles in the imaging process. Therefore, we have defined the relationship between object luminance and pupil diameter as "Retinal Imaging Brightness  $L_r$ ", as Equation (4).

$$L_r = a \cdot LD^2 \quad (4)$$

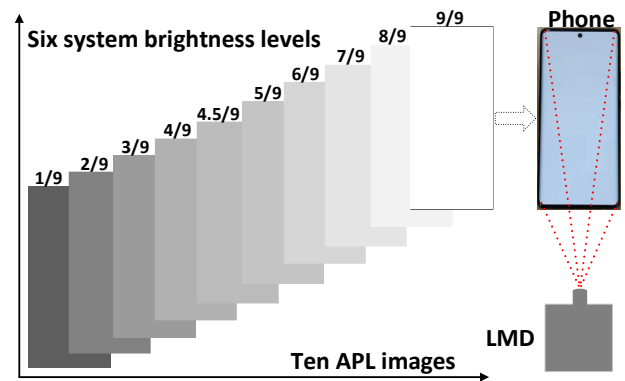
Through preliminary experiments, we have demonstrated that the perceived brightness of a target object increases with  $L_r$  and that subjective brightness ratings show a significant correlation with  $L_r$ . However, there are some flaws in directly using the equation for retinal imaging brightness to characterize perceived brightness. For example, using Equation (4), if the screen's physical luminance is much greater than in subjective experiments, the fitted equation may not converge within our preset perceived brightness grading range.

Innovatively, we consider  $LD^2$  as a collective variable factor to analyze its influence on the perceived brightness rating. Subsequent related analysis and experimental data processing will elucidate the specific functional form and constant-coefficient  $a$ . The above theoretical research will lay a theoretical

foundation for establishing our model of perceived brightness.

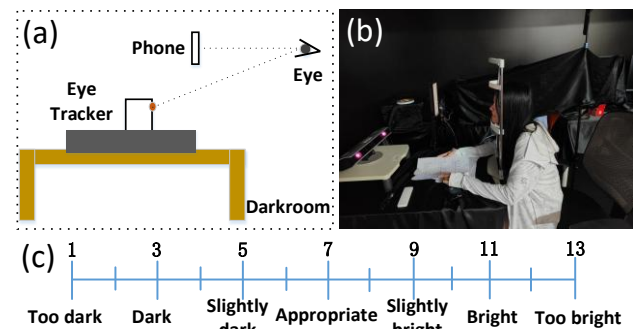
### 3. Experimental methods

In our first experiment, we prioritize using smartphones as the stimulus source. Smartphones are almost essential mobile display devices for people who have gradually developed the habit of using them before sleeping at night. The changing screen content in dark environments leads to abrupt brightness changes, causing eye discomfort; hence, this is also the rationale for using smartphones for subjective and objective experiments in this phase. The experimental mobile phone screen selected for this experiment is OLED, with a size of 6.78 inches, an aspect ratio of 20:9, and a resolution of 2800\*1260. We designed 10 grayscale-level test images with different average picture levels (APL) for testing. Each image has six system brightness settings, resulting in 60 sets of screen luminance, i.e., 60 stimuli in this experiment. Figure 3 shows the physical luminance of the phone displaying ten APL test images under six system brightness settings, which was measured with a light measuring device (LMD).



**Figure 3.** A total of ten APL test images were used for mobile phone display. LMD measured the physical luminance of the phone under six system brightness settings.

The pupil adjusts according to changes in external light; therefore, we used an eye tracker to record real-time changes in the participants' pupil diameters. The eye tracker records the video image of the participant's eyes using an infrared camera and then uses a built-in computer to analyze the image data. Next, we designed and built the perceptual experiment scene. An illustration of the experimental setup is shown in Fig. 4 (a).



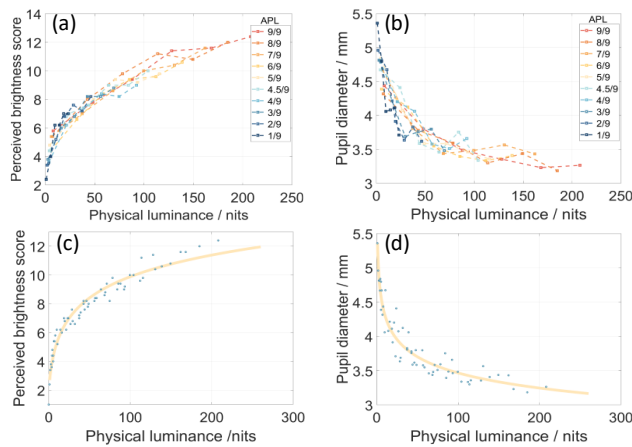
**Figure 4.** (a) Schematic diagram of the experimental setup. (b) Actual scene of a participant in the experiment. (c) The grading scale for perceived brightness.

As the actual scenario scene shown in Fig. 4. (b), we invited 17 participants to rate the perceived brightness levels of the phone

screen in the darkroom. with normal or corrected-to-normal vision, aged between 22 to 41 years old, with an average age of 26.4. The observation distance was set to 27cm based on user habits. Participants used the method of magnitude estimation from psychophysics to rate their perceived brightness level, following the 13-level grading scale shown in Fig. 4. (c), ranging from too dark at 1 to too bright at 13. Participants viewed each set of stimuli on the screen for 15 seconds to ensure adequate pupil adaptation time, while the eye tracker collected data on the pupil diameter of both eyes during this interval. Then, they closed their eyes to rest for 15 seconds before proceeding to the next set.

#### 4. Results and modeling

After completing the subjective experiments described above, we summed and averaged the perceived brightness ratings and pupil diameters. As shown in Fig. 5, we then analyzed the trends in perceived brightness ratings and human pupil diameters as they change with actual screen luminance.



**Figure 5.** (a) The trend of perceived brightness rating with changes in screen physical luminance. (b) The trend of pupil diameter with changes in screen physical luminance. (c) and (d) Fitted relationship of (a) and (b).

Figure 5. (a) indicates that the subjective ratings of perceived brightness increase with the increase in physical luminance. Meanwhile, (b) shows a decrease in participants' pupil diameters with increased screen luminance. Furthermore, we can deduce that images with a higher APL display greater actual luminance for a constant system luminance setting. The above monotone relation is further illustrated by the fitting curves of (c) and (d). Thus, both theory and experiment verify that the target screen luminance and pupil diameter directly affect participants' perceived brightness ratings.

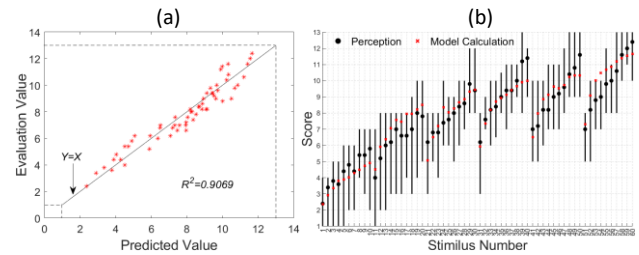
By selecting pupil diameter and screen luminance, which are significantly correlated with ratings, for quantitative analysis, and after pre-calculating  $LD^2$ , we use Equation (4) to derive the functional form of the fit for screen luminance, pupil diameter, and perceived brightness rating score, as shown in Equation (5):

$$L_p = \frac{24}{\pi} \cdot \arctan(a \cdot (LD^2)^b) + 1 \quad (5)$$

Where:  $L_p$  is the perceived brightness rating level (out of 13),  $L$  is the screen luminance in nits, and  $D$  is the pupil diameter in mm. The constant coefficient values were  $a = 0.023$  and  $b = 0.642$ .

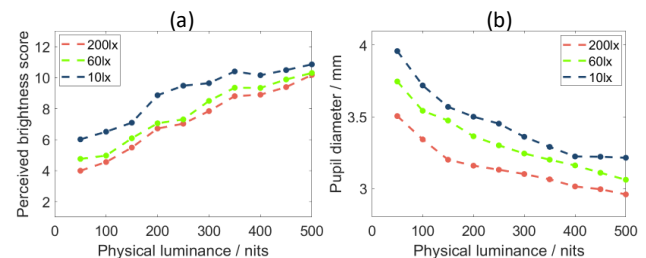
We have established the retinal imaging-based model for perceived display brightness. Fig. 6. (a) shows a high correlation

( $R^2 = 9069$ ). We further use the model to compare the derived values for each stimulus with the subjective perception experimental results, as shown in Fig. 6. (b). Since the modeling process results from both theoretical and experimental work, (a) and (b) both provide cross-validation for the model.



**Figure 6.** (a) Correlation of perceived brightness estimated by the model with subjective experimental results. (b) Comparison of perceived brightness ratings derived from the model with subjective experimental results.

However, display devices are often used in varying ambient light conditions. In indoor ambient light, the level of illuminance is the primary indicator of concern. In the use of display devices, the screen's brightness needs to provide a level of brightness that satisfies the visual perception needs of the human eye under ambient light levels in various living or application scenarios. This further necessitates the mutual adjustment of the ambient light illuminance level and the display brightness level to meet the perceptual needs of the human eye [18]. Therefore, we further designed subjective experiments on screen perceived brightness under different ambient lighting conditions. For the purpose of application validation, other types of displays (7-inch LCD screen) were used to design 10 screen luminance levels and 3 indoor illuminance levels, and 10 new participants were invited for the perception experiments.

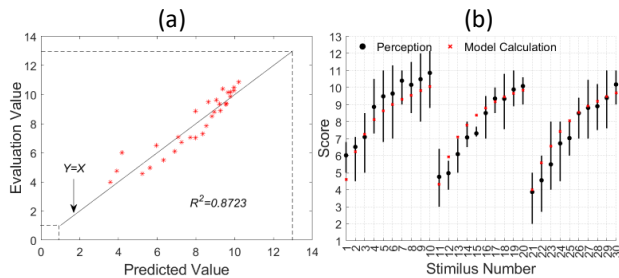


**Figure 7.** The trend of (a) perceived brightness score and (b) pupil diameter with changes in screen Physical luminance.

As shown in Fig. 7, (a) indicates that when ambient illuminance is constant, participants' perceived brightness level ratings increase with increasing physical screen luminance. When the screen luminance is constant, as the surrounding ambient light illuminance increases, participants' perceived brightness ratings of the screen gradually decrease. According to Fig. 7 (b), participants' pupil diameters decrease with increasing screen luminance; when the screen luminance is constant, their pupil diameters decrease with increasing ambient light illuminance.

Therefore, we again perform a fitting process using the form of Equation (5). However, the working mechanism of HVS varies with ambient light [1,3]. The constant coefficients in the presence of ambient light were  $a = 0.002$  and  $b = 0.839$ . In the presence of ambient light, the same physical luminance is lower than the perceived brightness in the absence of ambient light. At this point,  $a$  will significantly reduce the role of modulation.

Similarly, we analyzed the correlation between the calculated values of the model and the subjective perceived experimental evaluation values, as shown in Fig. 8. And (a) shows a high correlation between the two ( $R^2 = 0.8723$ ). Further illustrated in (b), we also compare the predicted values for each stimulus with the subjective perceived experimental values. Therefore, the screen luminance and pupil diameter significantly affect participants' perceived brightness ratings, and overall ambient light directly impacts pupil diameter.



**Figure 8.** (a) Correlation of perceived brightness estimated by the model with subjective experimental results. (b) Comparison of perceived brightness ratings derived from the model with subjective experimental results.

As discussed earlier, the physical luminance of the screen changes with the settings and the APL of the display device. Thus, to optimize the real-time luminance of the display device using this model, to meet the demand for comfortable display brightness. Through previous analysis, the pupil can be an important parameter for displaying visual comfort. Utilizing Fig. 5, we can infer the physical luminance likely required by the screen for comfortable vision in a dark environment based on pupil diameter. And experimental data reflected that the range of pupil diameter was between 3.18 and 5.36 mm, with the midpoint value being 4.27 mm. It can be further deduced that the corresponding physical luminance is about 10 nits. According to the evaluation of the perception experiment, the most comfortable brightness should be less than 10 nits.

## 5. Conclusion

In summary, we established a theoretical basis for converting retinal imaging illuminance to retinal imaging brightness by analyzing the structural and perceptual characteristics of the HVS. It identifies the display luminance and pupil diameter as the primary factors characterizing perceived brightness. Based on this theory, we designed subjective experiments using two types of display devices with and without ambient light.  $LD^2$  was used as an independent variable to establish the display brightness perception model based on retinal imaging, as shown in equation (5). The constant coefficient values corresponding to the calculation model are determined according to the ambient light condition ( $R^2 > 0.87$ ). The application of this model facilitates the optimization of real-time physical luminance of displays. Therefore, our model is of significant importance for guiding the development of brightness adjustment solutions for display devices that meet the visual perception characteristics of the human eye, for establishing related visual comfort standards, and for improving visual health.

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