BrightView: Increasing Perceived Brightness of Optical See-Through Head-Mounted Displays Through Unnoticeable Incident Light Reduction

Shohei Mori* — Keio University
Sei Ikeda — Ritsumeikan University
Alexander Plopski — Nara Institute of Science and Technology
Christian Sandor — Nara Institute of Science and Technology

(a) The proposed OST-HMD (b) LC off in dark scene (c) LC off in bright scene (d) Our method in bright scene

Figure 1: (a) Our prototype Optical See-Through Head-Mounted Display (OST-HMD) increases the *perceived* brightness of virtual objects in bright conditions by dynamically adjusting liquid crystal (LC) shutters according to the measured brightness of the environment. (b) The virtual teapot appears consistent with the background in a dark environment. (c) On the other hand, it appears transparent and dim in a bright environment. (d) By gradually adjusting the transparency of the LC shutters, the teapot is perceived as brighter, while the background is perceived as unchanged. Images (b), (c), and (d) were captured directly through our prototype with a PointGrey Flea3 camera with automatic shutter speed. We present psychophysics experiments validating that users indeed perceive an improvement akin to the difference between (c) and (d).

Abstract

Optical See-Through Head-Mounted Displays (OST-HMDs) lose the visibility of virtual contents under bright environment illumination due to their see-through nature. We demonstrate how a liquid crystal (LC) filter attached to an OST-HMD can be used to dynamically increase the perceived brightness of virtual content without impacting the perceived brightness of the real scene. We present a prototype OST-HMD that continuously adjusts the opacity of the LC filter to attenuate the environment light without users becoming aware of the change. Consequently, virtual content appears to be brighter. The proposed approach is evaluated in psychophysical experiments in three scenes, with 16, 31, and 31 participants, respectively. The participants were asked to compare the magnitude of brightness changes of both real and virtual objects, before and after dimming the LC filter over a period of 5, 10, and 20 seconds. The results showed that the participants felt increases in the brightness of virtual objects while they were less conscious of reductions of the real scene luminance. These results provide evidence for the effectiveness of our display design. Our design can be applied to a wide range of OST-HMDs to improve the brightness and hence realism of virtual content in augmented reality applications.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed/augmented reality Interaction devices Displays and imagers

*e-mail: s.mori.jp@ieee.org

IEEE Virtual Reality 2018
18-22 March 2018, Reutlingen, Germany

1 Introduction

Photometric consistency in augmented reality (AR) is important not only to provide realistic experiences but also to help users better understand the augmented space. For example, it is known that changing optical phenomena (e.g., shadows, specularity, refraction, and luminance fluctuation) can affect various perceptual issues related to scene understanding, such as the positional relationship between real–virtual objects [28], shape [3], elasticity [15], materials [29], and movement [14] of augmented objects.

Most studies on perception in AR are performed in a controlled environment and often make use of projection systems to achieve sufficient contrast and brightness between the virtual content and the real world [21]. It is difficult to apply their findings to optical see-through head-mounted displays (OST-HMDs), which have cameras and displays with a very limited dynamic range. OST-HMDs project graphics into the user's field-of-view without occluding the real world, and the virtual content's brightness should match with the world's brightness to create a realistic experience. Our visual system can perceive luminance in the range of approximately 10^{-2} cd/m^2 on an asphalt road under moonlight to 2×10^5 cd/m^2 on a sunlit beach [4]. On the other hand, current off-the-shelf OST-HMDs provide at most a few thousand cd/m^2 luminance. In bright environments, content shown on the OST-HMD thus appears transparent and dim, and the presented scene, therefore, suffers from the gap between real–virtual brightness (i.e., contrast). To address this issue, a number of commercially available OST-HMDs have an interchangeable visor to attenuate strong external lights (e.g., Epson BT-200/300 and Google Glass) or an optical combiner with low transparency (e.g., TRIVISIO LOC.20/ARS.30 and Brother AiR Scouter WD-200B).

Both approaches inevitably harm AR experiences. For example, light shielding is not necessary for some indoor AR applications where current OST-HMDs can match the brightness of the scene. On the other hand, constantly changing the visors is disruptive for the AR experience. Liquid crystal (LC) visors can mitigate this by controlling the amount of transmitted light. However, instant switching of the shielding will inevitably cause temporal discontinuities in brightness due to afterimages caused by visual adaptation delays. In this work, we address this issue by gradually adjusting the transmission ratio of the LC visor to prevent the temporal discontinuities (Figure 1). As a result, we show that the perceived decrease in scene brightness is lower than the decrease in its luminance. At the same time, we found that the amount of perceived brightness increase of the virtual content depends not only on the presented virtual content ut also on the background of the scene. To the best of our knowledge, this is the first study to investigate visual adaptation with OST-HMDs and attached LC-visors in AR scenarios.

- We show that, by gradually increasing the opaqueness of the LC visors, users become less aware of the ongoing darkening of the scene. Users of our OST-HMD thus perceive an increased brightness of the virtual object rather than a decrease of the brightness of the real background.
- We investigate how different dimming periods impact the perceived brightness of the virtual content in flat and 3D scenes.

2 Related Work

In this section, we review work that is highly related to our OST-HMD design. In particular, we first discuss some previous designs of wearable glasses that control the amount of transmitted light. We follow this up with a discussion of the impact of brightness adaptation on the user. Finally, we discuss studies on the detectability of illumination shedding.

2.1 Glasses Using a Shade with Variable Transparency

Besides the aforementioned attachable visors, the amount of transmitted light in an OST-HMD can be controlled by a variety of materials and designs. For example, the surface of the OST-HMD could be covered with photochromic materials that are applied to sunglasses (e.g., Seiko Transitions). These materials adjust their transparency in response to ultraviolet rays, thus automatically reducing the amount of light entering the eyes in bright environments and increasing it in dark environments. However, it is not possible to control the transmission rate of these materials, which means that they are not viable for the gradual adaptation studied in this paper.

An alternative is LC shutters with adjustable transparency control, which initially emerged in the military around 1995 and are now being marketed as consumer products (e.g., AlphaMicron e-tint). Similar concepts have been applied with OST-HMDs to control the amount of incident light [23, 31]. Miyashita [24] suggested adjusting the LC shutter's transparency through detection of a scene's illuminance and applied a system to welding masks. The mask automatically reduces the transparency of the visor whenever arc light is detected, which makes it unnecessary to constantly take it off and put it back on again.

Locally constrained LC shutters have been used with OST-HMDs to dim only the area that displays the virtual content [10, 16, 20]. While this improves the visibility of virtual content, a masking display has to have a sufficient number of pixels to cover a $w \times h$ pixel display for virtual content. On the other hand, our OST-HMD requires a uniform 1×1 pixel resolution display only (i.e., feasible). Further, our aim is to confirm perceptually high contrast OST-HMDs through a psychophysical experimental design with a prototype, while the pixel-by-pixel mask-based methods require geometrically correct virtual content masking.

To the best of our knowledge, there has been no attempt to improve the brightness of the virtual object without perceptually changing the brightness of the real scene using the homeostasis of the human eye. In addition, there is no case study that confirms the effect of using an actual OST-HMD [12, 17].

2.2 Brightness Adaptation

Brightness adaptation is a well-known phenomenon. It allows us to expand our limited range of visual sensitivity and sense a wide range of luminance variation in the real world [5]. We distinguish between dark adaptation and light adaptation [2, 8] and experience both effects on a daily basis. For example, after entering a cinema, we can see nothing, but our vision gradually recovers after a while. On the other hand, after exiting the cinema, our sight is filled with white but recovers in a few seconds. The literature describes models of visual adaptation at the rod and cone level, the chemical reaction of Rhodopsin and Photopsin, and the high-level visual systems [4]. However, because these phenomena complicatedly affect each other, a perfect model representing our visual event has not yet been clarified.

2.3 Illumination Shedding

Brightness adaptation has been taken advantage of in illumination shedding techniques, where the illuminance of the scene is gradually reduced without the user becoming aware of the change [1, 11, 13, 25]. Some studies have succeeded in dimming the environmental illumination by up to 40 to 50% without it being noticed by subjects by repeatedly dimming the light by 0.5% per min [13, 25]. Previous attempts have used both linear and signed functions for the dimming curve [1, 11, 26]. However, they found that differences between these curves do not affect the brightness change detectability in our vision [1]. In recent years, step curves according to logistic and square functions have also been used, but the effects of these curves have not been observed [11].

Shikakura et al. [26] pointed out that the detectability of illuminance changes depends on the task the user faces, and that users cannot detect a fluctuation of about 7% while focusing on a task. Akashi et al. [1] claimed that our perception of brightness changes is affected by neural detectors depending on transient and memory mechanisms. In other words, we perceive the variation in brightness due to the chemical response on the retina and the temporal ratio indicated by the curve of the rod cell spectral sensitivity curve, and the memory of how much the difference in brightness is perceived after the brightness change.

The effect of illumination shedding with gradually adjustable LC visors has not been studied in AR-related tasks. In AR, users are presented with illuminance from the observed environment and illuminance from the virtual content presented on the HMD. It is thus unclear if the gradual change of the LC visor's transparency is perceived as an increment of the brightness of the virtual object, while the brightness of the observed scene is perceived to be unchanged.

3 OST-HMD with Dimming Visors

In this section, we first describe the definitions of terminologies and their relationships to explain the physical and psychophysical phenomena in OST-HMDs with dimming visors. Next, we show how to set the visor transmittance used in the psychophysical experiment in the next section and how to calculate the visor's transparency in practical applications.

3.1 Preliminary

What we perceive as brightness of the real environment is the result of various interactions between light from light sources and objects. We distinguish between illuminance, the amount of light radiating from an object, luminance, the amount of light that is reflected into the eye, and brightness, the perceived intensity of the light. In the following section, we explain how the various factors are affected by our OST-HMD design.

Illuminance to Luminance. Illuminance is defined by the energy of light irradiated from every direction per unit area of the object surface over unit time. A part of the irradiated light is observed by the user as a light ray through various optical phenomena, such as reflection, transmission, absorption, and scattering on the surface or inside of the object. The intensity of this light ray reaching to the eye is the luminance defined by the energy of light traveling within a unit solid angle through a unit area per unit time. When the illuminance changes, the luminance received by the eyes changes accordingly depending on the field of view. Here, we assume that the illuminance L and the luminance R are in a linear relationship

$$R = kL,$$

where k is a proportionality constant. The LC visor attached to the OST-HMD further modifies R by a dimming value (transparency) α, as shown in Figure 2. L can be measured by illuminance sensors, which should be aligned to the eyes physically or virtually by calibration. Consequently, the luminance R' reaching the eye through the LC visor can be described as

$$R' = \alpha R = k(\alpha L).$$

In an OST-HMD, the user additionally observes virtual content presented with a luminance V, and thus the overall amount of luminance reaching the retina is $R' + V$. Note that there is a considerable amount of work suggesting the importance of considering the characteristics of the HMD optical components (e.g., reflectance and transmittance factors of the optics) [6, 7, 9, 19], although our model assumes simpler and perfect optics without any types of degradation due to the optics.

Luminance to Brightness. While luminance can be measured with a spectroradiometer or an illuminometer, the amount of perceived intensity, called brightness, cannot be measured as a physical quantity since it depends primarily on reactions on the retina and processing in the brain rather than on physical quantities of light reaching the retina. The amount of light that reaches the retina is controlled by the pupil, whose diameter changes in the range of 2–8mm [30], and the light is detected by photoreceptors such as rods and cones. This stimulates chemical reactions within the photoreceptor cells that are transmitted to the brain via the optic nerve. After the visual intersection, higher order processing is done in the V1 field and recognized by us as brightness. Therefore, straightforwardly measuring the quantity of incident light within the pupil or the retina does not equal the brightness we perceive. Instead, their relationship can be determined through psychophysics. Consequently, in this paper, we investigate the perceived brightness of the real background and virtual objects via a psychophysical experiment using a similar approach to the magnitude estimation method [27] to verify the influence of our OST-HMD.

3.2 Proof-of-Concept Prototype

Our prototype shown in Figure 1 consists of an Epson BT-300 OST-HMD (resolution: 1280×720 pixels for each eye, FOV: diagonal 23 deg, OS: Android 5.1) and Root-R RV-3DGBT1 shutter glasses as dimming visors. The dimming visors are rigidly attached to the display to cover the entire field of view. The BT-300 has a frontal camera (resolution: 2560×1920 pixels) and an illuminometer (unit: lux), as shown in the top row of Figure 1 (a). The transparency of the dimming visors is controlled by applying different voltages with an Arduino Yun mini. The content presented on the BT-300 and the amount of voltage applied by the Arduino is controlled via a PC. All of the external light needs to pass through the light shielding visor to fully control external light.

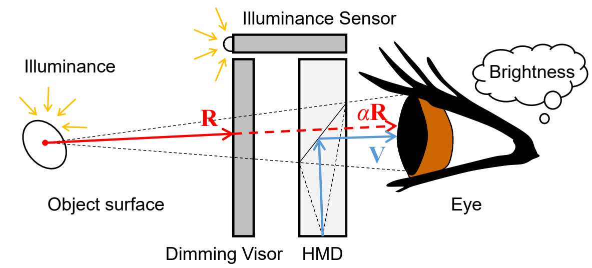


Figure 2: Schematic figure of the proposed OST-HMDs with dimming visors. The user receives the real light R through the unit angle ω. While the virtual light V is directly projected to the eye by a display of HMD, the real light R is dimmed by the dimming visors to αR.

3.3 Selection of Dimming Function

For the experiments, to prevent users from noticing the change in the luminance of the scene, we designed a dimming function based on the following observations:

- Linear functions will work adequately for illumination shedding unless the dimming speed remains at a certain level [1].
- As the luminance begins to change, the correct answer rate of the initial brightness decreases over time [1].
- If the luminance fluctuation ranges from several to ten-odd seconds, the detectability of the change does not depend on the initial luminance [26].
- A luminance fluctuation of about seven percent is not detectable irrespective of the time interval in a total change from several to ten-odd seconds (even zero to ten-odd seconds when a workload is provided) [26].

In this experiment, we assume that users will not be able to detect a gradual linear change of the transparency $\Delta\alpha$ of the LC visors, as long as it is less than seven% at a time over the course of several seconds. We chose a linear function because of the above-mentioned observations and its simplicity, although we cannot deny the potential effects of different dimming curves.

For practical applications, we compute the change of the transparency $\Delta\alpha$ at any given time as a function of the scene luminance and the luminance of the virtual content shown on the OST-HMD. We recover the scene luminance from the image taken by the frontal camera of the BT-300 and the attached illuminometer. For a given direction $\mathbf{u} \in \mathbb{R}^2$ in the field of view Ω_r, the linear relationship between the corresponding pixel value $p(\mathbf{u})$ of the camera image and the luminance $R(\mathbf{u})$ can be expressed by the following equation,

$$R(\mathbf{u}) = cp(\mathbf{u}), \tag{1}$$

where c is a scale factor that includes some auto-gain parameter and unit conversion coefficient. The illuminance L acquired by the illuminometer measures the irradiance of light over Ω_r, and it can be represented as

$$L = \iint_{\Omega_r} R(\mathbf{u})d\mathbf{u}. \tag{2}$$

Note that, here, we assume that L is proportional to the integral of $R(\mathbf{u})$, although the illuminance sensor measuring L can receive the other unnecessary light from all directions. It can be seen that c can be obtained from the above equations as

$$c = \frac{L}{\iint_{\Omega_r} p(\mathbf{u})d\mathbf{u}}. \tag{3}$$

By substituting c back into Equation 1, we can calculate the luminance $R(\mathbf{u})$ in cd/m^2 along $\mathbf{u}$ from the pixel value $p(\mathbf{u})$. When the maximum luminance $R_{\max}$ of the real scene exceeds the maximum luminance $V_{\max}$ of the OST-HMD, we activate our dimming visor to increase the perceived brightness of the virtual content by controlling the transmittance of the LC visors, α. Finally, the transparency change per unit time $\Delta\alpha$ can be determined as

$$\Delta\alpha = \begin{cases} \max\{(V_{\max} - \alpha R_{\max})/kV_{\max}, -T_0\} & \text{if } \mathrm{V}_{\max} < \alpha \mathrm{R}_{\max} \\ 0 & \text{otherwise} \end{cases},$$

where k and T_0 are constants for speed adjustment and limiting the dimming rate, respectively. We empirically measure the possible range of the dimming value α using the LC visors. The voltage to control the LC visors can vary from 1.57 V to 3.53 V using an Arduino Yun mini. Voltage outside this region resulted in the turbidity and non-uniformity effects shown in Figure 9. We measured the actual transparency changes within the range and determined the minimum and the maximum value of the transparency as 9.0% and 22.7%, respectively. Our linear dimming function, therefore, varies the dimming value α from $\alpha_s = 22.7\%$ to $\alpha_e = 9.0\%$. We empirically determined $T_0 = 10 \times (\alpha_s - \alpha_e)/20$ s and $k = 1$s.

Since the Arduino Yun mini provides only pulse width modulation as its analog output, we measured the luminance through the controlled LC visors using a linear camera (PointGrey Flea3) and did not observe any flickering or inconsistencies. Furthermore, the participants of our experiment did not report observing any issues either.

4 Psychophysical Experiments

We conducted psychophysical experiments to confirm our hypothesis that by gradually adjusting the transparency of the LC visors users will not notice a decrease in the luminance of the real world but will perceive an increase in brightness of the virtual content instead.

To validate this hypothesis, we evaluated the *deviation rate* ε between the expected and perceived brightness answered by participants. Therefore, our aim is to show that the deviation rate ε exceeds the expected value, which means that the participants reported that unchanged virtual luminance changed and changed real luminance unchanged irrespective of AR scene variations.

4.1 Analysis Method

According to Stevens' Law [27], the relationship between perceived brightness P and physical brightness S is

$$P = CS^k,$$

where C is a constant value. The exponent k depends on the experimental conditions. It is set to 0.31 for simple scenes illuminated by a point light source smaller than 2° and to 0.6 for more complex scenes [4]. Although the validity of Stevens' Law is not uniformly recognized, it can be a very good approximation of the perception of lightness under certain conditions [4].

In our experiments, the luminance of real and virtual objects did not change in the observation and evaluation phases, and thus S is a constant value. However, as the transmittance of the LC changes from α_s to α_e, the luminance of the real object observed by the subject changes accordingly from $\alpha_s S$ to $\alpha_e S$. Assuming the above-mentioned Stevens' Law, the ratio between the perceived brightness of the real scene before and after the change can be described as

$$\frac{P_e}{P_s} = \left(\frac{\alpha_e}{\alpha_s}\right)^k.$$

The left side describes the perceived change rate of the brightness, and the right side is the expected change rate of the perceived brightness from the actual brightness change.

Since this study is different from the experimental conditions of Stevens, there is a possibility that this equation will not hold. We describe the deviation rate as

$$\varepsilon = \frac{P_e}{P_s}\left(\frac{\alpha_e}{\alpha_s}\right)^{-k}.$$

As mentioned above, ε represents a degree of the deviation between the expected and the perceived brightness. That is, if ε is close to 1, then the perceived change is consistent with the actual change of the scene brightness. If ε is significantly larger than 1, the user's perception of the brightness change deviates from Stevens' Law.

In the experiments, we evaluated the deviation rate of the real scene ε_r and that of the virtual scene ε_v, respectively. Thus, for ε_v, $\alpha_s = \alpha_e$ holds since the transmittance of the LC visors did not affect to the virtual object (Figure 2). If $\varepsilon_r > 1$, the perceived brightness changes, P_e/P_s, are dissimilar to those of the model expected by Stevens' Law. So it is with $\varepsilon_v > 1$. Then, evaluating that P_e/P_s is larger than one or smaller than one, we can distinguish the perceived brightness increase or decrease, respectively. From these observations, we formulate three hypotheses.

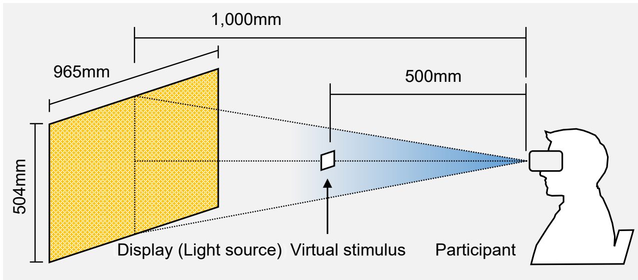
- **H1:** After a gradual increase in the opaqueness of the LC visors, participants will not notice a significant decrease of the brightness of the real scene ($\varepsilon_r > 1$).
- **H2:** After a gradual increase in the opaqueness of the LC visors, participants will perceive the virtual content to be brighter ($\varepsilon_v > 1$ and $P_e/P_s > 1$).
- **H3:** If the brightness is adjusted over a longer period, the perceived deviation values will be larger.

4.2 Procedures

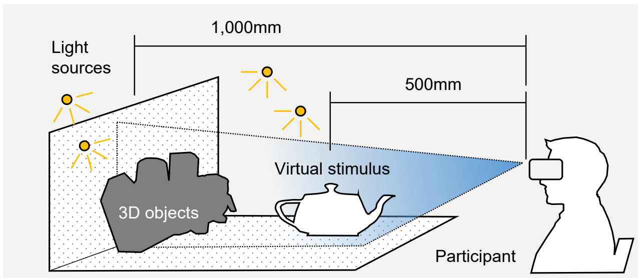
We investigated the perceived brightness of both dominant and non-dominant parts when the transparency α was changed. We followed a magnitude estimation method to investigate how the perceived brightness changed. In each trial, we showed a virtual object of a given brightness V. An example view of the experiment conditions is shown in Figure 3. We asked each participant to wear the OST-HMD with shutter glasses, as shown in Figure 4. The participant was then asked to look at the virtual object and rate the perceived brightness of the stimulus, assuming that of the reference to be 100. If the perceived stimulus was brighter than the reference, a score greater than 100 was given, and vice versa. Figure 5 shows the actual procedure of each trial. Each trial consisted of four phases: adaptation, observation, shutter change, and evaluation. The adaptation phase was set to eliminate the influence of the previous trial. In this phase, in order to acclimate the eyes under normal conditions, we presented scenes that were neither too bright nor too dark. In the observation phase, the participants looked at the virtual object or the real scene and memorized the brightness of one of them.

After the observation phase, the virtual object disappeared so that the participants did not notice the decrease in luminance of the real scene with reference to the virtual object. Meanwhile, in the shutter change phase, the transparency α was changed from $\alpha_s = 22.7\%$ to $\alpha_e = 9.0\%$, as shown in Figure 5. The durations of this change were 5s/10s/20s. For comparison, we added a control condition, where the transparency of the LC visors were kept at α_s for 20s. We limited the experiment to these four conditions to minimize participants' fatigue. The control condition was set to 20s for the following reasons: Comparing stimuli over a certain period of time is not an easy task for participants, and we expected them to reply differently, even with the same stimuli. Given the observations of the literature [1], we expected the error in the participants' replies to be the highest after the longest interval, which was 20s in our study. In order to increase the reliability of the comparison, we chose 20s as the control, where it is hardest to observe significant differences.

In the evaluation phase, the participants looked at the the virtual object or the real scene again and then inputed a magnitude with



(a) Scene 1



(b) Scene 2 & 3

Figure 3: Schematic layout of the experimental setups in our psychophysical experiment.

a numeric key. The evaluation order of the real scene and virtual object was counterbalanced across the participants. In concrete, the participants were divided into two groups, and half of them evaluated the center target for the first half of the trials, after which a display showed a real photo for the second half of the trials. The other half of the subjects performed the same task in reverse order.

4.3 Experimental Setup and Participants

Scene Design In the experiment, we used the following three scenes:

Scene 1:	Flat real scene	&	Virtual dot,
Scene 2:	3D real scene	&	Virtual dot,
Scene 3:	3D real scene	&	Virtual 3D object.

These scenes were designed in a gradual manner from Stevens' condition with a point light source in a dark environment to reach a realistic AR situation, where a virtual 3D object is overlaid over a 3D scene, as depicted in Figure 3. To control the scene illumination, the experiments were conducted in a dark room. Furthermore, the participants wore our OST-HMD with a mask to prevent luminance from entering the eye from areas not controlled by the LC visor.

In Scene 1, the background in Stevens' condition was replaced with a real image on a flat screen with similar luminance to the HMD, and the point light source was replaced with a floating dot displayed on the OST-HMD (Figure 3 (a)). Therefore, the situation remained close to Stevens in terms of the shape of the scene and the luminance. In Scenes 2 and 3, in order to further approximate the conditions faced in actual AR applications, the planar background was replaced with a three-dimensional scene containing multiple objects with various reflectance properties (Figure 4 (c)).

We used multiple projectors to create areas of varying luminance. To simulate the user going from inside to a bright outside scene, we turned off the projectors during the adaptation (Figure 6 (a)), which resulted in a slightly darker environment. Then the projectors were turned on for the observation phase, and were kept on during the shutter change and evaluation phases (Figure 6) (b)-(d)).

In Scene 2, similar to Scene 1, we displayed only a virtual dot to examine how the scene background affected the results. In Scene 3, we replaced the dot with the Utah teapot to investigate if augmenting a larger area would affect the results compared to Scene 2. We show the different conditions in our experiment in Figure 6.

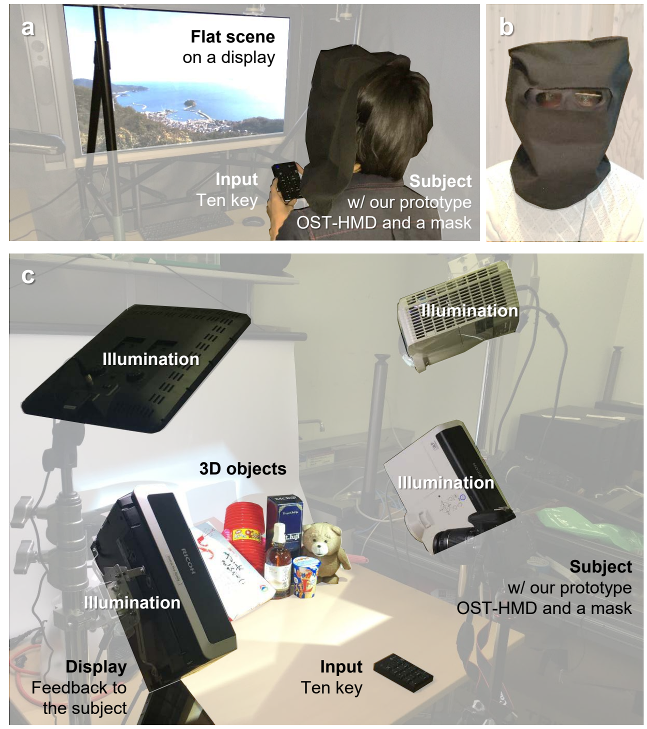


Figure 4: Experimental setups of our psychophysical study. (a) Experimental setup in Scene 1 for flat environment in a black box. (b) A subject with our prototype OST-HMD and a mask to shut off external lights. This fully covered mask is simply for complete avoidance of external lights and therefore could be replaced with commodity masks, such as covers for video see-through HMDs. (c) Experimental setup in Scenes 2 and 3 for the 3D environment.

Setup for Scene 1 For this experiment, we recruited 16 unpaid participants (14 males and 2 females; age 20 to 24) from a local university. All the participants were unaware of the experimental purpose and had normal or corrected to normal vision. We asked each participant to put on the OST-HMD and to sit still, one meter away from a flat display (Pioneer PDP-434CMX). We also asked him or her to look at a point displayed on the OST-HMD at the center of the field-of-view. The position of the point was adjusted so that it appeared to float at a distance of 50 cm in front of the user, as shown in Figure 3. For this scene, we conducted two trials for each condition. Overall, we collected 256 raw magnitudes (= 2 targets (real/virtual) × (1 control + 3 durations) × 2 times × 16 people).

Setup for Scene 2 & 3 For these experiments, we recruited 31 unpaid participants (26 males and 5 females; age 21 to 25) were recruited from a local university. Of the participants, 13 joined the Scene 1 experiment while the rest were unaware of the purpose of the experiment. All the participants had normal or corrected to normal vision. We asked each participant to sit still, one meter away from the 3D objects on the table, as shown in Figure 4 (c), and to look at the center of the objects. We adjusted the augmented position of the virtual dot and the Utah teapot so that they appeared to be 50 cm in front of the user at the center of the table (Figure 7). For each scene, we obtained 248 raw magnitudes (= 2 targets (real/virtual) × (1 control + 3 durations) × 31 people).

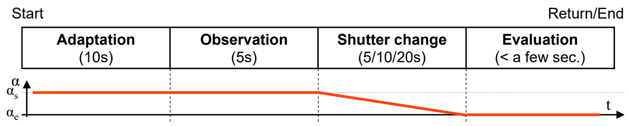


Figure 5: Experimental procedure and corresponding dimming values α. After being introduced to the experiment, a participant adapted to the scene for 10s. After the adaptation, the participant observed the augmented scene for 5s. Finally, the participant evaluate the augmented scene after the illumination dimming through our OST-HMD, and repeated or ended the experiment, followed by hearings.

4.4 Results

The transmittance of the LC visors was reduced from 22.7% to 9.0%. This means that the luminance of the real scene decreased to approximately 39.6% in the "shutter change" phase in Figure 5. Consequently, the dimming speed was 7.92, 3.96, and 1.96% per s over a period of 5, 10, and 20s. According to Stevens' Law, without a visor effect, i.e., for $\varepsilon_r = 1$, the participants were expected to answer that the brightness decreased by 57.4% (= $0.396^{0.6}$).

Scene 1 Figure 8 (a) shows comparisons between the control and the other conditions in terms of the real and virtual visual stimuli. For the real scene, the means and standard deviations of the evaluation values ε_r were 1.052 ± 0.067, 1.251 ± 0.363, 1.297 ± 0.401, and 1.477 ± 0.258 in the control, $d = 5$, $d = 10$, and $d = 20$ conditions. An analysis of variance (ANOVA) (Tukey Kramer test) found significant differences between certain conditions in real stimuli (F(3, 124) = 10.8, p = 2.4×10^{-6} (< 0.001)). Especially between the control and $d = 20$ conditions, a highly significant difference ($p < 0.001$) was observed. We observed medium significance ($p < 0.01$) between the control and d=10 conditions and low significances ($p < 0.05$) between the control and d=5 and d=5 and d=20 conditions. Similarly, for the virtual object, the means and standard deviations of the evaluation values ε_v were 1.014 ± 0.116, 1.105 ± 0.195, 1.142 ± 0.217, and 1.148 ± 0.245 in the control, $d = 5$, $d = 10$, and $d = 20$ conditions. The Tukey Kramer test on these scores yielded a significant variation among conditions: F(3, 124) = 3.1, p = 3.0×10^{-2} (< 0.05). It also showed low significance ($p < 0.05$) between the control and $d = 20$ conditions only. The $d = 10$ condition had the largest ε_v on average, although the difference between the control and $d = 10$ conditions was slightly less significant (p = 0.056) than that of the control and $d = 20$ conditions. We did not find any other statistically significant difference for the brightness of the virtual object in terms of duration d.

In summary, these results show that the participants less responsive to brightness changes in the real scene with the dimming visors but reported that they felt an increase in the brightness of the virtual content after the real illumination dimming over time in Scene 1.

Scene 2 Figure 8 (b) shows comparisons between the control and the other conditions in Scene 2. The means and the standard deviations of ε_r were 1.021 ± 0.066, 1.412 ± 0.220, 1.446 ± 0.229, and 1.493 ± 0.206 in the control, $d = 5$, $d = 10$, and $d = 20$ conditions (F(3, 120) = 39.8, p = 2.0×10^{-16} (< 0.001)). Those of ε_v were 0.969 ± 0.063, 1.075 ± 0.135, 1.109 ± 0.119, and 1.081 ± 0.145 in the control, $d = 5$, $d = 10$, and $d = 20$ conditions (F(3, 121) = 8.6, p = 3.4×10^{-05} (< 0.001)). For both the real and virtual objects, the ANOVA (Tukey Kramer test) finds a high significance ($p < 0.001$) between the control and the other conditions in the evaluation values ε_r and ε_v. However, we did not observe any statistical significances regarding duration d. We found a similar tendency as in Scene 1, the where $d = 10$ had the largest average ε_v.

Scene 3 Likewise, Figure 8 (c) shows comparisons between the control and the other conditions in Scene 3. The means and the standard deviations of the evaluation value ε_r were 1.021 ± 0.097, 1.414 ± 0.249, 1.458 ± 0.252, and 1.473 ± 0.195 in the control, $d = 5$, $d = 10$, and $d = 20$ conditions (F(3, 120) = 33.2, 1.1×10^{-15} (< 0.001)). Those of ε_v were 1.022 ± 0.153, 1.060 ± 0.167, 1.107 ± 0.149, and 1.086 ± 0.127 in the control, $d = 5$, $d = 10$, and $d = 20$ conditions. For the real scene, highly significant differences ($p < 0.001$) were found between the control and the other duration conditions. For the virtual scene, no statistical significance was observed on the ANOVA (Tukey Kramer test): F(3, 120) = 1.9, 1.3×10^{-1}. As well as the other scenes, $d = 10$ had the highest ε_r, although there was no significance.

In summary, these results show that the participants were less aware of brightness changes in the real scene with the dimming visors but reported that they felt an increase in the brightness of the virtual content after the real illumination dimming over time in Scenes 1 and 2.

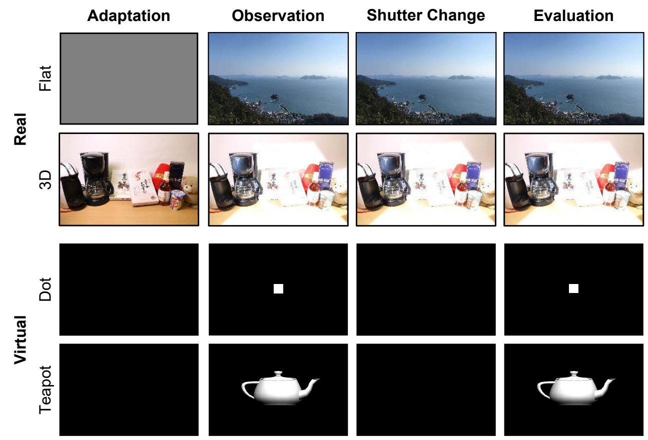


Figure 6: Real and virtual scenes used in the experiments. We show them as a combination of real and virtual; Flat + Dot, 3D + Dot, and 3D + Teapot, for Scene 1, 2, and 3 respectively. Virtual objects are presented in stereoscopic 3D. For the real scene the projectors were turned on after the adaptation phase to simulate users going from a darker to a brighter environment.

(a) Scene 1 (Flat + Dot) (b) Scene 2 (3D + Dot) (c) Scene 3 (3D + Teapot)

Figure 7: Participants' right-eye view through the combiner. The orange arrows indicate overlaid virtual objects.

4.5 Discussion

Summary of Experimental Results. Our experimental results support **H1**: ε_r was constant in the control condition, and compared to this, ε_r had a significantly larger value when the real environment brightness decreased gradually (i.e., the participants did not feel a significant decrease in real scene brightness when the brightness decreased slowly). We also found support for **H2** when the virtual object was a small dot. Here, ε_v was significantly larger than that in the control condition when the real environment brightness decreased gradually, although we kept the virtual object's brightness constant (i.e., the participants felt that the virtual object became brighter even though its brightness did not change). **H3** was supported for Scene 1 for the real-world condition. This means that the dimming effect was less noticeable when it was performed over a longer period of time. Additionally, in Scene 1, the condition

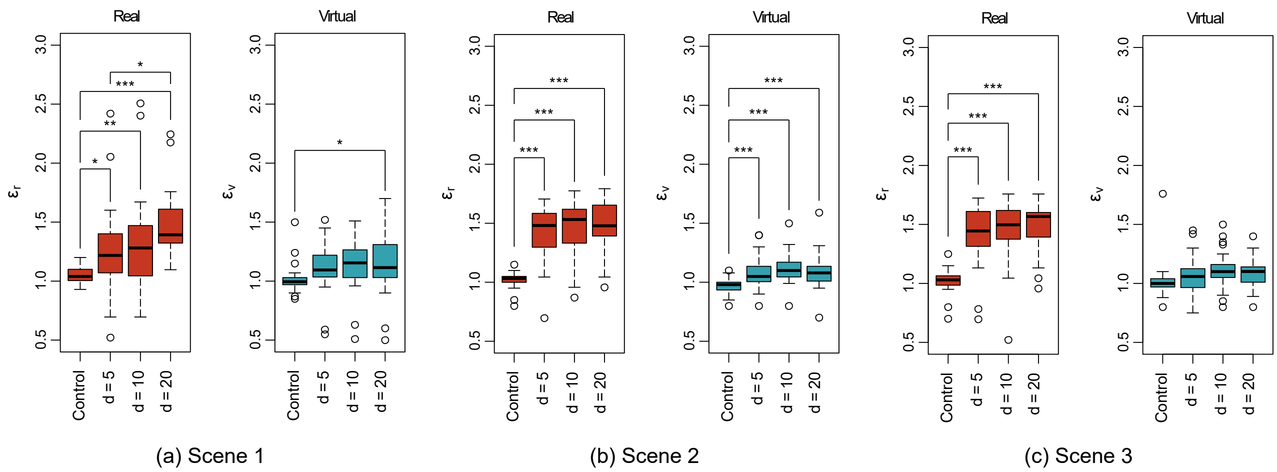


Figure 8: Results of the psychophysical study in Scene 1, 2, and 3. This figure shows the relationship between control and the other conditions in each scene and the impact of the LC visor change duration d on the perceived deviation values e_r and e_v. Remarks: [significance: [***] $p < 0.001$, [**] $p < 0.01$, and [*] $p < 0.05$]; The bottom and top of the whiskers indicate the 5^{th} and 95^{th} percentiles, respectively; The bottom, middle, and top of the boxes represent the 1^{st} quartile, the median, and the 3^{rd} quartile, respectively.

$d = 20$ was the only condition that had a significant increase in the perceived brightness of the virtual content. We did not observe any effect of the change duration in Scenes 2 and 3.

These results are in line with conventional psychophysical experiments showing that staying in a dark environment for a certain time makes people less aware of the darkness due to brightness constancy or adaptation [25]. The support of **H1** indicates that it is possible to reduce the effect of the overall luminance reduction in OST-HMDs by gradually changing the transmittance of the attached LC shutter.

Furthermore, our findings also indicate that, at least under certain conditions, it is possible to increase the perceived brightness of the virtual content at the same time. However, this may be affected by the size as well as the shading of the object, as we discuss in the following section.

Limitations and Future Improvements in Experiments. The results do not support **H2** in Scene 3, where the 3D scene and 3D virtual teapot were presented. We suspect that this could be due to the size of the object and the shading of the virtual content. Compared to the virtual dot in Scenes 1 and 2, the teapot occupied a larger area in the user's field of view (as shown in Figure 7). Therefore, it could have influenced the perceived brightness to a larger degree than the small dot [18, 22]. Since the luminance of the virtual teapot was constant, the participants could perceive the luminance as constant. In the future, it is necessary to investigate how the size of the virtual object, or the distribution of virtual content in the scene, affect the perceived brightness. The results could have also been affected by the diverse luminance of the scene. For Scenes 1 and 2, the dot was presented over a uniformly lit background. However, in Scene 3, the virtual content covered a background with different luminance, which could have affected the perceived brightness. Finally, the virtual teapot was shaded by virtual illumination, and some parts were invisible due to the shading. In Figure 7 (c), the left side of the virtual teapot is shaded and almost transparent so that the real table behind the virtual teapot is visible. Thus, the real brightness could largely influence the shaded parts of the virtual object. Consequently, the participants could have potentially perceived that the virtual content got darker when they observed the entire virtual object, which was partially transparent.

Interestingly, we could not confirm **H3** for the virtual object. One possible explanation could be that the luminance of the virtual object for the participants was almost saturated in our experimental setup. We plan to investigate the effect of the background brightness on the perceived brightening of the virtual content in future experiments. Another explanation could be that the virtual object disappeared during the shutter change phase. Therefore, the participants had to rely on the object brightness they memorized during the observation phase. As [1] pointed out, the perceived change in brightness depends on memory, which could have affected the results. In the future, we plan to conduct a study where the virtual content remains visible to understand how this affects the perceived results.

If participants did not notice any real light dimming at all, ε_r should be around $1/0.396^{0.6} = 1.742$, according to Stevens' Law. In reality, however, even for d = 20s, the obtained evaluation value was less than 1.742 (i.e., $\varepsilon_r = 1.442$). That means that participants of our experiment could notice some dimming of the scene by the LC shutters. While they perceived the scene as being brighter than it actually was, they did not perceive it as being as bright as before the change. In the future, it is necessary to investigate how to achieve this. One possible explanation could be that the duration d was too short, and the participants noticed the change in luminance (cf., [1, 26]). Another possible reason could be that our static environmental situation made the participants sensitive to the brightness changes (cf. previous illumination dimming studies allow participants to move, which is a more natural scenario [1, 26]). For example, since we did not advise the participants to look around, we cannot deny the possibility that some participants stayed still, focused at a point of the scene, and paid attention to brightness changes occurring there.

As described in Section 3.3, we chose to use a linear function as a dimming curve of the LC shutter based on the fact that the shape of the dimming curve does not affect the sensitivity to brightness in the illumination dimming [11, 26]. However, we cannot deny the potential effects of different dimming curves, especially in our OST-HMD scenarios, and therefore it is important to confirm the effects in future studies.

Finally, we used Stevens' Law to compare the expected and perceived brightness change. However, it is unclear if Stevens' Law applies in AR scenarios, where commonly a larger area is being augmented, such as Scene 3 in our experiment. In the future, it is necessary to conduct further experiments to better understand the degree to which brightness adaptations impact OST-HMDs.

Limitations of Prototype OST-HMD. In this prototype, the voltage applied to the liquid crystal was between 1.57 V to 3.53 V, and voltage outside this region resulted in the degraded performance shown in Figure 9. When less than 1.57 V were applied, we observed

(a) 1.37 V (b) 5 V

Figure 9: Turbidity (a) and non-uniformity (b) of the used LCD shutter.

turbidity effects, probably due to diffraction; on the other hand, when more than 3.53 V were applied, we observed non-uniform patterns in the transparency. The range of the applicable transparency could be extended in the future by using a dither pattern on an LC array filter and a time-division system.

Another limitation of our system is that if luminance from the scene reaches the eyes without being attenuated by the LC shutter, e.g., from the sides of the OST-HMD, it could lead to irregular reflections or non-uniform patterns. In preliminary experiments, we noticed that these help users notice changes in the LC transparency.

5 Conclusion

In this paper, we presented a prototype of an OST-HMD with LC visors that can increase the perceived brightness of virtual light while making users less conscious of decreases in the amount of real light. To demonstrate this fact, we formulated the deviation rate ε for real scenes and virtual objects. Our experimental results showed that the decrease in these values was not as large as the decrease in the estimated perceptual brightness based on Stevens' Law due to the change of physical brightness. Our design could be combined with existing and future OST-HMDs to improve the visibility and realism of virtual content in augmented and mixed reality applications with regard to brightness and contrast.

Although we expected a drastic increase in the perceived brightness of the virtual content, we could only verify this effect for small AR augmentations in front of a planar and a static background. It is thus necessary to further investigate how users adapt to brightness changes in OST-HMD AR scenarios.

In the future, we plan to formulate the real and virtual brightness relationship in our visual perception to control real and virtual light effectively. In addition, we will investigate the effects of dynamic backgrounds and a variety of virtual contents comprehensively using better LC visors. Finally, in this study we investigated how users react to dark adaptation in AR scenarios. In the future, we also aim to investigate whether light adaptation could also be used to improve the usability of AR. For example, very bright AR overlays could blind a user who goes from outside into a dark building.

Acknowledgments

This work is partly supported by JSPS Kakenhi Grant Numbers 15H02737, 17K12729 and 17K12726. The authors would like to especially thank Prof. Kiyoshi Kiyokawa for his helpful comments.

References

[1] Y. Akashi and J. Neches. Detectability and acceptability of illuminance reduction for load shedding. *J. of the Illuminating Engineering Society*, 33(1):3–13, 2004.

[2] B. A. Barsky. Vision-realistic rendering: Simulation of the scanned foveal image from wavefront data of human subjects. In *Proc. Symp. on Applied Perception in Graphics and Visualization*, pp. 73–81, 2004.

[3] A. Bermano, P. Brüschweiler, A. Grundhöfer, D. Iwai, B. Bickel, and M. Gross. Augmenting physical avatars using projector-based illumination. *ACM Trans. on Graphics*, 32(6):189:1–189:10, 2013.

[4] P. R. Boyce. *Human factors in lighting, 3rd Edition*. CRC Press, 2014.

[5] J. E. Dowling. *The retina: An approachable part of the brain*. Harvard University Press, 1987.

[6] T. Fukiage, T. Oishi, and K. Ikeuchi. Visibility-based blending for real time applications. In *Proc. IEEE Int. Symp. on Mixed and Augmented Reality (ISMAR)*, pp. 63–72, 2014.

[7] J. L. Gabbard, J. Zedlitz, J. E. Swan, and W. W. Winchester. More than meets the eye: An engineering study to empirically examine the blending of real and virtual color spaces. In *Proc. IEEE Virtual Reality (VR)*, pp. 79–86, 2000.

[8] C. Haig. The course of rod dark adaptation as influenced by the intensity and duration of pre-adaptation to light. *J. of General Physiology*, 24(6):735–751, 1941.

[9] J. D. Hincapi-Ramos, L. Ivanchuk, S. K. Sridharan, and P. Irani. Smartcolor: Real-time color correction and contrast for optical see-through head-mounted displays. In *Proc. ISMAR*, pp. 187–194, 2014.

[10] Y. Hiroi, Y. Itoh, T. Hamasaki, and M. Sugimoto. AdaptiVisor: Assisting eye adaptation via occlusive optical see-through head-mounted displays. In *Proc. Augmented Human Int. Conf.*, pp. 9:1–9:9, 2017.

[11] W. Hu and W. Davis. Dimming curve based on the detectability and acceptability of illuminance differences. *Optics Express*, 24(10):A885–A897, 2016.

[12] H. Hua and C. Gao. Design of a bright polarized head-mounted projection display. *Applied Optics*, 46(14):2600–2610, May 2007.

[13] K. M. K. and P. R. Boyce. Detection of slow light level reduction. *J. of the Illuminating Engineering Society*, 31(2):3–10, 2002.

[14] T. Kawabe, I. Fukiage, M. Sawayama, and S. Nishida. Deformation lamps: A projection technique to make static objects perceptually dynamic. *ACM Trans. on Applied Perception*, 13(2):10:1–10:17, 2016.

[15] T. Kawabe and S. Nishida. Seeing jelly: Judging elasticity of a transparent object. In *Proc. Symp. on Applied Perception*, 2016.

[16] K. Kiyokawa, M. Billinghurst, B. Campbell, and E. Woods. An occlusion-capable optical see-through head mount display for supporting co-located collaboration. In *Proc. ISMAR*, pp. 133–141, 2003.

[17] E. Kruijff, J. Swan, and S. Feiner. Perceptual issues in augmented reality revisited. In *Proc. ISMAR*, pp. 3–12, 2010.

[18] E. H. Land and J. J. McCann. Lightness and retinex theory. *J. Opt. Soc. Am.*, 61(1):1–11, Jan 1971.

[19] T. Langlotz, M. Cook, and H. Regenbrecht. Real-time radiometric compensation for optical see-through head-mounted displays. *IEEE Trans. Vis. Comput. Graph (TVCG)*, 22(11):2385–2394, 2016.

[20] A. Maimone and H. Fuchs. Computational augmented reality eyeglasses. In *Proc. ISMAR*, pp. 29–38, 2013.

[21] A. Maimone, X. Yang, N. Dierk, A. State, M. Dou, and H. Fuchs. General-purpose telepresence with head-worn optical see-through displays and projector-based lighting. In *Proc. VR*, pp. 23–26, 2013.

[22] J. McCann. *Retinex theory*. Springer New York, 2016.

[23] X. Miao. Adaptive brightness control of head mounted display, July 31 2014. WO Patent App. PCT/US2012/057,016.

[24] K. Miyashita and S. Suyama. Welding operation liquid crystal protection mask, Aug. 30 2005. US Patent 6,934,967.

[25] G. R. Newsham, R. G. Marchand, J. M. Svec, and J. A. Veitch. The effect of power constraints on occupant lighting choices and satisfaction: A pilot study. In *The Illuminating Engineering Society of North America*, pp. 115–131, 2002.

[26] T. Shikakura, H. Morikawa, and Y. Nakamura. Perception of lighting fluctuation in office lighting environment. *J. of Light & Visual Environment*, 27(2):75–82, 2003.

[27] S. S. Stevens. *Psychophysics*. Transaction Publishers, 1975.

[28] N. Sugano, H. Kato, and K. Tachibana. The effects of shadow representation of virtual objects in augmented reality. In *Proc. ISMAR*, p. 76, 2003.

[29] M. Tanaka and T. Horiuchi. Perception of gold materials by projecting a solid color on black materials. *Color Research & Application*, 2016.

[30] A. B. Watson and J. I. Yellott. A unified formula for light-adapted pupil size. *J. of Vision*, 12(10):12–12, 2012.

[31] Y. Zhou, J.-T. Ma, Q. Hao, H. Wang, and X.-P. Liu. *A novel optical see-through head-mounted display with occlusion and intensity matching support*, pp. 56–62. Springer Berlin Heidelberg, 2007.