CircadianVisor: Image Presentation with an Optical See-Through Display in Consideration of Circadian Illuminance

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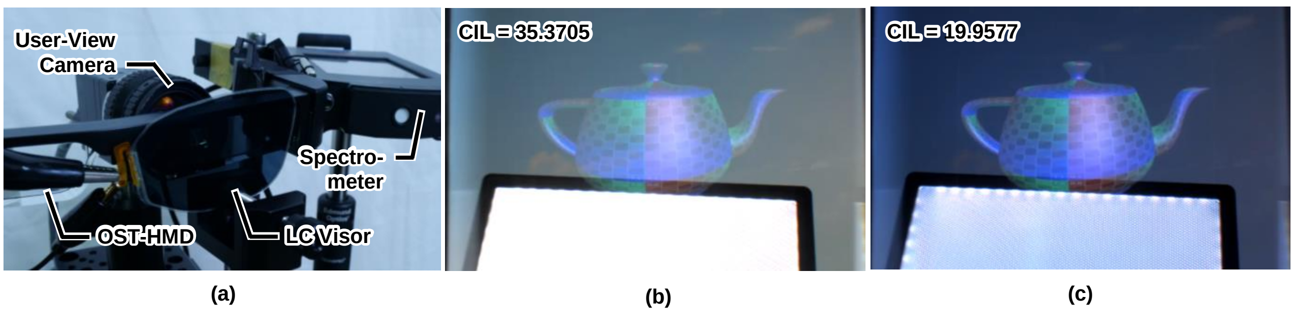

Figure 1: Overview of the Circadian Visor system. (a) The front view of our system. (b,c) Virtual images captured from the user-perspective camera and the corresponding circadian illuminance (CIL) (b) without and (c) with our system. Our system can overlay the virtual image on the real environment while suppressing light in the wavelength band around 555 nm, generally called "blue-light", that has a stronger influence on circadian rhythm by using the liquid crystal (LC) visor.

ABSTRACT

In modern society, the impact of nighttime artificial lighting on the human sleep/wake cycle, or in other words, the circadian rhythm, has long been an important issue. In augmented reality, these health hazards should be prevented if we are to become a society that wears optical see-through head-mounted displays (OST-HMDs) on a daily basis. We present CircadianVisor, an OST display system that controls circadian performance. Our system combines an OST-HMD with a liquid crystal (LC) shutter and a spectrometer to control the circadian illuminance (CIL, biolux) of light incident on the user's eyes. To prevent the CIL at the eyes from exceeding the threshold, correct for the displayed image based on RGB values, and adjust the transmittance of the LC visor to pass through the environment light based on spectral measurements. We build a proof-of-concept system to evaluate the feasibility of the system's CIL control and test it with a spectrometer installed at the user's viewpoint. The evaluation shows that the CIL at the user's viewpoint can be kept below the threshold.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**.

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KEYWORDS

Circadian Rhythm, Blue Light-Blocking Glasses, Augmented Reality, Head-Mounted Displays

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1 INTRODUCTION

This study proposes an optical see-through (OST) display system, CircadianVisor, which optimizes environment light and display images by considering human circadian rhythm.

Modern society is flooded with lights at all hours of the day and night, and this is not an inherently normal state for organisms. Exposure to blue-light in artificial lighting at night is known to disrupt the circadian rhythm, the human sleep/wake cycle (circadian rhythm, Sec. 2.1) [5]. Disruption of the circadian rhythm can cause a variety of health problems, including depression, sleep disorders, and jet lag [6, 9, 20].

In particular, light-emitting diodes (LEDs), which are widely used in modern lighting and displays, contain high levels of blue-light, and exposure to blue-light LEDs at night has been reported to impair cognitive function in the next day [12].

With the development of display technology and the proliferation of portable displays such as smartphones, exposure to blue-light at night is only increasing [18]. Smartphones have been shown to provide more blue-light to the eye than sunlight entering a room on a clear day, depending on the brightness of the smartphone and its proximity to the eye [1].

Optical See-Through Head-Mounted Display (OST-HMD) is a key display technology in Augmented Reality (AR) and is in constant widespread use with the release of high-profile products such as Microsoft Hololens. Because in OST-HMDs the images are projected directly into a person's field of vision, OST-HMDs can have a more severe effect on human circadian rhythm than smartphones.

Light pollution is often overlooked because direct health effects are difficult to see. If OST-HMDs become more widespread and are used by people on a daily basis in the future, these blue-light problems are likely to become more apparent. Looking at the example of smartphones, at least this is an easier problem to imagine than *predicting traffic congestion before the car is invented*[1]. And many of us do not turn off such useful display devices at sunset.

This study thus attempts to counter this issue by providing an OST-HMD system, CircadianVisor, which displays images with controlled circadian illuminance (CIL, biolux [24]. See also Sec. 2.1.), an objective index that affects the circadian rhythm, and examines the goal of a sustainable daily life with regular use of OST-HMD.

This system prevents the CIL at the eye from exceeding the threshold by adjusting the gain of the display image based on RGB values and by attenuating the environment light by a liquid crystal (LC) visor based on spectral measurements.

This study, to the best of our knowledge, is the first study that attempts to control the circadian characteristics of OST-HMD and includes the following major contributions:

- showing the OST-HMD framework to control the displayed image and environment light by focusing on the circadian characteristics.
- building a proof-of-concept system and show that it is possible to control CIL in multiple lighting conditions/AR images.
- providing insights into sustainable OST-HMD use that takes into account circadian rhythms.

2 RELATED WORK

2.1 Circadian Rhythm and Circadian Illuminance

The human circadian rhythm is a sleep/wake cycle during the 24-hour solar cycle, coordinating daily rhythms in the endocrine system which control vital processes for health, including xenobiotic detoxification, cell division, and nutrient metabolism [10].

In 2002, the third type of photoreceptor in the mammalian retina, the Intrinsically-photosensitive Retinal Ganglion Cells (ipRGCs), which are involved in the circadian rhythm, was discovered [3, 11]. Shortly thereafter, it was discovered that ipRGCs contain a photopigment called melanopsin, which is highly sensitive to short-wavelength visible light [2]. Melanopsin suppresses the secretion of melatonin by photosensitizing it, thereby improving human alertness [26]. By exposing the retina to a specific spectrum of light and measuring the amount of melatonin suppression, the action spectrum of melatonin suppression can be determined. This biological action curve is called the circadian spectral sensitivity function ($C(\lambda)$) and peaks in the 450-480 nm wavelength region [4, 8, 15, 21, 22].

[1] "It is easy to predict an automobile in 1880; it is very hard to predict a traffic problem", Isaac Asimov, Social Science Fiction, 1953

Circadian illuminance (CIL) is a parameter obtained by the inner product of the spectral power distribution (SPD) with $C(\lambda)$ of light [17, 23]. This parameter corresponds to the melatonin suppression value (MSV), and its influence on the circadian rhythm can be quantitatively assessed by measuring the CIL of the environment light [14, 17, 18, 24, 25, 27]. In other words, suppression of CIL can help to prevent adverse effects on circadian rhythms.

2.2 Circadian Illuminance by Proximity Displays

Because the illuminance of a display increases with the distance between the object and the eye, the impact of proximity displays, such as smartphones, on the circadian rhythm is significant.

Oh et al. evaluated the CIL and MSV of three commercial smartphones when used at night [18]. They reported that using a smartphone in a bright room at night significantly increased CIL and MSV levels in the range of 58.7-105.2 biolx and 15.4-36.1%, respectively, and this CIL level significantly reduced melatonin secretion. On the other hand, using a smartphone at the right distance and brightness settings in a dark room can bring MSV below about 1%, they said, concluding that simply turning off the smartphone is not the only way to deal with it.

Kim et al. investigated the effects of VR and AR display use on circadian rhythms [14]. They showed that environment light was more likely to affect the circadian rhythm in AR devices compared to VR displays. They attributed this to the relatively narrow area of exposure to the eye.

In light of these studies, it may be possible to reduce the effect of proximity displays on circadian rhythms by adjusting the brightness of the display content while controlling the circadian illuminance of the environment light.

2.3 Static Circadian Illuminance Control

The intensity of the frequency bands that affect the circadian rhythm are known and peak in the blue wavelength region, as described in the previous section. Therefore, uniformly cutting this region is a relatively easy solution, and countermeasures are generally widespread.

For example, blue light-blocking glasses block the blue-light in the field of vision. However, these methods of blocking the entire action spectrum of the circadian spectral sensitivity function significantly change the color appearance of the field of vision, making it impossible to recognize blue objects. The entire action spectrum cannot be blocked when changes in color vision are suppressed. Depending on the intensity of the lighting and the distance to the lighting, the circadian illuminance to the eye can increase, which can affect the circadian rhythm.

Although the blue-light reducing features of computers and smartphones limit the blue display color intensity depending on the time of day, eventually the influence of the surrounding lighting environment is inevitable.

Therefore, to effectively limit circadian illuminance, it is necessary to measure or predict the circadian illuminance to which a person is exposed and then adaptively control the light that enters the eye.

2.4 Adaptive Circadian Illuminance Control

Displays and glasses exist that adaptively control the light entering the eye.

Hiroi et al. proposed AdaptiVisor [13], a real-time dynamic range correcting see-through system consisting of a transmissive LCD and OST-HMD. Their system uses a transmissive LCD to reduce the brightness of a too bright field of view and an OST-HMD and a scene camera to superimpose a video see-through image on a portion of the field of view that is too dark to stabilize the brightness change in the field of view. Although the idea of dimming the glare is similar, it only considers constant visual illuminance, not control based on circadian illuminance.

Ota et al. proposed a system that allows multiple users in the same environment to experience different lighting environments by time synchronizing indoor lighting and multiple shutter glasses [19]. Although their study can dynamically control illuminance, the main focus is on ensuring that each user has their own preferred lighting environment. Also, as the number of lights in the environment increases, the number of lighting pairs to choose from is limited. Also, it would not work without a dedicated lighting device in the environment.

Mori et al. proposed a system to attach LC shutters and Illuminometer to OST-HMD to increase the perceived brightness of the displayed images [16]. Although their study appears to be similar to ours in that they use liquid crystal shutters and OST-HMD, the objectives and methodology are all different. Their research measures only the illuminance value (lux) of the environment light and also specializes only in increasing the relative brightness of the display image. Our research aims to suppress the influence of OST-HMD on human circadian rhythms, and we measure the spectral power distribution the environment light to control shutter transmittance and display images in terms of circadian illuminance.

3 PARAMETERS FOR CIRCADIAN PERFORMANCE EVALUATION

In this paper, we aim to present a virtual image by combining the OST-HMD and the LC visor while keeping the user's perceived circadian illuminance below a certain value. Before describing our system, we introduce the parameters that describe the relationship between the physical quantity of light entering the human eye and its circadian properties. Previous studies [14, 17, 18, 24, 25, 27] have defined circadian action factor (CAF) and circadian illuminance (CIL) as measures of the relationship between incident light entering the eye and human circadian perception. Based on [24], we introduce below how to derive these parameters.

The photopic luminous function $V(\lambda)$ represents the sensitivity of the human eye to the brightness of each wavelength of light. In contrast, the circadian spectral sensitivity function $C(\lambda)$ represents the sensitivity of melanopsin in the retina to the brightness of each wavelength of light, which affects the human circadian rhythm. In this paper, we use Gall's model as $C(\lambda)$ [8].

Figure 2 shows the normalized spectral sensitivities of $V(\lambda)$ and $C(\lambda)$. As shown in Fig. 2, $C(\lambda)$ has a peak in the 450-480 nm, while $V(\lambda)$ has a peak at 555 nm. This wavelength range between 450-480 nm, which has high circadian sensitivity, is generally referred to as "blue-light".

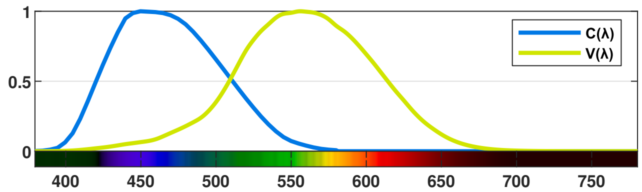

Figure 2: Spectral Sensitivity of $C(\lambda)$ and $V(\lambda)$. The color of each line is a spectral value converted to RGB using D65/2° observation function.

Luminous efficacy of radiation (LER) is a measure of how well a light source produces visible light and is defined as the ratio of the luminous flux to the radiant flux. Let $S(\lambda)$ be the spectral power distribution (SPD) of the light measured by a spectrometer. LER is calculated by weighting SPD with the $V(\lambda)$ to represent the efficiency of the human eye's view as

$$LER\ (\text{lm/W}) = 683\ (\text{lm/W}) \cdot \frac{\int S(\lambda)V(\lambda)d\lambda}{\int S(\lambda)d\lambda} \tag{1}$$

Similarly, circadian efficiency of radiation (CER) is a measure of the effect on human circadian sensitivity when a given lighting device emits light at a given energy, defined as the ratio of the circadian flux to the radiant flux. As with LER, CER is the SPD weighted by the circadian ratio visual sensitivity function as

$$CER\ (\text{biolm/W}) = 683\ (\text{lm/W}) \cdot \frac{\int S(\lambda)C(\lambda)d\lambda}{\int S(\lambda)d\lambda} \tag{2}$$

where biolm is the unit for the amount of circadian flux.

CAF is defined as the ratio of CER to LER and represents the circadian sensitivity per unit of visual response:

$$CAF\ (\text{biolm/lm}) = \frac{CER\ (\text{biolm/W})}{LER\ (\text{lm/W})} = \frac{\int S(\lambda)C(\lambda)d\lambda}{\int S(\lambda)V(\lambda)d\lambda} \tag{3}$$

For example, if we considers an illumination with high spectral power around 450-480 nm, the CER will be larger than the LER, resulting in a larger CAF. Hence, this illumination has a larger effect on human circadian rhythms.

CIL is the total circadian flux incident on a unit area of the surface and is defined as the product of visual illuminance (VIL) and CAF. In other words, CIL is a psycho-physical quantity used to measure how much the lighting illuminating a surface of a unit area affects the circadian rhythm:

$$CIL\ (\text{biolx}) = VIL\ (\text{lx}) \cdot CAF\ (\text{biolm/lm}) \tag{4}$$

VIL is a value measured by an illuminometer and can also be derived from SPD:

$$VIL\ (\text{lx}) = c \cdot \int S(\lambda)V(\lambda)d\lambda \tag{5}$$

where c is a constant value and can be derived by substituting the measured VIL and SPD into this equation. CIL can also be calculated by Eq. (3), Eq. (4) and Eq. (5):

$$CIL\ (\text{biolx}) = c \cdot \int S(\lambda)C(\lambda)d\lambda \tag{6}$$

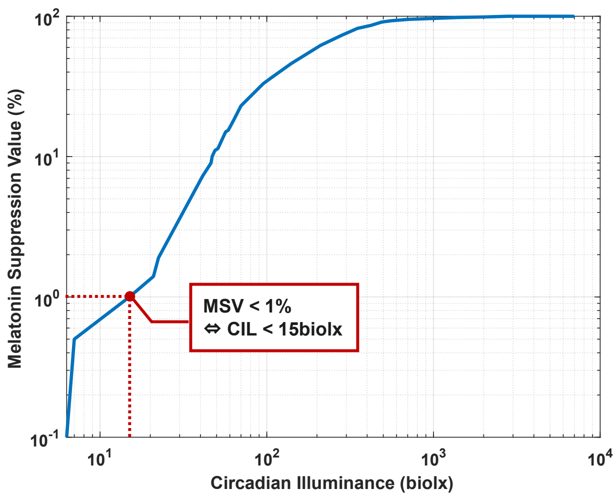

Figure 3: The relationship between MSV and CIL [24].

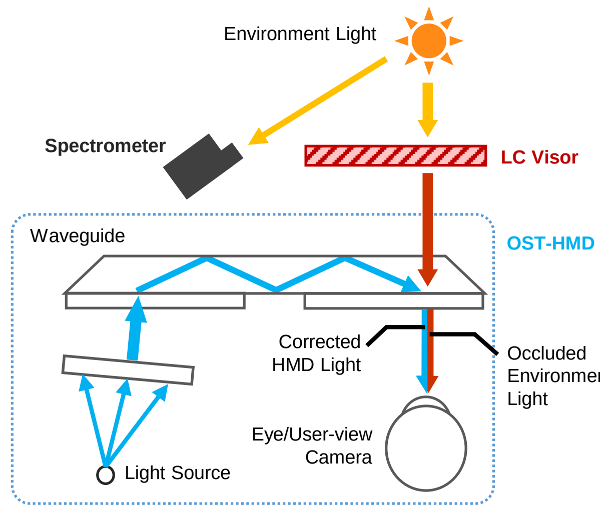

Figure 4: Schematic diagram of our proposed system.

CIL is positively correlated with melatonin suppression value (MSV), and is an important parameter in considering circadian performance. The higher the CIL of light, the greater the suppression of melatonin secretion and the stronger the effect on circadian rhythm.

The relationship between MSV and CIL is shown in Fig. 3 [24]. Figure 3 shows MSV after 1 hour of light exposure [7]. When the CIL of light is less than 15 biolx, MSV is less than 1% and little or no melatonin suppression occurs.

Therefore, when constructing a system that takes circadian performance into account, it is a reasonable requirement to keep the CIL at the eye below 15 biolx. The goal of the CircadianVisor system is to control the virtual image and the transmittance of the LC visor so that the CIL of the light reaching the user's eyes is less than 15 biolx as well.

4 CIRCADIANVISOR

4.1 System Overview

Figure 4 shows a schematic diagram of our system. First, the SPD of the environment light is measured by a spectrometer placed near the eye. In the current setup, we assume that the environment light is uniformly spread. In other words, the SPD measured by the spectrometer is assumed to be equal to the SPD of the environmental light incident toward the user's eye. This environment light is then attenuated by the LC visor controlled by a certain duty cycle calculated by the system, which is described in Sec. 5.1. After that, corrected HMD light is added to the attenuated environment light, then the light reaches the eye.

4.2 Control of OST-HMD with the LC Visor

Our goal is to control the decay rate of the virtual image and the LC visor's attenuation rate so that the CIL of light reaching the eye throughout the entire system is kept below a target CIL threshold β_e (biolx). As discussed in Sec. 3, we assume $\beta_e = 15$ (biolx).

Figure 5 shows the algorithm for controlling the decay rate of the virtual image and the attenuation rate of the LC visor. Our algorithm consists of the following procedures:

(a) Estimate the SPD of the light actually reaching the eye from the OST-HMD for each decay rate based on the virtual image's RGB values (Sec. 4.2.1).
(b) Determinate the virtual image's decay rate so that the CIL threshold of the virtual image is not exceeded (Sec. 4.2.2).
(c) Estimate the SPD of the light passing through the LC visor at each duty cycle by multiplying the environment light's SPD by the transmittance spectra of the LC visor (Sec. 4.2.3).
(d) Determinate the LC visor's duty cycle so that the threshold of the CIL of the eye is not exceeded by adding the SPD of the environment light passing through the LC visor and the SPD of the virtual image (Sec. 4.2.4).

In our algorithm, the virtual image's RGB values are decayed by a uniform rate. When decaying only the blue value, we can replace the decay rate in the method described in Sec. 4.2.1 with the one for blue value.

We use shutter glasses as the LC visor and is controlled by pulse-width modulation (PWM). Thus the transmission rate of the LC visor is determined by the duty cycle. When other occlusion-capable elements (e.g., a transmissive LCD or a DMD) are used, a similar method can be applied by measuring the relationship between the pixel value and the attenuation rate as described in Sec. 4.2.3.

The CIL threshold β_v for light from the OST-HMD is set to any value less than or equal to the CIL threshold β_e for total light reaching the eye. The larger β_v is, the brighter the virtual image becomes and the darker the environment light becomes. The reason for setting β_v and β_e instead of setting the CIL threshold of the virtual image and the environment light separately is that the CIL of the OST-HMD is small and usually does not exceed the threshold, which allows the environment light to be brighter. If the CIL thresholds of the virtual image and the environment light are set separately, or if the CIL threshold of the environment light is set to match the CIL

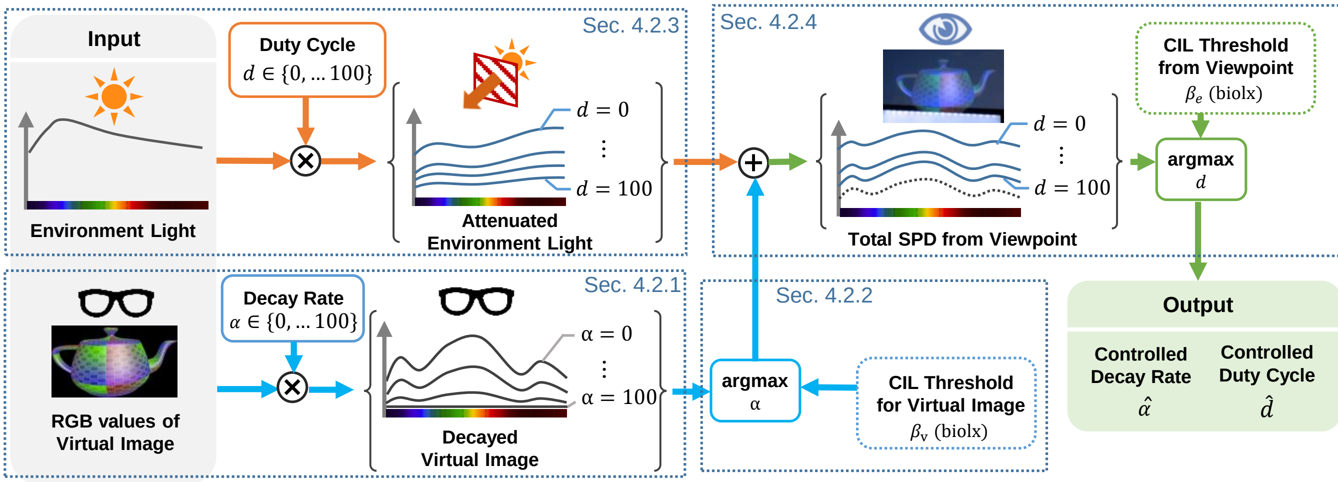

Figure 5: Algorithm for controlling the decay rate of the virtual image and the attenuation rate of the LC visor

of the virtual image to keep them in constant balance, this can be achieved by slightly modifying the method described in Sec. 4.2.2 and Sec. 4.2.4.

4.2.1 Estimation the SPD of a virtual image. First, we estimate the SPD of the virtual image presented on the OST-HMD for each decay rate from the RGB value per pixel of the virtual image.

We denote the SPD of the virtual image as $SPD_v(c, n, \lambda)$, where c is a color channel (i.e., $c \in \{R, G, B\}$), n is a 8-bit pixel value ($n = 0, \ldots, 255$) and λ is wavelength. For example, $SPD_v(R, 255, \lambda)$ represents the SPD of the virtual image when the RGB values of all pixels are set to (255, 0, 0).

$SPD_v(c, n, \lambda)$ is measured by varying all the pixels of the virtual image from $n = 0$ to 255 in each channel of R, G, and B. Note that to simplify the calculations, we assume that the light presented in OST-HMD is independent of each channel and that the SPD of the RGB-mixed light is represented as the sum of the SPD of each channel. With the above, we obtain $3 \times 256 = 768$ kinds of $SPD_v(c, n, \lambda)$.

$n_{ijc}(\alpha)$ denotes the value at pixel (i, j) in a channel c of the decayed virtual image. The RGB values of the virtual image displayed on OST-HMD is decayed by a uniform rate for all pixels and all channels:

$$n_{ijc}(\alpha) = \alpha \cdot n_{ijc} \tag{7}$$

where n_{ijc} is the RGB values of the virtual image before correction and α is the decay rate of the virtual image ($\alpha = 0, \ldots, 100$ (%)).

Using $SPD_v(c, n, \lambda)$, we estimate the SPD of entire virtual image $\overline{SPD}_v(\alpha, \lambda)$. $SPD_v(c, n, \lambda)$ is measured as the result of filling all the pixels of a virtual image with the same RGB value, thus the SPD of each pixel is calculated by dividing it by the total number of pixels. The SPD of the virtual image is estimated by adding up this SPD for all pixels and all channels:

$$\overline{SPD}_v(\alpha, \lambda) = \sum_{j=1}^{H} \sum_{i=1}^{W} \sum_{c \in \{R,G,B\}} \frac{SPD_v(c, n_{ijc}(\alpha), \lambda)}{WH} \tag{8}$$

where W and H are the width and height of the image, respectively.

4.2.2 Determining the decay rate of virtual image. Next, based on the virtual image's SPD, the decay rate α is determined to keep the CIL of the virtual image below β_v (biolx).

The CIL of the light entering the eye $CIL_v(\alpha)$ can be calculated by Eq. (6):

$$CIL_v(\alpha) = c \cdot \int \overline{SPD}_v(\alpha, \lambda) C(\lambda) d\lambda \tag{9}$$

The predicted decay rate $\hat{\alpha}$ is determined as the maximum $CIL_v(\alpha)$ that does not exceed β_v:

$$\hat{\alpha} = \underset{\alpha}{\operatorname{argmax}} \, (CIL_v(\alpha) \leq \beta_v) \tag{10}$$

4.2.3 Estimating the SPD of light passing through the LC visor. Next, we estimate the SPD of the light passing through the LC visor for each duty cycle from the LC visor's transmittance spectra.

Let $\alpha(d, \lambda)$ denote the transmittance spectra of the LC visor, where d is the duty cycle given to the LC visor ($d = 0, \ldots, 100$ (%)). To measure $\alpha(d, \lambda)$, we prepare a reference light whose SPD is given by $SPD_{ref}(\lambda)$, and measure the SPD of the light passing through the LC visor $SPD_{trans}(d, \lambda)$ at different duty cycles. Then $\alpha(d, \lambda)$ can be calculated as follows:

$$\alpha(d, \lambda) = \frac{SPD_{trans}(d, \lambda)}{SPD_{ref}(\lambda)} \tag{11}$$

Let $SPD_{env}(\lambda)$ be the SPD of the environment light measured by the spectrometer. Using the pre-calculated $\alpha(d, \lambda)$, the SPD of the environment light after passing through the LC visor $\overline{SPD}_{pass}(d, \lambda)$ can be calculated as follows:

$$\overline{SPD}_{pass}(d, \lambda) = \alpha(d, \lambda) \cdot SPD_{env}(\lambda) \tag{12}$$

4.2.4 Determining the duty cycle of the LC visor. Finally, based on the SPD of the virtual image and environment light, the duty cycle d is determined to keep the CIL of the light reaching the eye below β_e (biolx).

We denote the SPD of the light reaching the eye as $\overline{SPD}_{eye}(d, \lambda)$. $\overline{SPD}_{eye}(d, \lambda)$ is given as the sum of the light emitted by the virtual image and the environment light that passed through the LC visor:

$$\overline{SPD}_{eye}(d, \lambda) = \overline{SPD}_{pass}(d, \lambda) + \overline{SPD}_v(\lambda) \tag{13}$$

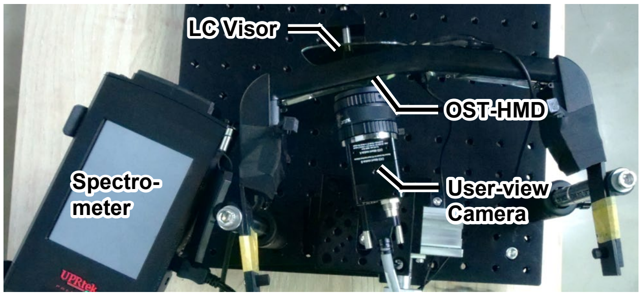

Figure 6: Hardware Setup

Similar to Sec. 4.2.2, the CIL of the light entering the eye $CIL_{\text{eye}}(d)$ can be calculated:

$$CIL_{\text{eye}}(d) = c \cdot \int \overline{SPD}_{\text{eye}}(d, \lambda) C(\lambda) d\lambda \tag{14}$$

The predicted duty cycle $\hat{d}$ is determined as maximum $CIL_{\text{eye}}(d)$ that does not exceed β_e:

$$\hat{d} = \underset{d}{\text{argmax}} \left(CIL_{\text{eye}}(d) \leq \beta_e \right) \tag{15}$$

5 TECHNICAL SETUP

We describe the hardware and software setup and preliminary tests to measure each of the parameters described in Sec. 4.2.

5.1 Hardware and Software Setup

Figure 6 shows the hardware setup. Our system consists of an Epson Moverio BT-30C (resolution: 1280 x 720 pixels, FOV: diagonal 23deg) as an OST-HMD, an LC visor (Root-R RV-3DGBT1), and a spectrometer (UPRtek MK350N Premium). All devices are connected to the same Windows 10 computer (Intel Core i5-7200U CPU 2.50 GHz, 8 GB RAM). The LC visor is connected to the computer via an Arduino Uno, which provides PWM as its analog output. Thus, the LC visor's transmittance is specified in a duty cycle. We set the PWM frequency to 80Hz. To obtain images from a viewpoint through the OST-HMD and LC visor, we installed a user-perspective camera (Ximea MC023CG-SY-UB) placed behind the left optical element of the display. All measurements were performed in a dark room to prevent noise effects due to environmental light.

5.2 Measurement of parameters to control OST-HMD and LC visor

To control the decay rate of the virtual image and the duty cycle of the LC visor, we need to measure the values of the parameters mentioned in Sec. 4.2: $SPD_{\text{v}}(c, n, \lambda)$ and $\alpha(d, \lambda)$. In the following, we show the results of preliminary experiments to measure each parameter. In the preliminary tests, a spectrometer was installed at the user's viewpoint to measure the SPD at the eye.

5.2.1 SPD of virtual images. We first measure the values of $SPD_{\text{v}}(c, n, \lambda)$. In this preliminary test, we vary all the pixels of OST-HMD from $n = 0$ to 255 in each channel of R, G, and B and measure the SPD at the eye. Figure 7 shows the results of the measurement for each channel. The measurement results are used as $SPD_{\text{v}}(c, n, \lambda)$, and the SPD of the virtual image can be estimated by Eq. 8.

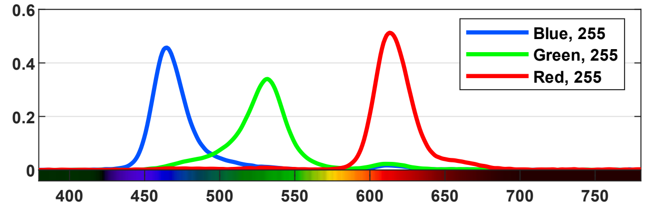

Figure 7: SPD of the OST-HMD in each channel: $SPD_{\text{v}}(B, 255, \lambda)$, $SPD_{\text{v}}(G, 255, \lambda)$ and $SPD_{\text{v}}(R, 255, \lambda)$.

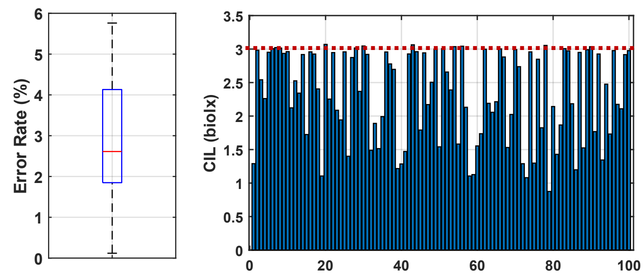

Figure 8: (left) Error rate between estimated and measured CIL of the virtual images. (right) Measured CIL of light from OST-HMD (β_v=3(biolx)).

To show the estimation's reliability, we displayed 100 random images on the OST-HMD and compared the estimated and measured CIL values at the eye. For the random images, we picked a random value selected from 0 to 255 and then added a random value from -128 to 128 as an offset for each pixel of each image. The value is trimmed to the range of [0,255] if the resulted value exceeds the range. We set up such uniform random images because the spectrometer's aperture is small, and the influence on the measured value is different for inner and outer pixels. Figure 8(left) shows the error rate between measured and estimated CIL values. The error rate is less than 5.8%, indicating that the virtual image's SPD estimation is reliable.

Similarly, we display 100 random images on the OST-HMD and set β_v to 3 biolx to show that our algorithm can prevent the CIL of the virtual image from exceeding the threshold. Figure 8(right) shows the measured CIL values when 100 random images were corrected, and it can be seen that the correction was able to keep the CIL of the light from the OST-HMD below β_v.

5.2.2 Transmittance of the LC visor. We then derive the values of $\alpha(d, \lambda)$. In this preliminary test, we prepare a reference light whose SPD is given by $SPD_{\text{ref}}(\lambda)$, and measure the SPD of the light passing through the LC visor $SPD_{\text{trans}}(d, \lambda)$ while varying the duty cycle d from 0% to 100%. Figure 9 shows the transmittance spectra at each duty cycle of the LC visor, calculated by Eq. 11. Note that, in this preliminary test, we place the OST-HMD that does not display anything, so the measured SPD is smaller than the LC visor only because the light also passes through the optical elements of the

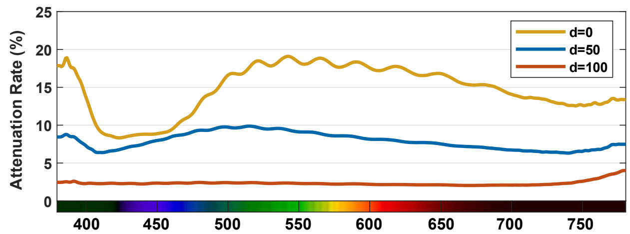

Figure 9: Transmittance spectra of LC visor per duty cycle

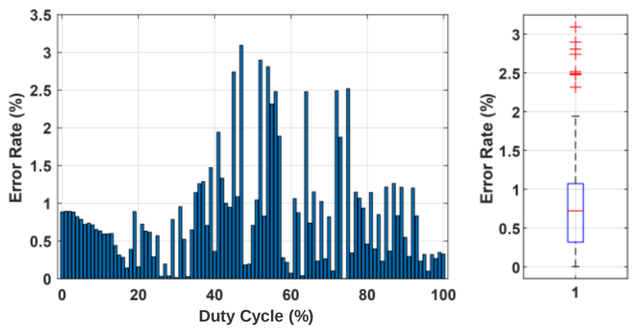

Figure 10: Error rate between estimated and measured CIL of passing light per duty cycle.

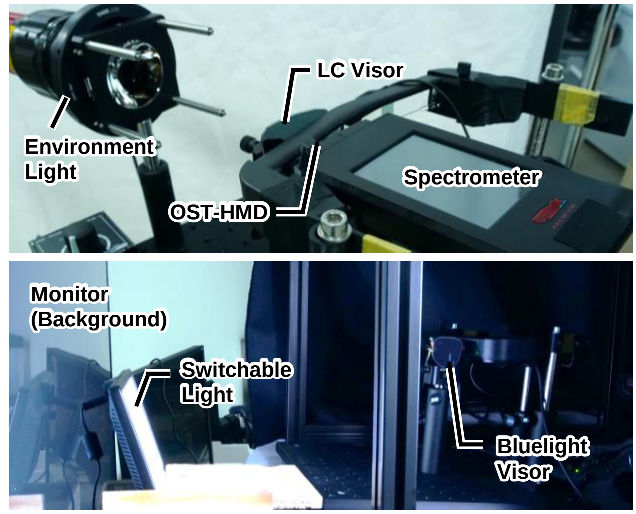

Figure 11: Experiment setups. (top) Setup for the static experiment. (bottom) Setup for the dynamic experiment and the comparison experiment with the illuminometer.

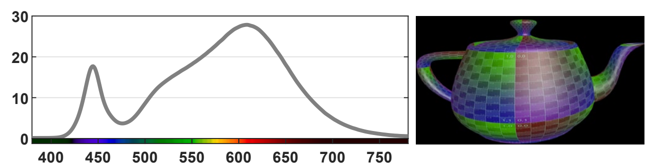

Figure 12: (left) The example of SPD for the environment light used in static experiments (Light condition (c) in Fig. 13, CIL=513.757 (biolx)). The environment light used in the other conditions is multiplied by a constant gain in all wavelengths with the SPD shape intact. (right) The virtual image displayed on the OST-HMD throughout the experiment.

OST-HMD. The derived results of $\alpha(d, \lambda)$ are used to estimate the SPD of the passing light by Eq. 12.

To show the estimation's reliability, we varied the duty cycle from 0% to 100% in the appropriate environment light. We then both estimate and measure the CIL of the passing light. Figure 10 shows the error rate between estimated and measured CIL values. The error rate is less than 3.1%, indicating that the SPD estimation of the passing light at each duty cycle is reliable.

6 EXPERIMENTS

We conducted three experiments to evaluate our proof-of-concept system. A static experiment quantitatively assessed whether the system suppressed the CIL of light entering the eye below a certain value in a controlled environment (Sec. 6.2). A dynamic experiment evaluated the proof-of-concept system's latency under dynamic lighting conditions (Sec. 6.3). A comparison experiment evaluated the effectiveness of our system in comparison to the methods of controlling the LC visor using an illuminometer [16] (Sec. 6.4).

6.1 Experiment Setup

Experiment setups are shown in Fig. 11. In static experiments, the spectrometer was placed at the user's viewpoint to evaluate the CIL of the light reaching the eye (Fig. 11, top). THORLABS MWWHLP1 was used for environment light, and an LED driver (THORLABS LEDD1B) was used to control the brightness of the environment light. The SPD of the environment light is measured in advance and applied to control the LC visor.

In both dynamic experiment and comparison experiment with the illuminometer, we installed a monitor as the background scene and Viltrox L116T as an external light source to be switched (Fig. 11, bottom). In the dynamic experiment, to evaluate our system's response, the external light source is switched on and off. In the comparison experiment, to compare with the illuminance meter configuration, the SPD of external light is adjusted to be red-leaning and blue-leaning by switching its color temperature. The monitor is installed about 50 cm away from the user-view camera. The user-view camera exposure is fixed throughout the experiment to ensure that comparisons between different conditions are fair.

6.2 Static Experiment Result

Firstly, to verify the system's static performance, we measured the CIL of light from the user's viewpoint by changing the transmittance of the LC visor using our method. The intensities of the environment light were set at 6 different brightness levels (Fig. 12, left). The virtual image displayed on the OST-HMD is a teapot image (Fig. 12, right).

The experiment results are shown in Fig. 13. The CIL at the viewpoint exceeds the threshold of 15 biolx without controlling

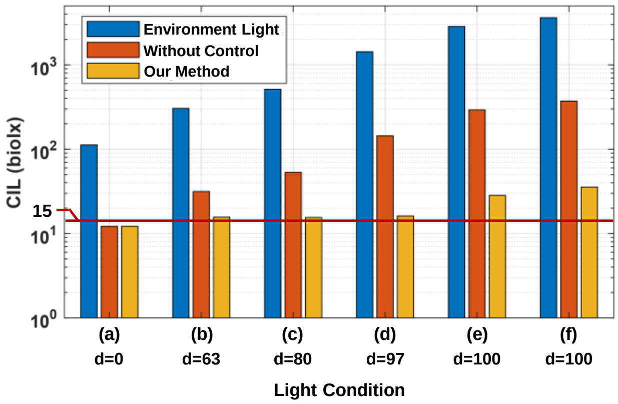

Figure 13: CIL of environment light in different static lighting environments, CIL of light entering the eye without our system and with our system. The red line indicates the target threshold (15 biolx). d **indicates the duty cycle of the LC visor under each condition.**

the LC visor. By controlling the LC visor according to our method, however, the CIL is kept near 15 biolx. However, if the environment light is bright enough to cause the duty cycle of the LC visor to reach 100%, the CIL will exceed the threshold of 15 biolx (Fig. 13 (e)(f)). Since the CIL of light incident on the eye from artificial lighting at night in daily life is at most a few hundred biolx, this result indicates that this system has sufficient performance to suppress the effect on circadian rhythms.

6.3 Dynamic Experiment Result

Although the system operates in real-time, there is a certain delay between the change in environment light brightness and the LC visor's control. To evaluate our system's dynamic response, we recorded user-view image sequences while switching the external light source on and off. After that, we set up a spectrometer at the viewpoint position under the same conditions and measure statically to obtain the time variation of CIL. The reason for using a user-view camera instead of the spectrometer to measure the temporal changes of this system is that the frequency of the spectrometer measurement is too low to evaluate the dynamic response. For each recording sequence, we set the external light sources off at first, then on, and finally back to off.

Figure 14 shows the time variation of the CIL of the incident light at the viewpoint. Looking at the CIL on the viewpoint after the LC visor is controlled, it is suppressed to 15biolx after switching external light (Fig. 14 c). From the result, our proof-of-concept system can adequately suppress the CIL even in a dynamic environment.

Immediately after the external light source is turned on and off, the duty cycle of the LC visor does not change. This causes the CIL of the light entering the eye to become 35.37biolx, which exceeded the threshold after the external light source is turned on (Fig. 14, b) and the LC visor to excessively occluded the environment light after the external light source is turned off (Fig. 14, d).

These results indicate that changes in environment light will affect circadian rhythms and visibility due to the system's latency. However, as mentioned in Sec 3, MSV is the value after 1 hour of light exposure, thus the effect of the delay on the circadian rhythm is small. Since daily nighttime lighting rarely changes brightness at high frequency, the time average of CIL is not expected to change significantly. If the system is to be applied to such an environment where the brightness changes frequently, it would be effective to use a time-varying control method in which the CIL threshold is reduced for a certain time based on the CIL of the eye and delay time when the CIL threshold is exceeded.

System delays have a larger impact on visibility loss. In order to investigate the relationship between delay and visibility, subjective user experiments are considered necessary in the future. One possible way to improve the visibility caused by such delay is gradual changes in the LC visor's duty cycle [16]. By gradually changing the environment brightness, the user will be less aware of the change.

One possible way to improve the visibility caused by such delay is gradual changes in the LC visor's duty cycle. By gradually changing the environment brightness, the user will be less aware of the change.

6.4 Comparison with a Configuration with an Illuminometer

We compared the method of controlling the light incident to the eye by using an illuminometer with our method and evaluate the advantages of using a spectrometer.

6.4.1 Method with an illuminometer. First, we describe the algorithm to control the LC visor based on the CIL when measuring environment light using an illuminometer. In this algorithm, we do not consider the correction of virtual images to focus on the control of environment light. First, the VIL of the light passing through the LC visor at each duty cycle is estimated by multiplying the VIL of the external light by the attenuation rate of the LC visor at each duty cycle. Next, the VIL for each duty cycle is converted to CIL. Finally, the duty cycle is determined so that the CIL threshold at the eye is not exceeded.

The data required by this algorithm is the attenuation rate of the VIL of the LC visor at each duty cycle and the ratio of the VIL to the CIL. The assumption is that when the SPD is blue-leaning, the CIL of the eye is higher than when the SPD is red-leaning (Fig. 15, top). However, the SPD of environment light cannot be measured when using an illuminometer. Therefore, to evaluate the CIL of the eye with the illuminometer, it is necessary to control the LC visor, assuming that the environment light has a blue-leaning SPD.

The attenuation rate of the VIL of the LC visor at each duty cycle is derived by replacing the SPD with the VIL in the method described in Sec. 4.2.1. The SPD of the reference light was set to the blue-leaning light as shown in the Fig. 15(top). Figure 15(bottom) shows the measurement results of the LC visor's attenuation rate. By using the same sample light, we obtain the ratio of the VIL to the CIL. The VIL of the sample light is 33.71 lx and the CIL of that is 26.10 biolx, so the conversion from VIL to CIL is done by multiplying VIL by 0.7743. These data were used to control the LC visor in the configuration of the illuminometer.

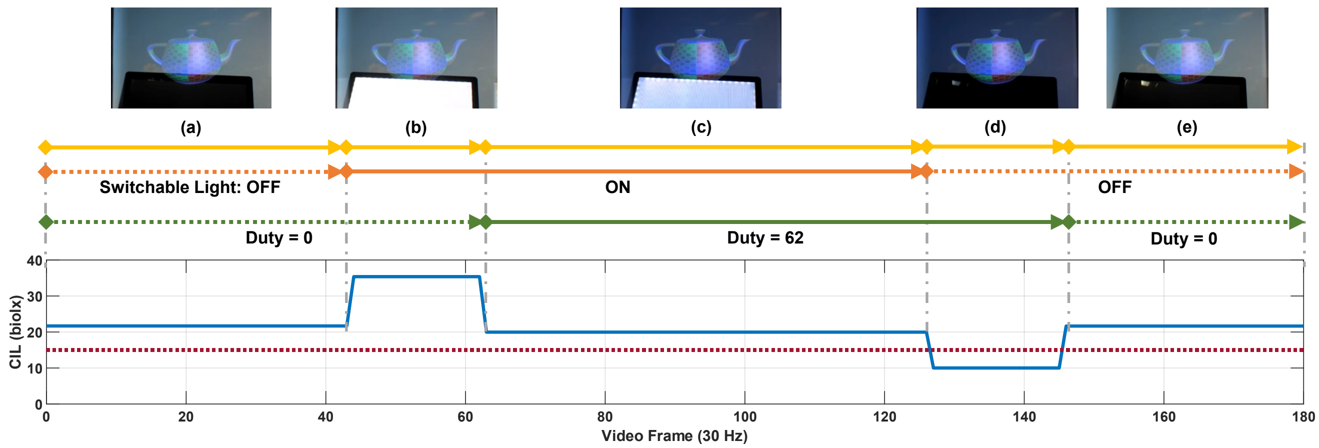

Figure 14: Overview of the dynamic experiment in Sec. 6.3

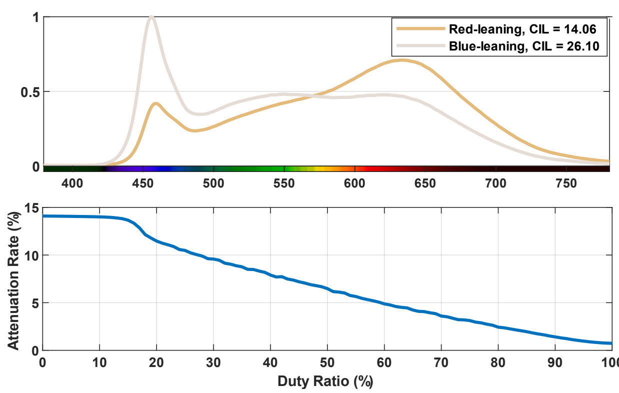

Figure 15: (top) The SPD and CIL of sample light sources with red- and blue-leaning temperature settings. The VIL of both light sources is equal (VIL=33.71 (lx)). The color of each line is SPD converted to RGB using D65/2° observation function. (bottom) The relationship between the duty cycle and the attenuation rate of VIL when sample light sources, the environment light, is set to blue-leaning temperature.

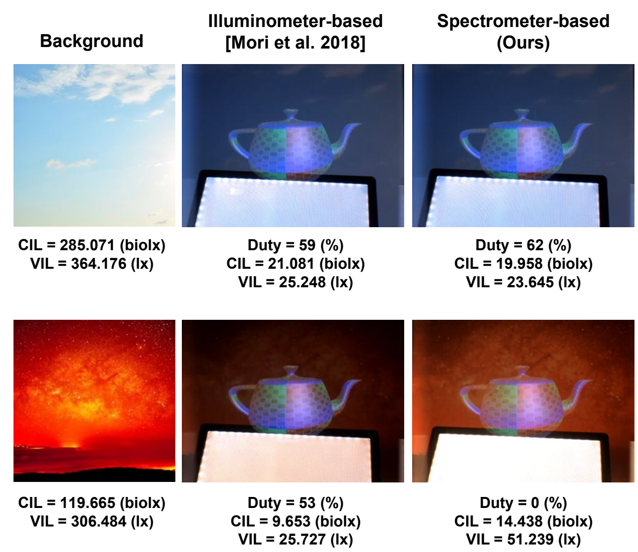

Figure 16: (From left to right) the background image displayed on the monitor in the comparison experiment, the viewpoint image with the illuminance-based control, and the spectrometer-based control. The CIL and VIL for each observation are shown below each image. (top) Results when the background color is blue-leaning and (bottom) the background color is red-leaning. Since the illuminometer method is calibrated on a blue background, the illuminometer-based approach makes the real world appear excessively dark on red backgrounds to reduce CIL.

6.4.2 Comparative experiments with an illuminometer. We compared the spectrometer's configurations and the illuminometer when the SPD of environment light was set to blue- and red-leaning, respectively.

The results are shown in Fig. 16. The results show that the CIL is below the target threshold for all environment light and sensor setup. On the one hand, when the environment light is red-leaning, the VIL of light entering the eye is 25.727 lx in the illuminometer setup. On the other hand, it is 51.239 lx in the spectrometer setup, indicating that the VIL of light entering the eye is 1.992 times brighter in the spectrometer. This is because the illuminometer setup assumes that environment light is blue-leaning, so the LC visor's transmittance needs to be greatly reduced to suppress CIL. The above shows that the spectrometer-based setup can present a more stable brightness to the user in any environment light with any SPD.

7 DISCUSSIONS AND LIMITATIONS

While the CirdianViosor system successfully demonstrated our concept, there is much room to improve it for more practical systems that considers circadian rhythms. We describe below issues with our current system and future research directions.

7.1 Controlling the LC Visor

In the current system, we control the LC visor by PWM for the ease of setting the duty cycle by a development board. Since the LC visor has a certain delay between applying the voltage and the end of the transmittance change, the transmittance spectra of the LC visor becomes unstable when the PWM frequency is set high. To mitigate the effect, we can set the PWM frequency lower, yet the user will feel a flicker due to the longer interval between the voltage on and off. In a practical system, therefore, we should avoid PWM and apply an analog voltage value by mapping the value to the LC visor's transmittance spectra.

7.2 Low Latency System

Our current system has a delay of roughly about 1900msec. This delay is due to the spectrometer's measurement frequency, the serial communication between the C++ program and the Arduino Uno, and the calculation loop for the SPD estimation of the light from the OST-HMD and the light passing through the LC visor. As described in Sec. 6.3, the delay in brightness change is inconvenient for the user, which is an issue that needs to be solved to make the CircadianVisor system practical. The prime source of the above delays is serial communication, which causes 1200msec of delay, which is due to the unoptimized serial communication library in C++. Optimizing the serial communication or applying better interfaces such as serial peripheral interface and ethernet connection would drastically improve this latency. Additional solutions to improve the latency is to optimize the code and switching to a higher performance development board.

7.3 Changing the Color of Virtual Images and Environment Light

In our system, we uniformly attenuate the spectra of the virtual image and the environment light to reduce the effect of light on the circadian rhythm. Another effective way to reduce the effect of light on the circadian rhythm is to change the color by attenuating the action spectral region of the circadian spectral sensitivity function. The problem with this method, as described in Sec. 2.3, is that if we block all the blue spectral region, blue-light information will be missing, and if we set a constant block rate for the blue region, the CIL at eyes will exceed the threshold depending on the brightness of the virtual image and environment light. Thus, when introducing color changes into our system, it is reasonable to implement a uniform light attenuation according to the blue region's block rate so that the CIL does not exceed the threshold. For this implementation, it is necessary to consider changing the spectrum of the virtual image and the environment light and how much change is acceptable.

7.4 Use throughout the Day

To keep the circadian rhythm, our system reduces the suppression of melatonin secretion by keeping the CIL of the eye at night below a threshold value. When we consider using this system throughout the day, we must consider the light that enters the eyes during the daytime. Suppressing melatonin secretion during the daytime is important for circadian rhythms because suppressing melatonin secretion during the daytime enhances its secretion at night [14]. In other words, optimal CIL values at the eyes for circadian rhythms differ between nighttime and daytime. If the system is designed to keep the eye exposed to the optimal CIL values at different times of the day, it could help regulate circadian rhythms regardless of the light in the environment.

8 CONCLUSION

We proposed an OST display system, CircadianVisor, to optimize environment light and display images by considering human circadian rhythm. Our system combines an OST-HMD with a spectrometer and an LC visor to adjust the environment light in terms of the CIL. We control the attenuation rate of the LC visor and the decay rate of the virtual image by estimating the CIL of the light incident on the eyes based on the SPD of the environment light measured by the spectrometer and the RGB values of the virtual image.

Our quantitative evaluation showed that our system can suppress the CIL of the eye to a maximum of 16.21 biolx by setting the CIL threshold to 15 biolx when the environment light is below a few hundred biolx, the value of common artificial lighting. The corresponding melatonin suppression value for this CIL value is about 1%, indicating that it has little effect on circadian rhythms.

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