https://doi.org/10.2352/issn.2169-2629.2020.28.6

Relationship between perceived room brightness and light source appearance mode in different media: reality, virtual reality and 2D images

Ching-wei Lin*[*1], Peter Hanselaer[1], Kevin A.G. Smet[1]
[1] KU Leuven, TELEMIC/Light&Lighting Laboratory, BELGIUM
chingwei.lin@kuleuven.be

Abstract

The appearance mode of an object, whether it appears self-luminous or reflective, depends on its luminance and its surrounding. This research aims to verify whether the appearance mode of a spherical lamp ("on" / "off") and perceived room brightness is influenced by the presentation medium: real 3D scenes (R-3D), rendered virtual 3D scenes (VR-3D) presented on a head-mounted-display (HMD) and 2D scenes presented on a regular display (D-2D). Twenty observers evaluated the lamp's appearance mode when presented in different luminance values and rated the apparent room brightness of the scene under four viewing conditions: R-3D and D-2D with warm-white scene lighting, and D-2D and VR-3D with cool-white scene lighting. Threshold luminance, defined as the luminance corresponding to a 50-50 chance of perceiving a lamp as switched on, showed large observer variability, which might originate from the diversity of the observers' understanding of the lamp material and their strategy to judge the appearance mode. Respectively, threshold luminance and room brightness were significantly lower and significantly higher for the virtual reality scene than for the other conditions. However, no evidence was found that the appearance mode of a spherical lamp can relevantly predict room brightness.

Introduction

Accurate evaluation of room brightness is important for interior lighting design, as a good design ensures that the lighting is neither too dark nor too bright. A room which is too bright wastes energy, while a room which is too dark creates discomfort. Nowadays, international standards for interior lighting design are based on illuminance. However, people don't perceive illuminance directly, but rather perceive brightness, which is the result of various visual processing stages to take the effect of viewing conditions into account. It has been found that the luminance distribution in a room changes the required working plane illuminance to achieve equal room brightness perception [1]. It remains therefore unclear to what extent illuminance based design can accurately predict perceived room brightness.

The impact of viewing conditions on brightness, is clearly illustrated by, e.g. the much higher perceived brightness of a candle flame at night than under daylight conditions, the clear difference in the visibility of the stars during day-time and night-time or the more difficult viewing of display content outdoors than indoors. The latter example, also illustrates another important, related effect: the impact of viewing conditions on appearance mode. When objects have a relatively low brightness compared to their surrounds, they tend to appear in reflective mode, while at sufficiently higher levels they appear self-luminous. For colored objects, there is an intermediate stage, at which they appear 'fluorent', to use a term coined by Evans [2]. Given the well-known, but much less understood, interaction between viewing conditions and object luminance on its appearance mode, it is worth considering whether this relationship can be exploited to predict room brightness from estimates of the transition point from reflective to self-luminous or fluorent appearance modes.

One of the first to investigate this were Yamaguchi and Shinoda, who tested the relationship between the appearance mode of a flat gray object and perceived 'room' brightness of a small-scale mock-up [4]. They defined "border luminance", in this paper referred to as "threshold luminance", as the luminance of the flat object when its appearance mode changes from normally reflective to "不自然な" (a Japanese term that refers to 'a situation that cannot be true in normal conditions'). In their study, 4 observers judged the threshold luminance of a 12 × 15 mm Munsell N6.25 paper, which was set at the middle of a 36 × 45 × 25 cm mock-up of a room. Unfortunately, the field of view nor the viewing distance was mentioned in the paper. According to their results, threshold luminance of the flat paper was not only proportional to the illuminance of the mock-up but also to the room brightness of the mock-up. Furthermore, threshold luminance evaluations were consistent among observers. An equation of threshold and room brightness was proposed, with which, they concluded that threshold luminance can predict room brightness.

However, further study is necessary to verify the impact of viewing conditions on perceived room brightness evaluation and on the threshold luminance. First, according to previous research from Kato and Sekiguchi, room brightness evaluations made by observing a small-scale mock-up of a room differ from those obtained from within an actual full-scale room [5]. Therefore, Yamaguchi's study, based on a mock-up, probably cannot be applied to immersive viewing conditions, which is more common and more important for lighting design than non-immersive viewing conditions. Second, a 3D object has a more complex geometry than a flat surface, such that it is more likely to be more impacted by spatial non-uniformity of the room lighting through e.g. shading, multiple specular highlights, luminance gradients, etc. Thus, a 3D object is expected to offer additional information of the surroundings and illumination conditions compared to a flat object.

Virtual reality technology and images on a display have been applied in room brightness research. Whether the media affects the brightness perception has been studied either by using rendered scenes [6] or by using pictures taken from a real room [7]. Some indicated no difference between a real room and images on a display [7], while others pointed to significant differences [6]. Also, brightness perception from a virtual reality room tends to be lower than in a real room [7]. The impact of media on room brightness is still unclear.

In this study, Yamaguchi's concept of threshold luminance is applied to a spherical lamp, as such a spherical geometry maximally integrates the illumination conditions in different regions of the scene. Evaluations and perceived room brightness ratings were made using three presentation media, with different levels of immersiveness: a real 3D scene (R-3D), 3D renderings of the real scene presented in a VR-HMD (VR-3D) and 2D images of the real room shown on a regular display (D-2D). This study aims to verify the influence of the presentation medium on threshold luminance of a spherical lamp and on perceived room brightness.

Methods

Experimental setup(s)

The scene in all three presentation media was a simple neutral room with blank grey walls, a single ambient illumination source in the ceiling and a uniform spherical white translucent matte lamp serving as the threshold luminance stimulus. The spherical lamp was illuminated from the inside by a dimmable 3500 K warm-white LED (Xicato XTM19803520CCA) and had a field-of-view of 10° from the observer's viewing position. The correlated color temperature (CCT) of the ambient illumination in the real room was 2800 K (u' = 0.2588, v' = 0.5210).

The real 3D scene was simulated in the game-engine Unreal Engine 4 and displayed on an Oculus Rift CV1 head-mount-display (HMD). The ambient illumination and stimulus in the 3D rendered virtual reality scene was set to a cool-white of approximately 6700 K (u' = 0.1940, v' = 0.4638), the white point of the HMD. The stimulus size was again 10°, while that of the scene was limited by the HMD to approximately 110°. For the 2D display presentation medium, images were taken of the real scene from the observer's eye position with a luminance camera (TechnoTeam LMK4) and then color corrected to have either the same warm-white (ww) or cool-white (cw) ambient illumination (i.e. background wall chromaticity) as those in the real and virtual scenes, respectively. During the experiments, these color corrected images were presented on a calibrated high-quality 32-inch display (EIZO CG3212) with the observer position being such that the scene's horizontal field of view was 62° and that of the stimulus was 10°. Images of the 4 conditions (wwR-3D and wwD-2D, and cwD-2D and cwVR-3D) are shown in Figure 1. All colorimetric values reported for the real and 2D display scenes were obtained from spectral measurements with a JETI specbos1211L spectroradiometer, while those for the 3D VR-HMD scenes were obtained with a TechnoTeam LMK5-color colorimetric imaging camera. The average luminance, CCT and D_{uv} of the background wall near the spherical lamp are given in Table 1. The luminance ranges achievable for the spherical lamp under the four conditions, as well as the mean CCT and D_{uv} of the threshold-luminance stimulus is given in Table 2.

Observers

Twenty observers (10 male, 10 female) with normal color vision (tested by the Ishihara 24 plate test) and with ages ranging from 23 to 43 years old, participated in this experiment.

Procedure

At the start of the experiment observers were given written instructions on the experiment procedure. All conditions were presented to the observers twice during a single experiment session, which lasted about 5 to 10 minutes. Prior to starting the first test in each viewing condition, observers were allowed to adapt to the viewing conditions for at least 3 minutes (Figure 2). Viewing conditions were arranged across observers using a 4-by-4 counter-balanced Latin square design, as shown in Table 3. Observers were equally divided into groups with similar gender and age distribution.

Table 1: Mean luminance *L*, CCT, D_{uv}, *u'* and *v'* values of the background wall near the spherical lamp

	wwR-3D	wwD-2D	cwD-2D	cwVR-3D
L_{mean} (cd/m^2)	7.74	8.12	8.13	6.73
CCT_{mean} (K)	2567	2650	7127	7075
$D_{uv\ mean}$	-0.003	-0.001	0.004	0.005
u'_{mean}	0.2694	0.2651	0.1945	0.1940
v'_{mean}	0.5259	0.5265	0.4624	0.4638

Table 2: Luminance ranges, and mean CCT, D_{uv}, *u'* and *v'* values measured at the center of the spherical lamp

	wwR-3D	wwD-2D	cwD-2D	cwVR-3D
L range (cd/m^2)	17-167	17-160	16-164	5-92
CCT_{mean} (K)	2806	2857	8627	6848
$D_{uv\ mean}$	-0.003	-0.001	0.014	0.001
u'_{mean}	0.2589	0.2563	0.1805	0.1978
v'_{mean}	0.5208	0.5223	0.4579	0.4631

Table 3: Four-by-four counter-balanced Latin square design, with the gender and min, max and mean ages of the observers for each cell.

Group	Conditions presented				Gender		Age		
	1st	2nd	3rd	4th	M	F	min	max	mean
A	wwR	wwD	cwVR	cwD	2	3	23	42	30.4
B	wwD	cwD	wwR	cwVR	3	2	23	42	30.4
C	cwD	cwVR	wwD	wwR	3	2	24	43	30.8
D	cwVR	wwR	cwD	wwD	2	3	23	41	31.2

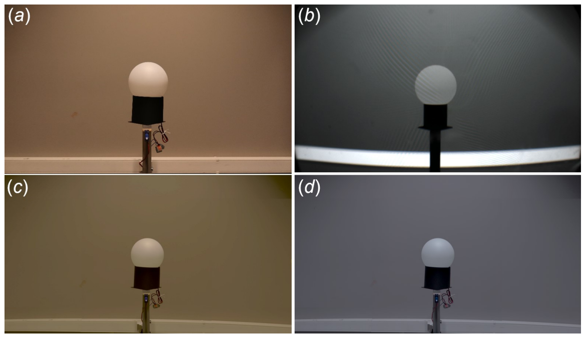

Figure 1. *Examples of the scene and threshold-luminance stimulus in all viewing conditions. (a): wwR-3D (b): cwVR-3D (this photo was distorted by the lens of the luminance camera when taking it.) (c): wwD-2D (d): cwD-2D.*

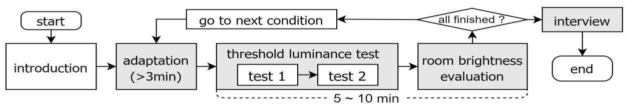

Figure 2. *Experimental procedure*

Threshold luminance was determined using the method of limits (staircase). In a staircase method, an observer is shown a starting stimulus (in this study: a very high luminance stimulus in order to avoid anchoring effects) on which he/she has to make a binary decision (in this study: "lamp on" or "lamp off"). After making a decision, the observer is presented with the next trial stimulus luminance, whose value depends on the answer given to the previous stimulus ("on": decrease luminance, "off": increase luminance). Between two stairs, the luminance difference between the two stimuli is decreased until the smallest difference is reached. After the smallest differences, reached in the 4th stair in the experiments, four more stairs, the 5th to the 8th, were presented to converge the luminance to a final value. Each observer completed two tests for each condition with 8 stairs in each test. The luminance difference between two stairs was assigned by a random number. (Figure 3 shows an example.)

After the two threshold luminance tests, a shutter blocked the lamp. Each observer judged the room brightness (without seeing the lamp) for each condition on a 7-point scale ranging from very-dark (-3) to very bright (+3).

Threshold luminance and threshold brightness logistic regression analysis

In the analysis, the probability of an average observer rating a "switched-on" lamp, *p(on)* was determined by pooling all data in the two tests of all observers together and performing a logistic regression (using a logit function) for each condition:

$$p\,(\text{on}) = 1 / (1 + e^{-(\beta 0 + \beta 1\, L)}) \qquad (1)$$

Threshold luminance L_{thres}, defined as the 50-50 probability that the lamp is evaluated as switched on, can then be determined as:

$$L_{\text{thres}} = -\,\beta 0/\beta 1 \qquad (2)$$

A similar regression was also done for each individual observer, resulting in individual logit functions and threshold luminance values for each of the conditions.

Since the CIE 1964 10° absolute tristimulus values X_{10}, Y_{10} and Z_{10} are not available with the colorimetric imaging camera, the latest color appearance model for self-luminous stimuli (CAM18sl) cannot be applied [8]. Brightness values Q of each stimulus were calculated based on Steven's law with a one-third power [9]:

$$Q = L^{1/3} \qquad (3)$$

Similar to threshold luminance, threshold brightness Q_{thres} of an average observer and each individual observer for each condition were determined using logistic regression.

Analysis of the impact of presentation medium and CCT

The impact of media and CCT on threshold brightness and perceived room brightness ratings was investigated using two Friedman Tests applied to the four conditions.

Result

Threshold luminance and threshold brightness

In this study, 20 observers judged whether the spherical lamp looked switched-on or switched-off under four different conditions. By pooling the data, average and individual L_{border} values are determined for each condition using logistic regression. The 20 logistic regression curves (thin colored lines) of the 20 observers, as well as the one for the average observer (thick black line) are plotted in Figure 4 for each condition (subgraphs a-d). The histogram of the threshold luminance values for these observers were plotted at the top. Q_{thres} was determined in a similar way and is presented in Figure 5. Table 4 and Table 5 list the means, medians, standard deviations, and the interquartile range (IQR) of all observers' L_{thres} and Q_{thres} in each condition, respectively. L_{thres} and Q_{thres} of the average observer are listed, too. The results show that L_{thres} has a positively-skewed distribution for all conditions, and that they varied considerably between observers. Since the distributions are non-symmetric, the coefficient of variation (CV), which is based on the standard deviation, is a biased measure of the inter-observer variability. Therefore, the ratio of the IQR and median was used instead (see Table 4 and 5). Q_{thres} is closer to a normal distribution than L_{thres}, but its distribution for the wwD-2D condition is significantly non-normal ($p = 0.040$, Shapiro-Wilk test). Therefore, a non-parametric Freidman test was therefore applied and significant ($p < 0.001$) threshold brightness differences among the four conditions were detected. A post hoc analysis, with the Wilcoxon-Nemenyi-McDonald-Thompson test [10], revealed that Q_{thres} in the cwVR-3D was significantly lower than in the other three conditions and that cwD-2D was significantly lower than wwR-3D (Figure 6). The same non-parametric test and post hoc analysis revealed that L_{thres} in the cwVR-3D was significantly lower than in the other three conditions (Figure 7). No other differences between conditions could be detected.

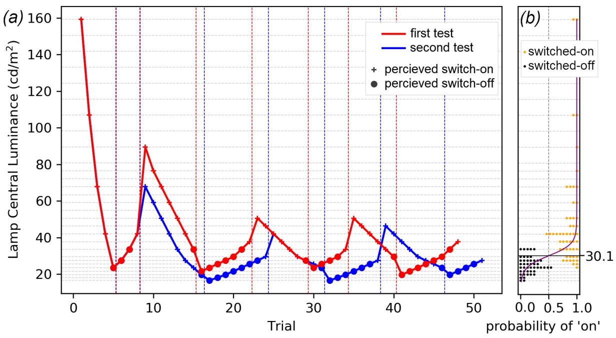

Figure 3. *(a) Trials and responses of one observer in the two repeat tests (red and blue respectively) for condition wwR-3D. +: observer perceived switch-on lamp, ●: observer perceived switched-off lamp. Vertical dashed lines indicate the change between stairs. Horizontal dashed gray lines present all lamp central luminance values applied in this study.*
(b) Distribution of on- and off-counts as a function of luminance of this observer for wwR-3D. The purple line is the logistic regression curve, and the threshold luminance is therefore determined as 30.1 cd/m².

Table 4: Statistical values of L_{thres} and inter-observer variability in each condition (n = 20, unit: cd/m²)

Condition	L_{thres} (each observer)				L_{thres}	inter-
	Mean	Median	Std. dev.	IQR $Q_3 - Q_1$	(average observer)	(IQR / Median)
wwR-3D	37.4	32.3	20.5	19.3	36.8	0.60
wwD-2D	35.7	30.0	18.5	16.4	35.0	0.55
cwD-2D	29.0	26.2	10.0	11.0	29.0	0.42
cwVR-3D	16.5	12.7	9.6	16.6	15.7	1.30

Table 5: Statistical values of Q_{thres} and inter-observer variability in each condition (n = 20)

Condition	Q_{thres} (each observer)				Q_{thres}	inter-
	Mean	Median	Std. dev.	IQR $Q_3 - Q_1$	(average observer)	(IQR / Median)
wwR-3D	3.26	3.16	0.53	0.62	3.25	0.20
wwD-2D	3.22	3.13	0.50	0.55	3.20	0.18
cwD-2D	3.01	2.97	0.38	0.43	3.03	0.15
cwVR-3D	2.43	2.31	0.49	0.87	2.42	0.38

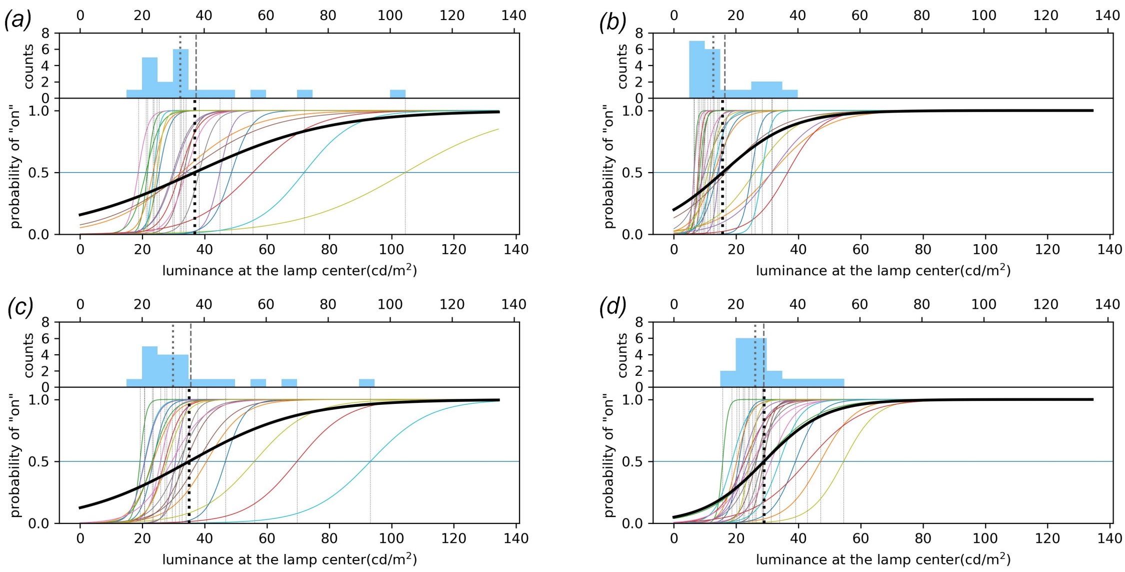

Figure 4. *Logistic regression curves and the histogram of their 50% threshold (threshold luminance) distributions of each observer for each condition. (a): wwR-3D (b): cwVR-3D (c): wwD-2D (d): cwD-2D. In the regression plot, each thin colored curve represents one observer, while the thick black curves are based on the pooled data from all observers (average observer). Vertical gray lines and black dotted line show the threshold luminance of each observer and the average observer, respectively. In the distribution plots, the dashed lines represent the mean, while the dotted lines represent the median.*

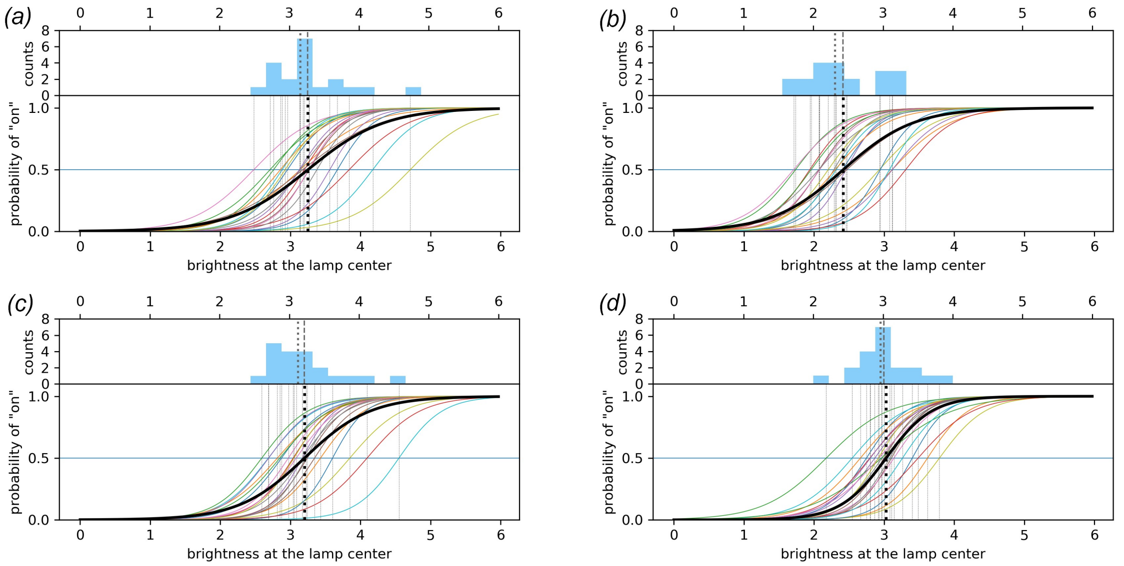

Figure 5. *Logistic regression curves and the histogram of their 50% threshold (threshold brightness) distributions of each observer for each condition. (a): wwR-3D (b): cwVR-3D (c): wwD-2D (d): cwD-2D. In the regression plot, each thin colored curve represents one observer, while the thick black curves are based on the pooled data from all observers (average observer). Vertical gray lines and black dotted line show the threshold luminance of each observer and the average observer, respectively. In the distribution plots, the dashed lines represent the mean, while the dotted lines represent the median.*

Room Brightness

At the end of the experiment for each condition, observers evaluated the room brightness on a -3-to-3 7-point scale. Means, medians, standard deviations, and standard errors on the ratings for each condition are listed in Table 6. The table includes the IQR/median ratio as a measure of inter-observer variability. A Shapiro-Wilk test indicated that the data was not normally distributed. A non-parametric Friedman test was therefore applied, which detected a significant (p = 0.001) difference in perceived room brightness between the four conditions. Post hoc comparisons, similar as the ones for threshold brightness, indicated that the room in the cwVR-3D condition is perceived significantly brighter than in the cwD-2D and the wwD-2D conditions. Furthermore, although perceived room brightness values for cwVR-3D were substantially higher than for wwR-3D, no significant difference could be detected. There were no significant differences between the wwR-3D, wwD-2D and cwD-2D conditions (Figure 8).

Table 6: Statistical values of perceived room brightness and inter-observer variability in each condition (*n* = 20)

Condition	Mean	Median	Std. dev.	IQR $Q_3 - Q_1$	inter- (IQR / Median)
wwR-3D	- 0.20	- 1.0	1.24	2.0	- 2.0
wwD-2D	- 0.65	- 1.0	0.88	1.0	- 1.0
cwD-2D	- 0.20	- 0.5	1.20	2.0	- 4.0
cwVR-3D	0.65	1.0	1.23	2.0	2.0

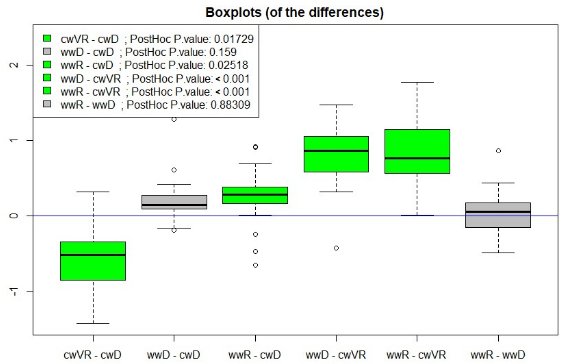

Figure 6. *Post hoc comparison for* Q_{thres} *including the boxplot of the threshold brightness differences for each condition pair and the post hoc p-values. Green: the pairs with significant difference (p < 0.05)*

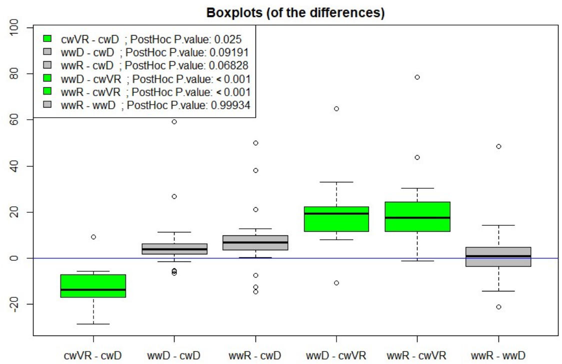

Figure 7. *Post hoc comparison for* L_{thres} *including the boxplot of the threshold luminance differences for each condition pair and the post hoc p-values. Green: the pairs with significant difference (p < 0.05)*

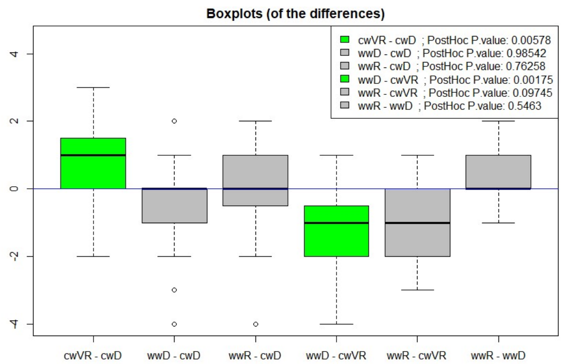

Figure 8. *Post hoc comparison for perceived room brightness including the boxplot of the perceived brightness differences for each condition pair and the post hoc p-values. Green: the pairs with significant difference (p < 0.05)*

Discussion

Comparison to the state-of-the-art

This study focuses on the threshold luminance L_{thres} and threshold brightness Q_{thres} of a spherical lamp, respectively defined as the luminance and brightness corresponding to a 50-50 percent chance of perceiving the lamp as switched on. For the current study, L_{thres} of the spherical lamp was found to have a positively skewed distribution with a very large spread compared to the quite small range of values reported for the flat object in Yamaguchi's study [4]. The large spread was consistently found in our all pilot experiments [11]. Some possible reasons for the discrepancy are listed below.

First, the inconsistency is probably due to the diversity of observers' strategies and their understanding of the lamp material, as suggested by the responses and comments in a short interview with each observer after the experiment. Nine of the twenty observers mentioned that they used the spatial brightness uniformity of the lamp as a hint to make a judgment. Since the spherical lamp has a more complex geometry than a flat surface, its appearance is more heavily impacted by the spatial non-uniformity of the room lighting than a flat piece of paper. An example of the differences in spatial brightness uniformity between the dark (less spatially uniform) and bright (more spatially uniform) lamp conditions is illustrated in Figure 9. When spatial brightness uniformity is sufficiently low, i.e. when there were clearly visible differences between the top and bottom due to shading differences, these nine observers used this as a cue that the lamp is switched off. On the other hand, increasing the lamp luminance increasingly masked these shading differences, so that at a certain point the lamp appears sufficiently uniform to have it judged as switched on. Contrary to spatial brightness cues across the lamp surface, nine other observers reported using the contrast between the lamp and the background (wall) as a hint. The lamp looked switched-on for them when the contrast was large. Two observers compared the lamp with a reference brightness: one chose the horizontal white bar in the scene as the reference brightness, while the other chose the gray wall. Both these two sets of observers used spatial brightness contrast, either across the lamp surface or with the surround, to evaluate whether its brightness was consistent with a lamp that is switched on or switched off.

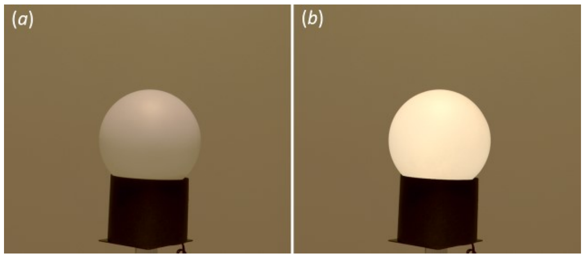

Figure 9. *The appearance of a dark lamp and a bright lamp. (a): LED current 0.25 mA, central luminance 17.4 cd/m*^{2} *(b): LED current 6 mA, central luminance 66.4 cd/m*^{2}

Single observers sometimes also used several hints to judge the appearance of the lamp. One observer used the color of the lamp as a second hint besides its spatial uniformity: a more yellowish lamp is switched on while a grayish lamp is switched off. Another used the contrast to the wall and the texture of the lamp and noticed that the lamp appears rough when it's dark, while it appears smooth when it's bright. In contrast, not all the applied strategies in this study could have possibly been used by Yamaguchi's observers. For example, the spatial luminance uniformity of a flat object changes less with its luminance, and it is unlikely that observers in Yamaguchi's study use it as a hint. This reduced the diversity of observers in Yamaguchi's study and can be one reason to explain the discrepancy in the size of the threshold luminance variability. Moreover, the understanding of the material of the lamp can be different from one observer to another. Everyone knows the appearance of a flat paper while observers were not familiar with the lamp used in this study before the experiment. Some observers complained it's difficult for them to judge the lamp without knowing the material. One observer reported that the lamp can be interpreted as a switched-on gray lamp or a switched-off white lamp at the same time. With these differences in their strategies and their understanding of the materials, the threshold luminance value of the spherical lamp can vary substantially from one observer to another. However, with the relatively small amount of observers in this study, the threshold luminance difference between observers with different strategies could not be determined.

From the results, there is no indication that a spherical object is more relevant or useful than a flat object to evaluate room brightness, despite it providing a more integrated impact of the overall illumination in a room. Secondly, the discrepancy may also have been caused by the two different experimental designs. In the current study, an immersive real room setup was used to evaluate room brightness, while a non-immersive small scale mock-up was used in Yamaguchi's study. To investigate the possible impact of non-immersive viewing conditions, a 2D display setup was also used. However, no significant differences were found between the wwR-3D and wwD-2D conditions, indicating that immersiveness versus non-immersiveness did not lead to significantly different threshold luminance (brightness) values.

Effect of CCT and medium

In this study, a lamp in cwVR-3D was found to be perceived as "turned on" at substantially lower luminance values than in reality or when presented as an image on a display. This phenomenon is likely due to one of several reasons. First, the virtual reality scene in this study was rendered using a game-engine, which does not use physical based rendering, nor allows for input of realistic spectral reflectance spectra and bi-directional reflectance distributions, luminaires with specific light-intensity-distributions, etc. To the best the materials could be rendered given these limitation, the shading differences of the virtual lamp were more easily masked by the luminance increase than in the other conditions, i.e. it looked more uniform than others at the same luminance level. Since some observers used the spatial brightness uniformity of the lamp as a hint to judge the lamp is switched-on or switched-off, this uniformity might have led them to perceive the lamp is switched on. Second, the lens in the HMD leads to color dispersion at the edge of the lamp, which offers a 'bloom' effect. This may have biased observers into perceiving or interpreting the lamp as turned-on. Third, the chromaticity difference between the lamp and the wall is slightly less in VR-3D than the other conditions. However, the design of this study did not allow to identify the effect from these three hypotheses separately; further studies are therefore required to verify them one by one.

Normally, an object at low to moderate luminance tends to be perceived as reflective instead of self-luminous in a brighter room. However, in this study, the virtual room was perceived brightest among all conditions but the lamp was more easily perceived as switched-on. This is inconsistent with Chen's result [7]. This difference is possibly caused by some disparity between the rendered virtual reality scene and the others, possibly due to the presence of the dark surround around the entire scene because of the limited field-of-view in the HMDs. Stimuli with a dark surround tend to be perceived as brighter.

Conclusion

This research studies the appearance mode of a spherical lamp, i.e. whether it looks switched-on or switched-off, depending on its luminance. The luminance of the lamp when its appearance mode changes is named 'threshold luminance', which was assumed to be correlated to the room brightness. This experiment aims to verify the impact of the presentation medium on threshold luminance and on perceived room brightness. It compared four viewing conditions including a warm-white real scene, a series of warm-white images on a 2D display, a series of cool-white images on the same display, and a cool-white virtual reality scene. The threshold luminance distribution was positively skewed with very large variations for all conditions. By converting to brightness based on Steven's law with a one-third power, threshold brightness was estimated and approximately followed a normal distribution (except for one condition) with a large variation. This variation may have been caused by the diversity of observers' strategy to judge the appearance mode and their understanding/interpretation of the lamp material. Commonly used hints were the spatial luminance uniformity (internal brightness contrast) of the lamp and the contrast between the lamp and its background (external brightness contrast).

The study revealed two significant differences between the virtual reality scene and the others. The threshold brightness – calculated from the threshold luminance using Steven's law – and perceived room brightness in the virtual reality scene were respectively significantly lower and higher than in the other conditions. This is probably due to the disparity between the rendered VR scene and the others, such as the presence of a dark surround (due to the limited field-of-view) in the HMD, which could have increased the overall perceived scene brightness (Stimuli with a dark surround tend to be perceived as brighter). Other possible reasons are differences in the spatial luminance uniformity of the rendered lamp, the 'bloom' effect caused by the HMD lens and the slight chromaticity difference between the rendered lamp and its background.

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