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Influence of Subjective Impressions of a Space on Brightness Satisfaction: an Experimental Study in Virtual Reality

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ABSTRACT

This paper investigates the relationship between participants' satisfaction with brightness and other key perceptual attributes of the scene to gain insight in how user satisfaction with brightness is influenced by factors other than brightness levels. In this study, a total of 100 participants were immersed in an office space using virtual reality (VR). The brightness level in all immersive scenes were held constant while the office shading system's design pattern, rendering materials, and furniture were varied to examine how different factors influence the participants' satisfaction with brightness. Statistical analyses indicate that there is a strong association between participants' satisfaction with brightness and other perceptual attributes. Additionally, while the effect of furniture on brightness satisfaction was not statistically significant, the analyses revealed that colored materials had a significant effect on participants' evaluations of their satisfaction with brightness.

Author Keywords

Daylight; brightness; perception; preference; immersive virtual reality.

1 INTRODUCTION

Light has an undeniable influence on our perception of space, as recognized in the fields of architecture [1]–[3] and of lighting [4]–[6]. The design of the luminous conditions in a space aims to address the needs of the occupants, and substantial research effort is devoted to identifying the characteristics of ideal lighting conditions for different social situations and for various tasks. In the case of work environments, lighting is used to ensure that workers can perform their tasks quickly, accurately and easily [7].

In one study people were asked to freely describe the lighting in an office-like room and brightness was the second the most commonly used attribute [8]. Interestingly, the most commonly used description was that the lighting in the room was dull. Although this finding could be a result of the stimulus range used in the experiment, it raises the question of which features of the luminous environment matter most in occupants' perception.

This question was tackled in a seminal study by Flynn and colleagues in which the appearance of a conference room was examined under different configurations of artificial lighting [4]. Their experiment showed that people prefer lit environments that appear 'bright', an attribute linked to the perception of 'spaciousness', and 'interesting', related to a degree of non-uniformity. They concluded that lighting conditions can be characterized by three dimensions: brightness, uniformity, and the presence of peripheral or overhead lighting. In another study with artificial lighting configurations in an office environment, Hawkes et al. found that the perception of light in the space could be described by the dimensions of brightness and interest, which related to the intensity and the uniformity of the lighting conditions, respectively [5]. Similarly, Loe et al. identified the factors of visual lightness and visual interest as descriptors of the luminous environment, using the same procedure as Flynn [9]. The work of Loe et al. supported the findings of previous research regarding people's preference for their working environment to appear 'bright' and 'interesting', but also noted a key criterion for lighting design, stating that both factors are required to create preferred lighting conditions, i.e. people do not prefer a 'bright' space if it is not 'interesting', or an 'interesting' space that is not 'bright'. In a later study by Veitch and Newsham on the appearance of an open-plan office lit with different lighting systems, the authors found three factors that described the appearance of the space: brightness, visual attraction, and complexity [10]. Brightness is a consistent factor across these studies, which establishes its importance as a central feature of the luminous environment.

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Considerable research has been conducted to identify physical measures of the lighting conditions that can predict occupants' impressions of brightness. The perception of brightness in a space has been related to objective indicators such as the average luminance within a 40 degree horizontal band center at the eye height of an observer [9], [11], the logarithm of the vertical illuminance at the eye of the observer [5], and the spectrally-weighted irradiance at the eye of the observer [12].

In related work, numerous studies have investigated the influence of physical properties other than light intensity on the perceived brightness of a space. For instance, Tiller and Veitch investigated the effects of luminance distribution on perceived room brightness in office spaces using brightness matching tasks in offices. Their findings showed that rooms with non-uniform luminance distribution required five to ten percent less working plane illuminance compared to the brightness of the rooms with uniform luminance distribution [13]. The spectrum of the light source has also been consistently shown to affect the perceived brightness of the scene [14]–[17]. The presence of color in the scene in the form of colored objects (in this example, flowers and fruit) was also shown to increase the perception of brightness in the same illuminance [8]. However, other studies showed no or only a negligible effect from the presence of colored objects on the perceived brightness of the scene [14], [17], indicating the need for further investigation.

It is important to note here that a common component of all these studies is the use of artificial lighting. In fact, very few studies have addressed the effect of daylight on occupants' preference and satisfaction. However, sunlight penetration has been shown to increase feelings of relaxation [18] as well as well-being and job satisfaction [19]. In the same vein, in an experimental study where occupants of office environments were asked to control the shading system and create their preferred conditions, the majority of the participants chose to introduce some amount of direct sunlight into the room [20]. Studies investigating the effect of daylight on participants' subjective impressions in virtual environments have shown that the lighting conditions significantly influence the extent to which a space is perceived as pleasant, interesting, and exciting [21]–[23]. Following these findings, a question arises: could occupants' perception and satisfaction with brightness be affected by other perceptual attributes of the space rather than just the actual brightness level of the space? Such a finding could suggest the potential for energy savings if the same level of satisfaction with brightness can be achieved at lower actual levels of illuminance by manipulating other attributes of the luminous environment.

This paper investigates the influence of perceptual attributes—such as the perceived pleasantness or complexity of the scene—on occupants' satisfaction with the brightness in a daylit office space through subjective experiments. The visual stimuli in these experiments are shown to the participants using a novel experimental method which combines physically-based renderings from Radiance with projection in immersive virtual reality, and has been shown to be a promising surrogate to real daylit spaces for experiments investigating occupant perception [24]. Specifically, an experimental study comparing this method against real environments demonstrated its adequacy in terms of perceptual accuracy, as well as reported presence and physical symptoms of the users of the VR headset [24]. The use of virtual reality allows the control of the brightness to the same level across multiple presented scenes, and the simultaneous variation of the shading system applied to the same space to create different impressions of visual interest and complexity. Controlling the brightness level of the scene across conditions that trigger widely different perceptual impressions allowed us to examine the interrelationship between the satisfaction with brightness and some of the key attributes related to office preference. Additionally, the presence of color and furniture in the virtual environment was varied to investigate the influence of these factors on participant satisfaction with brightness.

2 METHOD

2.1 Visual Stimuli

The scenes used as visual stimuli in this experimental study correspond to six variations of a typical office space with one large window facing south. In these variations, developed in previous work [26], a different shading system was applied to the façade of the space, shown in **Figure 1**. Each façade variation was based on designs from existing buildings, ranging from simple vertical or horizontal louvers to an asymmetrical complex pattern. These variations of the scenes were used to impart different subjective impressions, following existing work which demonstrated the influence of shading system geometry on occupant perception [25], [26]. Although the shading systems varied in design, all were modified to have a 40% perforation in order to create scenes with the same amount of brightness and with distinct perceptual attributes. A 3D model of the office space with six shading system variations was created in Rhinoceros (Rhino, version 5.0) modelling software. Six different spaces were modeled both with and without furniture. Each was rendered in three different color modes—fully colored, partly colored (using the default materials in DIVA-for-Rhino v. 4.0), and grayscale. A view position in the center of the room was established at approximately 2.5 meters from the window and 1.63 meters from the floor, corresponding to the eye height of a standing person. Each model was exported to Radiance [27], an extensively validated physically based lighting simulation tool, using the DIVA-for-Rhino (v. 4.0) simulation toolbar [28]. Immersive scenes were generated in Radiance by rendering a 360° over-under equirectangular HDR image using the script *view360stereo*.cal.

The parameters for the Radiance simulation are provided in Table 1. This procedure resulted in a total of 30 images, which were tone-mapped to a low dynamic range using the

Reinhart02 tone-mapping operator [29] and shown to participants using the Oculus Go virtual reality headset. The resulting scenes are automatically mapped to a sphere in Oculus Go and are perceived as a fully immersive 360° stereoscopic scene (**Figure 2**). The vertical illuminance of the projected scenes was measured at the level of the lens of the VR headset with a Konica Minolta T-10 Illuminance Meter from the viewpoint of a participant looking towards the main view direction, to provide a measure of similarity in terms of actual brightness. These measurements show that the studied scenes differ between them in vertical illuminance with a maximum factor of 1.13, which is well below the threshold of a noticeable change in illuminance [30], and thus is not expected to result in a difference in the participants' judgements regarding their satisfaction with the brightness of the space.

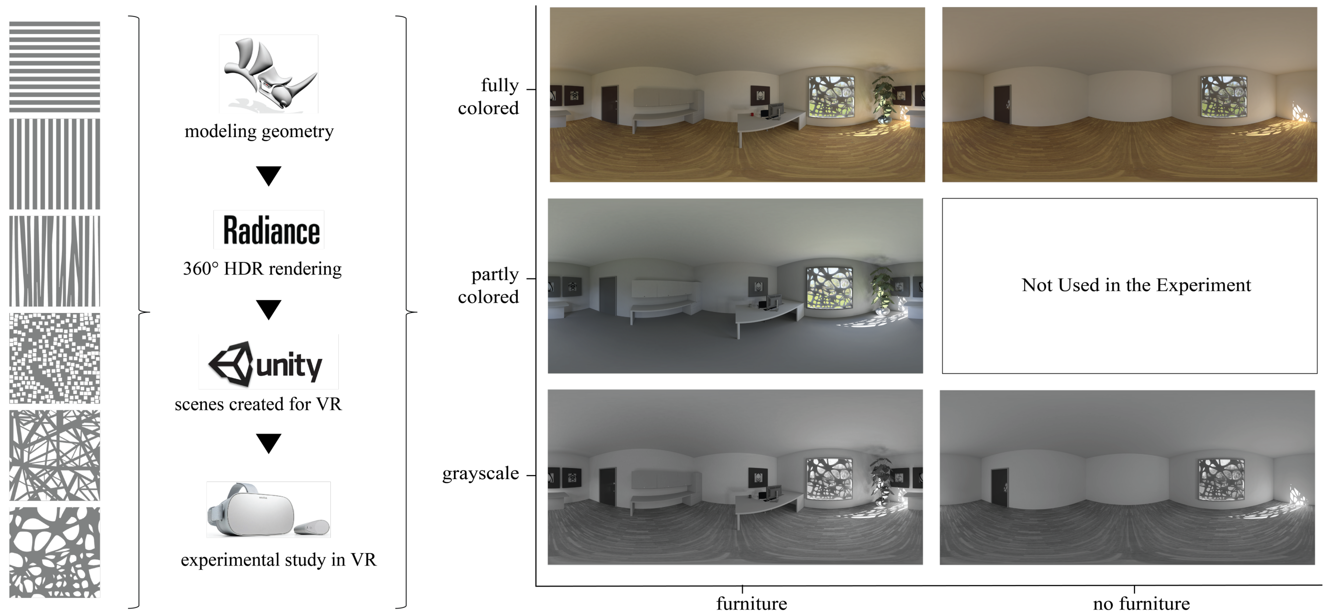

Figure 1. Example scene variations for one window treatment across different levels of scene materials (fully colored, partially colored, grayscale) and simulation level of detail (with/without furniture). Each participant saw a random selection of scenes.

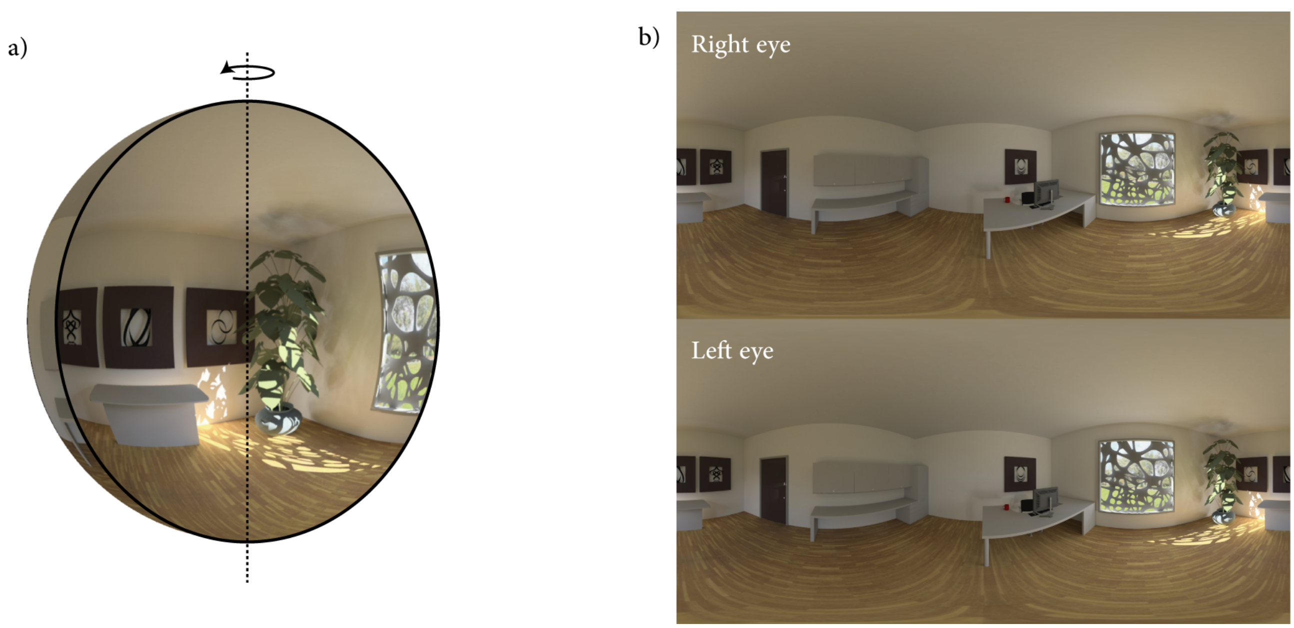

Figure 2. Illustration of participant perception (a) and example of immersive scenes rendered for each eye (b).

dj	ds	dt	dc	dp	St	ab	aa	ar	ad	as	Lr	lw
0.02	0.05	0.05	0.5	256	0.5	4	0.02	32	25000	12500	4	0.000004

Table 1: Radiance parameters for the 360° HDR renderings for viewing in Oculus Go

2.2 Verbal Questionnaire

A verbal questionnaire consisting of 11-point unipolar rating scales was used to collect participants' subjective impressions while they were immersed in each scene. In this paper, we focus on the participants' satisfaction with brightness and its association with a selection of rating scales: how pleasant, interesting, and complex the scene was perceived, as well as their satisfaction with the view out and the ambiance of the space, shown in **Table 2**. It is important to note here that the question on brightness was specifically framed to assess the participants' satisfaction with brightness as an indicator for acceptable range of brightness rather than their perception of brightness levels.

Independent Variables
IV1. Façade variations (six different shading systems of an equal perforation ratio applied to the window of the office room).
IV2. Scene materials (fully colored, partly colored (with default materials in DIVA-for-Rhino), and grayscale.
IV3. Level of detail (simple room without furniture, simple room with furniture).
Dependent Variables
DV1. On a scale of 0 to 10, how pleasant is this space?
DV2. On a scale of 0 to 10, how interesting is this space?
DV3. On a scale of 0 to 10, how complex is this space?
DV4. On a scale of 0 to 10, how satisfied are you with the brightness of the space?
DV5. On a scale of 0 to 10, how satisfied are you with how much you can see of the view outside?
DV6. On a scale of 0 to 10, how satisfied are you with the ambiance of the space?

Table 2. Overview of the experimental variables

2.3 Equipment

An Oculus Go VR headset was used in this study. This is a standalone headset that works without a computer or a phone. Its screen measures 5.5 inches, 538 ppi, at 2560 x 1440 Wide Quad High Definition (WQHD) resolution. The display can run at a maximum refresh rate of 72 Hz, delivering enhanced brightness and colors. The maximum vertical illuminance of a white scene displayed in Oculus Go measured at the level of the lens is 44 lux (lm/m2).

2.4 Experimental Design and Participants

Each participant was presented with a total of six scenes in a randomized order, from the pool of 30 combinations of shading system, color, and furniture variations. Due to the randomization of the scenes, not all participants viewed all six shading patterns used in the study. Analysis of the effect of the shading system on subjective impressions exceeds the scope of this paper and will be reported in a future publication.

The VR experimental study was conducted in Ann Arbor, Michigan over the course of four weeks during the summer of 2018. A total of 100 participants (63 female, 37 male) took part in the study. Participants were unpaid volunteers over 18 years of age, recruited by email or in person. Each experimental session lasted no more than 20 minutes.

Prior to the start of the experimental session the interviewer discussed with the participant possible associated risk with wearing the headset. When they were ready to start the experiment, they were instructed on how to use the Oculus headset and how to customize its fit for comfort. Participant were informed that they would view a total of six scenes of an office space. The scenes were presented in a randomized order and were preceded by a number identifying the condition to the interviewer. Participants were instructed to report this number and were then immersed in an office scene. When the participant was ready, the interviewer verbally asked the questions in a randomized order.

This research was approved by the University of Michigan Health Sciences and Behavioral Sciences Institutional Review Board (IRB-HSBS).

2.5 Statistical Analysis

A linear mixed effects model was used for statistical analysis of the data to account for the repeated measures design in which each participant was asked to rate multiple images. Model analyses were conducted in R [31] for each of the dependent variables using the R software package *lmerTest* [32]. The linear mixed effects model describes the conditional associations between the participants' satisfaction with brightness and the five other perceptual attributes, while controlling for latent participant attributes such as positivity. Statistical analyses were performed by specifying a 0.05 significance level.

Additionally, following the results regarding the associations between the participants' satisfaction with brightness and the other studied dependent variables, a composite index of *satisfaction with selected attributes* was constructed in R by averaging the responses of the attributes *pleasant*, *interesting*, *satisfaction with access to the view outside*, and *satisfaction with ambiance*. This composite index is used to quantify a potential effect on satisfaction with brightness that could stem from a change in the participants' perception of these four attributes, rather than a change in the actual brightness of the scene.

3 RESULTS

The following subsections present the results of the statistical analyses used to study the subjective responses related to the effect of color and furniture on participants' satisfaction with brightness, the associations between satisfaction with brightness and other perceptual attributes, and the comparison of satisfaction with brightness with a composite index of satisfaction with perceptual attributes in the space.

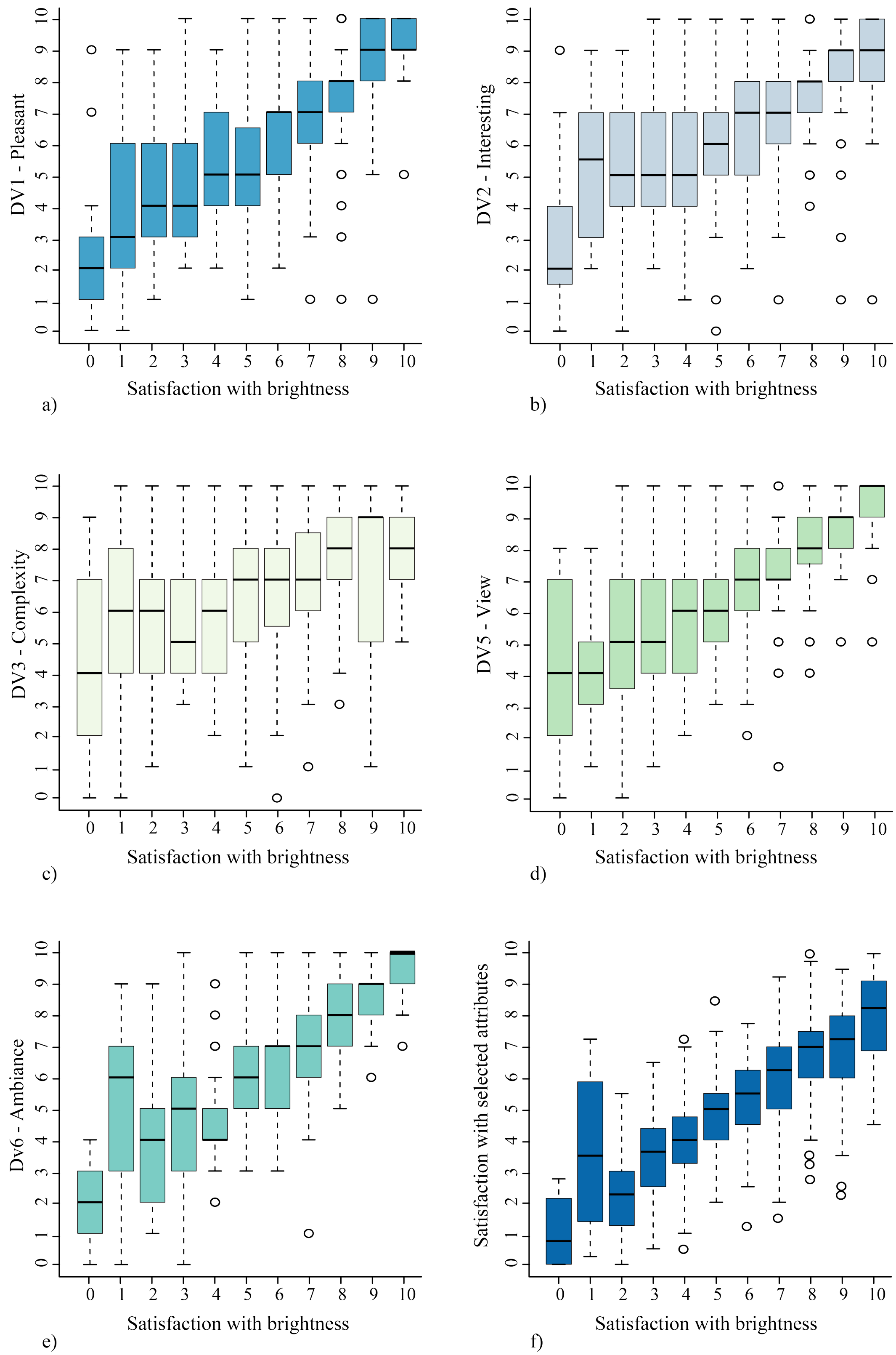

Figure 3. (a)-(e) Boxplots of evaluations of participants' perceptual impressions of the space (y axis), plotted against the equivalent ratings of satisfaction with brightness (x axis), and (f) ratings of the composite index of satisfaction with selected attributes (y axis) plotted against the equivalent ratings of satisfaction with the brightness of the space (x axis).

3.1 Influence of Color and Furniture on Satisfaction with Brightness

Although the actual brightness level of all scenes was the same, participants' evaluations of their satisfaction with brightness spanned the full range of the rating scale (0 to 10 units), with a mean of 6.1 and a standard deviation of 2.18. Linear mixed model analyses were conducted to investigate separately the effect of color and of furniture on the participants' responses. For these analyses, a Bonferroni-corrected significance level of 0.05/2=0.025 is used to account for the multiple comparisons. Results show a statistically significant main effect of color ($F(2,600) = 75.33$, $p<0.001$) on participants' evaluations of their satisfaction with the brightness in the space. In particular, participants' satisfaction with brightness in the scenes with fully colored materials were on average 1.3 units higher than the ratings in the corresponding grayscale scenes. The effect of furniture was not statistically significant on participants' satisfaction with brightness ($F(1,601) = 4.80$, $p=0.028$).

3.2 Associations Between Satisfaction with Brightness and Subjective Impressions of the Space

Further analyses were performed to investigate the association between satisfaction with brightness and the perceptual impressions of other attributes examined in the study. Positive statistically significant associations were found between the evaluations of *satisfaction with brightness* and evaluations of how *pleasant* ($b=0.16$, $p<0.001$) and *complex* ($b=0.08$, $p<0.05$) the space is perceived, as well as with the ratings of the *satisfaction with access to the view outside* ($b=0.11$, $p<0.01$), and the *satisfaction with the ambiance of the space* ($b=0.24$, $p<0.001$). No statistically significant association was found between the *satisfaction with brightness* and how *interesting* the space was perceived ($b= -0.04$, $p=0.35$). These associations can be observed in the plots (a) to (e) in Figure 3, showing the distribution of participants' evaluations of the space plotted against the corresponding ratings of satisfaction with brightness.

3.3 Composite Index of Satisfaction with Perceptual Attributes

Following the findings of positive statistically significant associations, we constructed a composite index representing participants' *satisfaction with selected attributes* (as described in section 2) to understand its association with participants' perception more broadly. To visualize this index using unadjusted data, we constructed a box plot of satisfaction with brightness in terms of *satisfaction with selected attributes* (Figure 3f). This plot shows a strong positive relationship between these two attributes, suggesting a possible effect on satisfaction with brightness that could be due to the participants' satisfaction with the selected attributes in the composite index. We then used a linear mixed effect model to statistically assess the strength of this relationship. We found that a one-unit difference in overall satisfaction corresponds to a 0.7-unit increase in perceived brightness ($p<0.001$).

4 CONCLUSION

This experimental study investigates the influence of key aspects of participants' perceptual impressions of a scene, such as the pleasantness, the satisfaction with the access to the view or the ambiance of the space, on ratings of satisfaction with the brightness of that scene. Through the use of an experimental method which couples physically-based renderings with projection in virtual reality, a total of 100 participants were immersed in virtual scenes of an interior an office space with different façade shading systems, colored materials and with or without furniture.

Although the studied scenes were similar in terms of illuminance levels, findings demonstrate a significant effect of colored materials on the participants' satisfaction with brightness. Although the addition of colored materials in virtual environments adds a layer of complexity in the simulation workflow, this finding highlights the importance of colored materials in assessing user's satisfaction with the brightness in the scene.

The results of this experimental study also demonstrate that there is a clear association between participants' satisfaction with brightness and other perceptual impressions, such as the access to the view outside, perceived pleasantness, interest, complexity and the overall ambiance. This indicates that our perception and satisfaction with brightness cannot be studied on its own without understanding how the overall design of the environment affects occupants' perception and visual impressions.

Our fitted regression model quantifies how people perceive brightness in a range of settings in which other perceptual attributes are varied while actual brightness is held constant. While we cannot directly control the perceptual impressions of people in a space, we can use this model to investigate how their satisfaction with brightness might change if we were able to design for the other attributes, again without changing the actual brightness of the scene. To do this, we used our fitted mixed effects model to investigate the satisfaction with brightness for a range of hypothetical scenarios, when all four other attributes are scored equally at levels ranging from 0 to 10. The relation between the two ratings indicates that the participants' satisfaction with brightness could potentially be shifted by five units, contrasting a building with minimal ratings on all other perceptual categories with a building with maximal ratings on all other perceptual categories. This result is important in the realm of design, especially in designing 'green' buildings, as post-occupancy surveys on occupants' satisfaction with lighting may be less related to the actual light levels and more to the overall quality and the ambiance of the building. Additional studies with a wider range of stimuli are needed to investigate the validity of the presented findings in different types of spaces, and with different brightness levels. Further research is encouraged to investigate the replicability of these results in a real environment.

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