https://doi.org/10.2352/CIC.2024.32.1.29

Evaluating lightness constancy in a high-definition VR environment

Khushbu Y. Patel[1], Laurie M. Wilcox[1], Laurence T. Maloney[2], Krista A. Ehinger[3], Suyash Singh[1], and Richard F. Murray[1];
[1]Department of Psychology, York University, Toronto, Canada, [2]Department of Psychology, New York University, New York, USA, [3]School of Computing and Information Systems, The University of Melbourne, Melbourne, Australia

Abstract

As VR technology has advanced, its use in performance-critical fields such as medical training and vision research has grown, driving a need for increasingly realistic VR environments. In previous work [27], we evaluated lightness constancy in a task where viewers matched the reflectance of surfaces at different 3D orientations, and we found substantially poorer lightness constancy in VR than in a physical apparatus. Poor constancy in VR may have been due to simplified rendering of scenes in that study, e.g., largely achromatic Lambertian surfaces. Motivated by these findings, here we evaluated lightness constancy in more realistic VR scenes, rendered with a broad array of materials, colors, textures, and specular highlights, as well as more realistic shadows. We tested two conditions: a Full-Context condition, where these lighting and material cues were available, and a Reduced-Context condition, where they were not. Participants had significantly better lightness constancy in the Full-Context condition than in the Reduced-Context condition, indicating that they exploited these additional cues. However, lightness constancy was still quite poor in absolute terms, despite the availability of rich lighting and material cues. The reasons for this failure of constancy are unclear from previous literature, and this finding suggests a promising research problem with both fundamental interest and practical applications.

Introduction

Virtual reality (VR) technology has advanced significantly in recent years, finding applications in diverse fields such as gaming [35], training simulations [24], therapeutic interventions [10], and vision research [14]. A key goal of VR development has been to enhance realism, particularly in the accurate rendering of light and its interaction with surfaces, which is important for ensuring good performance in many applications.

Achieving realism in VR is a challenge due to limitations in current technology, such as low image resolution, limited field of view, and a constrained dynamic range for luminance and color. These constraints, coupled with the need for real-time rendering, often lead to compromises in physical accuracy [28], and result in a discrepancy between perception in real and virtual environments. This perceptual gap affects user performance in VR, as shown by discrepancies in tasks such as navigation [16], size perception [29], depth judgments [13], and estimating egocentric distance [9].

Color constancy is one component of for realism in VR, as it prevents unnatural color shifts between different lighting conditions. *Reflectance*, or *albedo*, is the proportion of visible light reflected by a surface, and *lightness* is defined as perceived reflectance. Lightness constancy is a special case of color constancy, and refers to the ability to perceive reflectance, i.e., achromatic surface color, accurately across varying lighting conditions and environments. Achieving lightness constancy requires taking into account surface orientation, material properties, and scene lighting [3, 11, 12, 17].

Some previous studies have examined lightness constancy using relatively simple tasks that required matching the perceived reflectance of two patches on a flat surface, on opposite sides of a shadow boundary [7, 15]. We have found that in this case, viewers achieve similar levels of lightness constancy in real and VR environments, though with larger individual differences in VR [26].

In a similar but more demanding task, viewers match the lightness of a patch at some 3D orientation relative to a light source, to another patch at a different orientation on a separate object [4, 19, 25, 2]. We have found that in this task, lightness constancy is much weaker in VR than in real environments [27], consistent with earlier work that compared results from a range of experiments that used real and virtual environments [19].

Equivalent illumination models

Equivalent illumination models (EIMs) have been a useful tool for understanding color and lightness constancy [6, 8, 5]. The EIM we use here represents achromatic lighting as the sum of a directional light source with illuminance D, in a direction given by unit vector $\mathbf{s}$, and an ambient source with illuminance A in all directions. Although lighting in real scenes is more complex than this, theoretical work has shown that the directional-plus-ambient model captures most of the properties of complex lighting that are relevant to convex Lambertian objects, such as the reference and match patches in the experiments we report below [1]. For a surface with unit normal $\mathbf{n}$, the total illuminance in such a configuration is

$$I = D\max(\mathbf{n}\cdot\mathbf{s},0)+A \tag{1}$$

Here $\max(x,y)$ is the greater of x and y, and $\cdot$ is the vector dot product. A Lambertian surface with reflectance ρ under this illumination produces image luminance given by

$$L = \frac{\rho}{\pi}(D\max(\mathbf{n}\cdot\mathbf{s},0)+A) \tag{2}$$

The division by π takes into account the diffusion of light over a hemisphere, which is characteristic of matte surfaces [18].

Solving equation (2) for ρ gives a model of how a viewer might estimate surface reflectance from luminance and lighting parameters:

$$\rho = \frac{\pi L}{D \max(\mathbf{n} \cdot \mathbf{s}, 0) + A} \tag{3}$$

The EIM assumes that the viewer recovers the luminance L correctly, but may have mistaken estimates of the lighting parameters D, A, and $\mathbf{s}$, and may also misperceive the surface orientation $\mathbf{n}$. An EIM analysis uses this model to describe the viewer's lightness matching behavior in an interpretable way, by finding the lighting parameters (and possibly also the surface orientation bias) that best account for the viewer's reflectance matches ρ over a range of stimuli. That is, we infer an 'equivalent illuminant' that appears to guide the viewer's lightness matching behavior.

EIM analyses have typically found that viewers estimate the lighting direction $\mathbf{s}$ accurately, and have a small fronto-parallel bias for the surface orientation $\mathbf{n}$, but that they often dramatically over-estimate the ambient-to-directional ratio A/D, resulting in a characteristic pattern of failure of lightness constancy that tends towards luminance matching [27, 2, 4]. Brainard and Maloney (2011) and Patel et al. (2024) [26, 8] review EIMs and their application to modelling color and lightness constancy.

Present study

In a previous study [27], we found weaker lightness constancy in VR compared to a physical apparatus, in a task where viewers matched the lightness of patches at different 3D orientations. One reason for the failure of constancy in VR may have been that we used achromatic matte surfaces in the real and virtual scenes, and a Lambertian shading model in VR that was only an approximation to the surfaces in the real scenes. In fact, [3] found that realistic features such as specular highlights were important for good lightness constancy in virtual environments.

In the present study, we create a VR environment that offers more realistic lighting and material cues, to test whether this improves constancy compared to our previous findings. We use Unity's High Definition Render Pipeline (HDRP), to render more realistic materials and shadows, and we include a wider range of material types, colors, and textures. We also incorporate a wider range of surrounding and background objects, to enhance overall realism and provide additional lighting cues. We evaluate viewers' reflectance matching behavior and degree of lightness constancy using an EIM analysis.

In the present study we do not include a physical scene for comparison. Our goal is to make the VR scene as realistic as possible in the ways outlined above, and precisely matching multidimensional features such as material properties and specularities to specific physical objects is very difficult. We aim to test whether, under these improved stimulus conditions, lightness constancy in a virtual scene can be approximately as good as in typical physical scenes.

We implement two sets of experimental conditions: Full-Context and Reduced-Context. In the Full-Context conditions we show scenes with the wide range of material and lighting cues described above. In the Reduced-Context conditions we show test patches with minimal context, and no surrounding objects that could provide lighting cues to support lightness matching. The Reduced-Context conditions are control conditions where we expect viewers to have poor constancy and make matches that are close to luminance matching. Comparison of the Full-Context and Reduced-Context conditions allows us to test whether viewers exploit the lighting cues available in the Full-Context conditions, and comparing absolute levels of lightness constancy to those in our previous study [27] allows us to test whether viewers benefit from the more realistic lighting and material cues in the present experiment. In each condition, viewers also perform an orientation matching task, so that we can assess the effect of any biases in orientation perception on their lightness matching behaviour.

Methods

Participants

There were 21 naive participants. Eleven were female, nine were male, and ages ranged from 18 to 34 years. All reported normal or corrected-to-normal visual acuity and no known anomalies in color vision. All procedures were approved by the Office of Research Ethics at York University.

Stimuli

Stimuli were shown in a Meta Quest Pro headset (FOV 106° × 96°, resolution 1920 × 1800 pixels per eye, refresh rate 90 Hz), driven by an NVIDIA GeForce GTX 3090 Ti graphics card on a PC running Windows 10. Scenes were rendered in Unity 2022.2 using the High Definition Render Pipeline (HDRP), version 14 [32]. We calibrated the VR headset so that physical luminance was proportional to rendered achromatic RGB value (0-255). We followed the procedure in [22], except that instead of the LUT file required by Unity's Built-in Render Pipeline, we used a .cube file and the tonemapping feature of the HDRP.

Lightness task. Participants viewed a virtual scene that showed equipment on a table (Figure 1), from a simulated viewing distance of 74 cm. The equipment had two components: the reference apparatus and the match apparatus.

The reference apparatus was on the left. In the Full-Context conditions, it included a reference patch surrounded by objects of various colors and materials (Figure 1(a)). The reference patch was a 3 × 3 cm grey square, whose orientation and reflectance varied from trial to trial (details under Procedure).

The match apparatus was on the right. It was a 31.5 cm square, covered with randomly placed grey circles and rectangles, with reflectances ranging from 0.07 to 0.71, on a grey background of reflectance 0.20. A 3 × 3 cm match patch, whose reflectance could be adjusted by the participant, was on the left side of the panel. The match patch was frontoparallel throughout the experiment.

The scene surrounding the reference and match apparatus included objects such as tables, chairs, trees, rocks, a globe, and small plants, all within an area enclosed by walls. In Figure 1 the viewing direction is shifted to the left in order to capture more of the surrounding objects, but in the experiment the participant's view was directed toward the reference patch.

The Reduced-Context conditions were the same as the Full-Context conditions, except that the only visible objects were the reference patch, the match apparatus, and a large, distant, grey wall that served as a backdrop (Figure 1(b)). The reflectance of the grey wall was chosen so that its luminance was the same as that of the grey panel behind the reference patch in the Full-Context conditions.

Simulated lighting consisted of a directional source and an omnidirectional light probe. The directional source was located

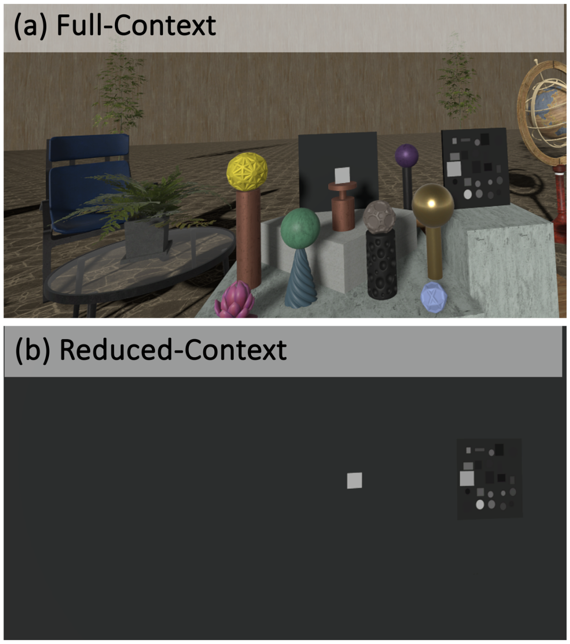

Figure 1. VR scenes from the participant's viewpoint. (a) The Full-Context condition. (b) The Reduced-Context condition, which showed only the reference patch and the match apparatus.

behind the participant at an elevation of 22°. There were two sub-conditions of the Full-Context and Reduced-Context conditions, with different lighting directions. In the Full-Context-Right and Reduced-Context-Right conditions the directional source was 22° to the right of directly behind, and in the Full-Context-Left and Reduced-Context-Left conditions it was 22° to the left. The light probe was the default ambient lighting in Unity (Default-HDRISkyGrey.exr), except that we averaged together the three color channels to produce an achromatic light. This light probe consists of smoothly graded light, with the most intense light coming from near the horizon. The combination of directional light and light probe were well-approximated by a combination of directional and purely ambient light, where the directional source had 7.7 times the illuminance of the ambient source.

Orientation task. In the orientation matching task, a small panel was added to the scene, in front of the reference apparatus. The panel showed a fixed horizontal line, and an adjustable line that the participant could rotate using a thumbstick on the VR hand controller. Both lines were 7 cm long, and were white on a grey background.

Procedure

There were four conditions: Full-Context-Left, Full-Context-Right, Reduced-Context-Left, and Reduced-Context-Right. Each participant completed one condition. Participants completed the lightness task first, and then the orientation task.

On each trial of the lightness task, the reflectance of the reference patch was randomly set to 0.41 or 0.58, and the orientation was randomly set to -50°, -33°, -17°, 0°, 17°, 33°, or 50°. Here 0° indicates an orientation facing the participant, and positive angles indicate that the patch was rotated to the right. The participant used a thumbstick to adjust the reflectance of the match patch so that it appeared to be the same as the reflectance of the reference patch. Response time was unlimited. Each combination of reflectance and orientation was repeated ten times, for a total of 140 trials.

On each trial of the orientation task, the reference patch (always with reflectance 0.58) was randomly set to one of the seven orientations used in the lightness task. The participant adjusted the line on the orientation-matching panel so that it matched the orientation that the reference patch would have if viewed from above. Each orientation was repeated five times, for a total of 35 trials.

Analysis

We fitted the EIM in equation (3) to each participant's reflectance matches, as follows. The reference patch surface normal **n** and the lighting direction **s** can be written in spherical coordinates with azimuth ψ and elevation ϕ:

$$\mathbf{n} = (\cos\phi_n \cos\psi_n, \cos\phi_n \sin\psi_n, \sin\phi_n) \quad (4)$$

$$\mathbf{s} = (\cos\phi_s \cos\psi_s, \cos\phi_s \sin\psi_s, \sin\phi_s) \quad (5)$$

The reference patch was upright, so $\phi_n = 0$. Following [27, 2, 4], we incorporated a free multiplicative parameter k on the right-hand side of equation (3), to allow the participant's reflectance matches to be off by an arbitrary scale factor. Writing equation (3) with the additional scale factor k, using spherical coordinates for **n** and **s**, setting $\phi_n = 0$, and simplifying, we find

$$\rho = \frac{L}{\alpha(\max(\cos(\psi_n - \psi_s), 0) + \beta)} \quad (6)$$

$$\text{where } \alpha = \frac{D\cos\phi_s}{\pi k}, \; \beta = \frac{A}{D\cos\phi_s} \quad (7)$$

We made a least-squares fit of equation (6) to participants' reflectance match settings. In this analysis, L was set to the luminance of the reference patch on each trial, and ϕ_s was set to the elevation (22°) of the light source. α, β, ψ_s, and k were free parameters. Assuming that the participant perceived the lighting elevation ϕ_s correctly, we can use the fitted value of β to find the ambient-to-directional illuminance ratio that is consistent with their responses:

$$A/D = \beta\cos\phi_s \quad (8)$$

Morgenstern et al. [19] define illuminance contrast energy (ICE) as the coefficient of variation (standard deviation divided by mean) of illuminance over all 3D surface orientations at a given point in space. ICE is therefore a measure of the directionality or diffuseness of lighting [34], and ranges from 0 for completely ambient light to 1.29 for a distant point source. Morgenstern et al. show that an ambient-to-directional illuminance ratio A/D corresponds to an ICE value of

$$\lambda = \frac{\sqrt{5/48}}{(A/D) + 0.25} \quad (9)$$

The simulated lighting in the present experiment had $A/D = 1/7.7$, corresponding to ICE = 0.85.

Following the criterion used in [27], we excluded from the analysis one participant who had a mean absolute error greater than 10° in the orientation matching task. This left five participants in each of the four conditions.

Results

Lightness matches

Figure 2(a) shows reflectance matches as a function of reference patch orientation for a typical participant in each of the four conditions. If participants had perfect constancy, their reflectance matches would fall along the horizontal black lines, indicating no effect of reference patch orientation. If participants had no constancy and simply matched luminance, their reflectance settings would follow the inverted-U pattern of the blue data points, which show the stimulus luminance, scaled to make a sum-of-squares fit to the mean reflectance matches. Participants' reflectance matches fell between these two theoretical extremes, as is the case in most studies of lightness constancy. The green lines show sum-of-squares fits of the EIM in equation (6) to mean reflectance matches. The illuminance at the match patch was constant throughout the experiment, so the reflectance matches in Figure 2(a) are also proportional to participants' luminance matches.

Figure 2(b) shows mean ICE values in each condition. Independent-samples t-tests showed no significant differences between Full-Context-Right (M = 0.11, SD = 0.05) and Full-Context-Left (M = 0.11, SD = 0.05; $t(8) = 0.20$, $p = 0.84$) conditions, or between Reduced-Context-Right (M = 0.04, SD = 0.02) and Reduced-Context-Left (M = 0.04, SD = 0.01; $t(8) = 0.29$, $p = 0.78$). Consequently, we pooled data within the Full-Context conditions (M = 0.11, SD = 0.04) and Reduced-Context conditions (M = 0.04, SD = 0.02) for subsequent analyses.

Mean ICE values in pooled Full-Context and Reduced-Context conditions were both significantly less than the veridical value of 0.85 and significantly greater than 0, as determined by individual one-sample t-tests, with all p values below the Bonferroni-corrected alpha level of 0.025. Thus participants' reflectance matches were consistent with an overestimate of lighting diffuseness [8, 19, 27].

An independent samples t-test showed that mean ICE was significantly higher in the pooled Full-Context conditions than in the Reduced-Context conditions ($t(18) = 4.60$, $p < 0.05$). Thus participants benefited from the additional lighting and material cues in the Full-Context conditions, and exhibited better lightness constancy in those conditions than in the Reduced-Context conditions.

Orientation matches

Participants' orientation matches were proportional to the simulated azimuth of the reference patch, but were biased toward fronto-parallel. The average slope of a linear regression of match azimuth against true azimuth was 0.80, significantly less than the value of 1 that would indicate veridical matches ($t(19) = -4.55$, $p < 0.05$). This bias towards fronto-parallel slant is well-documented [5, 2, 30, 27]. Importantly, we find no significant differences in this bias across the four conditions ($F(12, 3) = 0.30$, $p = 0.83$).

Discussion

In an EIM analysis of lightness matching, a low ICE value, meaning an overestimate of lighting diffuseness in the equivalent illuminant, indicates imperfect lightness constancy. An overestimate of diffuseness means that the participant behaves as if a change in reference patch orientation should change the reference patch luminance relatively little, and so the participant mistakenly attributes the change in luminance to a change in reflectance. We found that the mean ICE was closer to the veridical value in the Full-Context conditions than in the Reduced-Context conditions, indicating that partcipants exploited the lighting cues available in the former conditions to support lightness constancy. However, another clear and important result was that all mean ICE values were much lower than the true ICE of the simulated lighting (Figure 2(b)), indicating generally poor constancy in all conditions. This aligns with previous research using similar stimuli and tasks [19, 27].

Lightness constancy can also be quantified using the Thouless ratio, a measure that facilitates comparisons of constancy across studies [31]. The Thouless ratio is defined as

$$\tau = \frac{\log r_m - \log r_0}{\log r_1 - \log r_0} \tag{10}$$

where r_m is the participant's reflectance match setting, r_1 is the setting that would result from perfect constancy, and r_0 is the setting that would result from luminance matching. The Thouless ratio ranges from 0 to 1, with $\tau = 1$ indicating perfect constancy, and $\tau = 0$ indicating luminance matching, i.e., no constancy.

In previous work, we showed how to convert equivalent-illuminant ICE parameters to Thouless ratios [27]. The methods developed there show that with a true ICE value of 0.85, as in the present experiment, the mapping from equivalent ICE parameters to Thouless ratios is approximately given by

$$\tau = (\mathrm{ICE}/0.85)^{0.65} \tag{11}$$

Figure 3 shows the mean ICE values from Figure 2b, pooled across -Left and -Right conditions, and converted to Thouless ratios using equation (11). Thouless ratios were low, and even in the Full-Context condition the mean was just 0.22, indicating very weak constancy. In complex physical scenes with rich lighting and material cues, where lightness is evaluated across a shadow boundary, Thouless ratios are typically around 0.8 or 0.9 [26]. In a previous study with a similar task to the present experiment, we measured a Thouless ratio of 0.68 in a physical apparatus. In the same study, in VR conditions with less realistic rendering than in the present experiment, and in a design where each participant ran in just one condition as reported here, Thouless ratios ranged from 0.35 to 0.12. Thus despite enriching the VR scene with additional lighting and material cues in the present study, lightness constancy did not improve.

This substantial failure of constancy even in complex and carefully rendered VR scenes is surprising. It is unclear from previous literature why constancy should be weaker in such scenes than with physical stimuli. Errors in perception of surface orientation cannot explain this result. As reported above, the mean slope in regressions of perceived vs. true slant was 0.80, which is similar to values measured in physical and VR scenes in previous studies [5, 2, 30]. We do note, though, that this result was based on explicit orientation matches, which may differ from implicit depth estimates that guide lightness constancy, and so it remains possible that failures of depth perception play a role in our findings.

One possibility is that the rendering of the VR scenes was still unrealistic in some way. For example, fine 2D and 3D surface

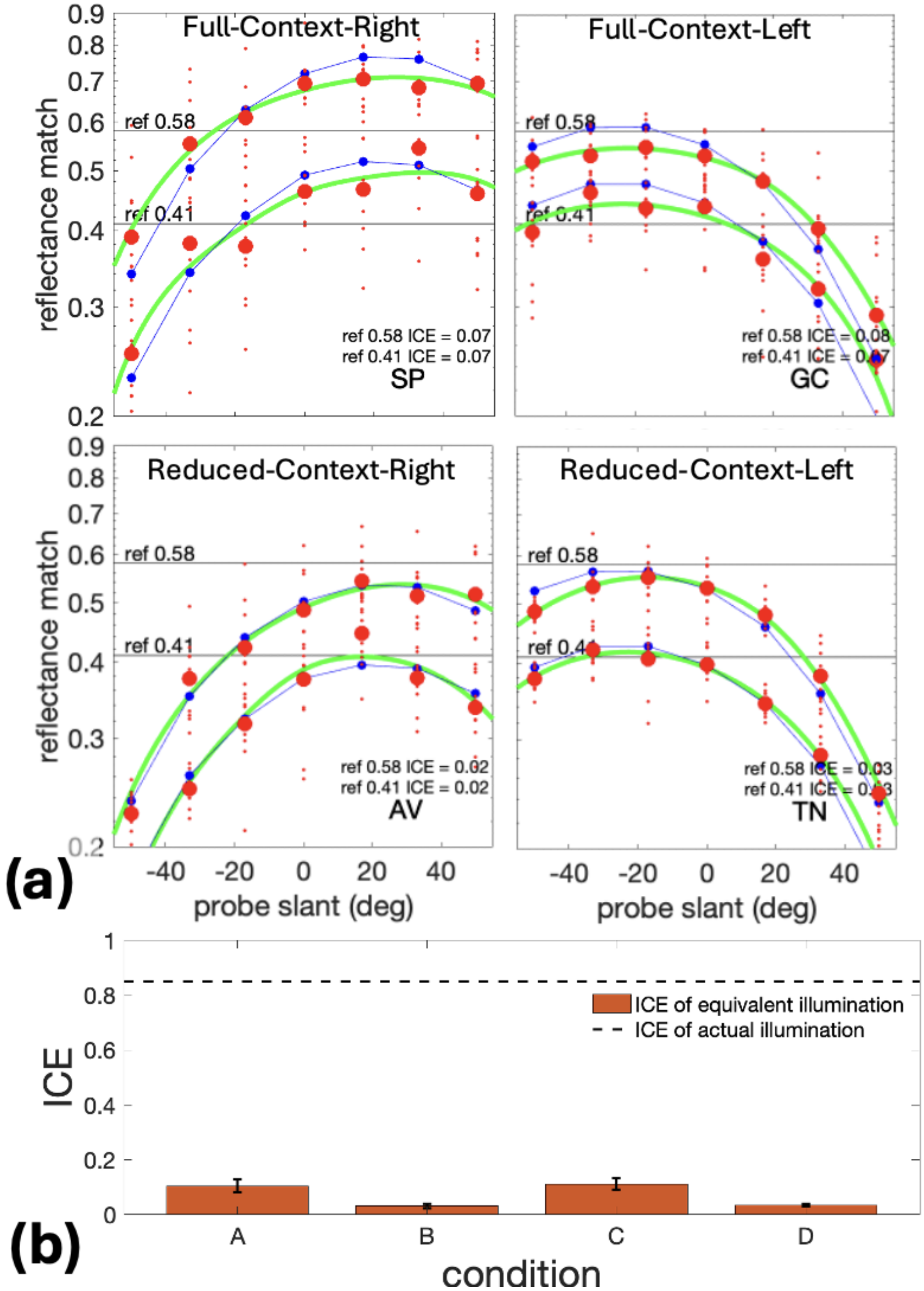

Figure 2. *(a) Reflectance matches as a function of the orientation of the reference patch for a typical participant in each condition. Small red dots are reflectance matches on individual trials, and large red dots are means. Green fitted lines show least-squares fits of the EIM model. Horizontal black lines indicate the reflectance of the reference patches. Blue curves show stimulus luminance, scaled to make a least-squares fit to mean reflectance matches.*
(b) Mean values of the fitted ICE parameter, averaged over participants. Error bars show standard errors. The black dashed line shows the true ICE value of the simulated lighting in the VR scene.

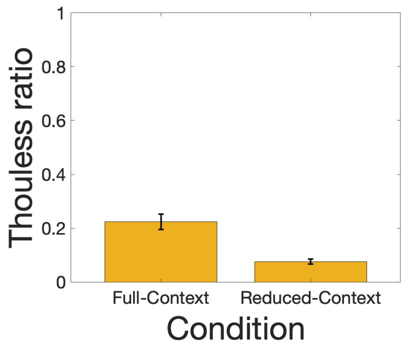

Figure 3. *Mean Thouless ratios in Full- and Reduced-Context conditions. Error bars show standard errors.*

textures and subsurface scattering were not rendered in our VR scenes, and it may be that these features play an important role in perception of materials and lightness. Similarly, pixellation is often visible in VR, and this departure from realism may interfere with mechanisms of lightness constancy.

Another possibility is that we did not arrive at accurate estimates of the parameters of the EIM, and that more accurate estimates would provide insight into why constancy was so poor. For example, it may be that the explicit orientation judgements we used to examine participants' orientation perception are different from the implicit judgements that guide lightness perception. If these implicit orientation judgements have a much stronger fronto-parallel bias in VR scenes than suggested by participants' explicit, effortful orientation matches, this could explain poor constancy. To take another example, in order to infer the diffuseness of the equivalent illuminant using equation (8), we assumed that participants estimated the lighting elevation accurately ($\phi_s = 22°$). Although [3] provided evidence that viewers do perceive lighting azimuth and elevation accurately, this assumption may need to be investigated further. If viewers over-estimate lighting elevation, as we might expect from the well-documented bias to perceive light from above [21], this would also explain their poor constancy.

A third possibility is that constancy is particularly poor with isolated test patches. In the present experiment, the reference patch was an isolated square supported on a thin pole. Previous work has shown that viewers are highly insensitive to lighting inconsistencies within scenes [33, 23] (but see [20]). This suggests that viewers are poor at integrating lighting cues across different objects, so lightness constancy might be substantially better when reference and test patches are parts of solid, many-sided objects that provide rich local lighting cues.

Conclusion

Real-time rendering in VR inevitably requires approximations, and it is encouraging that the human visual system responds to rendered scenes as well as it does. Nevertheless, the present results highlight significant perceptual differences in lightness constancy between real and virtual environments. This finding is consistent with previous studies that also found differences in a wide range of tasks, including self-orientation [16], size judgements [29], depth judgements [13], and distance estimation [9]. Despite advances in VR that allow for the creation of rich, complex environments, our findings show that lightness matching in VR only marginally surpasses simple luminance matching. It remains unclear why lightness constancy is so poor in VR. This question poses an interesting and important research problem, both for a fundamental understanding of visual perception, and for improving virtual environments where realistic and accurate performance is critical.

References

[1] R Basri and D J Jacobs. "Lambertian reflectance and linear subspaces". In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 25.2 (2003), pp. 218–233.

[2] Marina Bloj et al. "An equivalent illuminant model for the effect of surface slant on perceived lightness". In: *Journal of Vision* 4.9 (2004), pp. 6–6.

[3] Huseyin Boyaci, Katja Doerschner, and Laurence T Maloney. "Cues to an equivalent lighting model". In: *Journal of Vision* 6.2 (2006), pp. 106–118.

[4] Huseyin Boyaci, Katja Doerschner, and Laurence T Maloney. "Perceived surface color in binocularly viewed scenes with two light sources differing in chromaticity". In: *Journal of Vision* 4.9 (2004), pp. 664–679.

[5] Hussein Boyaci, Laurence T Maloney, and Sarah Hersh. "The effect of perceived surface orientation on perceived surface albedo in binocularly viewed scenes". In: *Journal of Vision* 3.8 (2003), pp. 541–553.

[6] David H Brainard. "Color constancy in the nearly natural image. 2. Achromatic loci". In: *JOSA A* 15.2 (1998), pp. 307–325.

[7] David H Brainard, Wendy Brunt, and Jon Speigle. "Color constancy in the nearly natural image. 1. Asymmetric matches". In: *JOSA A* 14.9 (1997), pp. 2091–2110.

[8] David H Brainard and Laurence T Maloney. "Surface color perception and equivalent illumination models". In: *Journal of Vision* 11.5 (2011), pp. 1–1.

[9] Sarah H Creem-Regehr, Jeanine K Stefanucci, and Bobby Bodenheimer. "Perceiving distance in virtual reality: theoretical insights from contemporary technologies". In: *Philosophical Transactions of the Royal Society B* 378.20210456 (2022), pp. 1–12.

[10] Ophelie Puissegur Dennis and Rita M Patterson. "Medical virtual reality". In: *Journal of Hand Therapy* 33.2 (2020), pp. 243–245.

[11] Katja Doerschner, Huseyin Boyaci, and Laurence T Maloney. "Human observers compensate for secondary illumination originating in nearby chromatic surfaces". In: *Journal of Vision* 4.2 (2004), pp. 3–3.

[12] Howard Flock and Edmund Freedberg. "Perceived angle of incidence and achromatic surface color". In: *Perception & Psychophysics* 8.4 (1970), pp. 251–256.

[13] Brittney Hartle and Laurie M Wilcox. "Stereoscopic depth constancy for physical objects and their virtual counterparts". In: *Journal of Vision* 22.4 (2022), pp. 1–19.

[14] Paul B Hibbard. "Virtual Reality for Vision Science". In: Springer, 2023.

[15] David Katz. *The world of touch*. London: Kegan Paul, Trench, Trubner and Co., 1935.

[16] Kazushige Kimura et al. "Orientation in virtual reality does not fully measure up to the real-world". In: *Scientific Reports* 7.1 (2017), pp. 1–8.

[17] James M Kraft and David H Brainard. "Mechanisms of color constancy under nearly natural viewing". In: *Proceedings of the National Academy of Sciences* 96.1 (1999), pp. 307–312.

[18] Ross McCluney. *Introduction to radiometry and photometry*. Artech House, Inc., 1994.

[19] Yaniv Morgenstern, Wilson S Geisler, and Richard F Murray. "Human vision is attuned to the diffuseness of natural light". In: *Journal of Vision* 14.9 (2014), pp. 1–18.

[20] Yaniv Morgenstern, Richard F Murray, and Laurence R Harris. "The human visual system's assumption that light comes from above is weak". In: *Proceedings of the National Academy of Sciences* 108.30 (2011), pp. 12551–12553.

[21] R F Murray and W J Adams. "Visual perception and natural illumination". In: *Current Opinion in Behavioral Sciences* 30 (2019), pp. 48–54.

[22] R F Murray, K Y Patel, and E S Wiedenmann. "Luminance calibration of virtual reality displays in Unity". In: *Journal of Vision* 22(13):1 (2022), pp. 1–9.

[23] Yuri Ostrovsky, Patrick Cavanagh, and Pawan Sinha. "Perceiving Illumination Inconsistencies in Scenes". In: *Perception* 34.11 (2005), pp. 1301–1314.

[24] Solomon Sunday Oyelere et al. "Exploring the trends of educational virtual reality games: a systematic review of empirical studies". In: *Smart Learning Environments* 7 (2020), pp. 1–22.

[25] K Y Patel, Anudhi Munasinghe, and R F Murray. "Lightness matching and perceptual similarity". In: *Journal of Vision* 18.5 (2018), pp. 1–18.

[26] K Y Patel et al. "Lightness constancy in reality, in virtual reality, and on flat-panel displays". In: *Behavior Research Methods* (2024), 5 March 2024.

[27] K Y Patel et al. "Lightness constancy in reality, in virtual reality, and on flat-panel displays". In: *Behavior Reseach Methods* (submitted).

[28] M Pharr, W Jakob, and G Humphreys. *Physically based rendering, fourth edition*. The MIT Press, 2023.

[29] Anna M Rzepka et al. "Familiar size affects perception differently in virtual reality and the real world". In: *Philosophical Transactions of the Royal Society B* 378.1869 (2023), pp. 1–14.

[30] J A Saunders and Z Chen. "Perceptual biases and cue weighting in perception of 3D slant from texture and stereo information". In: *Journal of Vision* 15.2:14 (2015), pp. 1–24.

[31] Robert Thouless. "Phenomenal regression to the real object". In: *British Journal of Psychology* 21.4 (1931), pp. 339–359.

[32] Unity Technologies. *Unity, version 2022.3 (LTS)*. 2022. URL: `https://docs.unity3d.com/2022.3/Documentation/Manual/UnityManual.html`.

[33] J D Wilder, W J Adams, and R F Murray. "Shape from shading under inconsistent illumination". In: *Journal of Vision* 19(6):2 (2019).

[34] Ling Xia, Sylvia Pont, and Ingrid Heynderick. "Separate and simultaneous adjustment of light qualities in a real scene". In: *i-Perception* 8.1 (2017), p. 2041669516686089.

[35] Michael Zyda. "From visual simulation to virtual reality to games". In: *Computer* 38.9 (2005), pp. 25–32.

Author Biography

Dr. Khushbu Patel recently completed her Ph.D. in the Department of Psychology and Centre for Vision Research at York University, specializing in the Brain, Behaviour, and Cognition stream. Her dissertation research used psychophysical methods to evaluate lightness constancy in virtual environments, including VR, AR, and flat-panel displays.

Dr. Laurie Wilcox is a faculty member in the Department of Psychology and of the Centre for Vision Research. She holds the York University research chair in 3D Vision. Her research Her research focusses on both fundamental and applied aspects of binocular depth perception, including cue integration, vision in natural environments, and 3D display systems.

Dr. Laurence T Maloney is a faculty member in the Department of Psychology and Center for Neural Science at New York University. He is interested in mathematical models of human perception and movement planning.

Dr. Krista Ehinger is a faculty member in the School of Computing and Information Systems at the University of Melbourne. Her research areas are computer vision and computational models of human vision, with a focus on models of visual search and scene recognition.

Suyash Singh is a software engineer with a B.Sc. in Computer Science from York University. He specializes in AI model deployment and full-stack development using MERN stack. His research interests include AR/VR and computer vision. He is also the author of the fiction series 'Shades of Perception.

Dr. Richard Murray is a faculty member in the Department of Psychology and Centre for Vision Research at York University. His laboratory develops computational models of human visual perception, recently with a focus on achromatic surface color.