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PERFORMANCE OF MELANOPSIN-BASED SPATIAL BRIGHTNESS METRICS

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Abstract

Traditional photometric measures fail to accurately estimate perceived brightness, leading to the development of spatial brightness as a concept to quantify overall scene brightness. Recent research has revealed that melanopsin-containing intrinsically photosensitive retinal ganglion cells (ipRGCs), in addition to cone cells, contributes to brightness perception, and new metrics have been developed to predict cone and melanopsin-driven brightness perception. This study evaluates the performance of three melanopsin-based spatial brightness metrics through a two-alternative forced choice (2AFC) simultaneous brightness experiment involving 15 pairs of lighting conditions. Results indicate that the melanopsin-based spatial brightness metrics perform poorly, with a maximum accuracy of 50%, which is on par with chance. Future research should explore a wider range of illuminance, melanopic illuminance, and correlated colour temperatures (CCT) levels.

Keywords: Melanopsin, Visual Scene Brightness, Indoor Lighting, Circadian Entrainment, Visual Perception, Indoor Environmental Quality.

1 Introduction

Brightness is often associated with photometric measures (i.e. luminance, illuminance) despite their well-documented limitations (Stevens and Stevens, 1963; Duff, Kelly, and Cuttle, 2017). The basis of photometric measures, the CIE photopic luminous efficiency function (aka 2-degree standard observer), has been criticised for its limitations, such as the small field of view (Kaiser and Wyszecki, 1978), and alternatives have been proposed, including the CIE physiological axes (CIE, 2015). Despite the significant differences between the standard and alternative functions (Wangyang and Durmus, 2021), the standard observer is still used today to calculate photometric measures.

Meanwhile, spatial brightness, “attribute of a visual perception according to which a luminous environment appears to contain more or less light” (CIE, 2020), has gained attention in lighting research (Royer and Houser, 2012; Ju, Chen, and Lin, 2012; Islam et al., 2015). It is evident that increased light levels cause an increase in brightness, albeit non-linearly, an effect known as the Steven’s power law or Weber’s law. On the other hand, a secondary effect of spectral power distribution (SPD) has been documented with mixed results. While some studies connect higher CCT with increased brightness (Toftum et al., 2018), others found no statistical impact of CCT on brightness when controlled for colour fidelity and gamut (Van de Perre et al., 2024). Interestingly, a couple of studies showed that colour gamut can also contribute to spatial brightness, where increased gamut was linked with increased brightness, albeit without controlling CCT (FOTIOS and Cheal, 2011; Fotious et al., 2015). All these studies indicate a potential impact of SPD on brightness perception, but the modelling of this effect has been elusive so far.

Recently, the discovery of melanopsin photoreceptors in intrinsically photosensitive retinal ganglion cell (ipRGCs) and their role in visual and non-visual mechanisms brought a new direction for brightness studies. Studies suggest that ipRGC-influenced light (iIL) responses (CIE, 2024) is a key part of visual mechanisms, such as brightness perception (Brown et al., 2012; Zele et al., 2018; Yamakawa et al., 2019; Hu et al., 2022). On the other hand, studies controlling both chromatic and melanopsin contents suggest that melanopsin’s contribution to brightness can be secondary to the chromatic contribution (Delawyer et al., 2020; Royer et al., 2024). Despite the unclear role of melanopsin in brightness perception, there has new spatial

brightness models to predict the effects of melanopsin (Rea et al., 2016, Yamakawa et al., 2019, Khanh et al., 2023). However, none of these melanopsin-based brightness models have been independently assessed. This study evaluates the performance of the melanopsin-based spatial brightness metrics using data from a psychophysical experiment.

2 Methods

A psychophysical experiment was conducted to investigate the effects of melanopsin and colour gamut on spatial brightness perception. Here, the data from this visual experiment are analysed to test the performance of three spatial brightness metrics that account for melanopsin contribution to visual mechanisms.

2.1 Spatial Brightness Metrics

Rea and colleagues' (2016) proposed scene brightness spectral sensitivity function (B_v), which is calculated:

$$B_v(\lambda) = V(\lambda) + (0.264 \ln E_v + 1.093) S(\lambda) + 0.5 \text{Mel}(\lambda), \tag{1}$$

where

- $V(\lambda)$ is the photopic luminous efficiency function;
- $S(\lambda)$ is the S-cone spectral sensitivity;
- $\text{Mel}(\lambda)$ is the ipRGC spectral sensitivity;
- E_v is the vertical illuminance at the eye.

Yamakawa and colleagues (2019) formulated brightness (R) as a function of melanopsin:

$$R = 4.84 \cdot 10^{-3} \cdot \left(M \pi \left(\frac{d}{2} \right)^2 \right)^{1.1} + 2.31 \cdot \left(L \pi \left(\frac{d}{2} \right)^2 \right)^{0.48}, \tag{2}$$

where

- d is the pupil diameter;
- M is the melanopsin stimulation;
- L is luminance.

In their model, pupil diameter (d) and melanopsin (M) contributions are calculated

$$d = 1.74 / (1 + e^{(0.0040 \cdot M + 0.0012 \cdot L)}) + 2.58, \tag{3}$$

$$M = 4557 \int P(\lambda) \text{Mel}(\lambda) d\lambda, \tag{4}$$

where

- $P(\lambda)$ is the spectral power distribution of the light source.

Khanh and colleagues' (2023) 17th model that predict brightness (M_{17}) is

$$M_{17} = 8.9974 [E_v^{0.2629} (S^{0.074} + 0.5 G^{0.0424})] - 1.3307, \tag{5}$$

where

- E_v is the illuminance;
- S is the S-cone response normalised using relative light source SPD;
- G is the ipRGC response normalised using relative light source SPD.

These three spatial brightness models will be referred to as B , R , and M_{17} for brevity.

2.2 Lighting Conditions

Twelve pairs of lighting conditions (plus three null condition) were generated using a multi-colour LED lighting system (Thouslite LEDCubes) at two nominal CCT (2700 K and 4700 K) and

three vertical illuminance (40 lx, 75 lx, 120 lx) levels at the eye level, as shown in Table 1. To account for the limitations of CCT (Durmus, 2022), the spectral optimisation algorithm used to generate the test stimuli targeted minimal differences in the CIE 1931 (x, y) chromaticity coordinates. The CCT difference between trials was average 15 K, and even the maximum difference of 170 K was below the perceivable threshold (Chen et al., 2023).

Table 1 – The spectral characteristics of the stimuli

| Pair - trial | T_{cp} (K) | D_{uv} | E_v (lx) | $E_{v, mel}^{D65}$ (lx) | R_g | $R_{cs, h1}$ | B | R | M_{17} |
|--------------|--------------|----------|------------|-------------------------|-------|--------------|-------|------|----------|
| 1 – 1 * | 2800 | 0.001 | 120.12 | 47.5 | 97.3 | -0.11 | 193.5 | 78.1 | 41.8 |
| 1 – 2 * | 2800 | 0.001 | 120.12 | 47.5 | 97.3 | -0.11 | 193.5 | 78.1 | 41.8 |
| 2 – 1 * | 4742 | 0.0121 | 75.06 | 40.5 | 94.3 | -0.18 | 157.2 | 65.1 | 38.3 |
| 2 – 2 * | 4742 | 0.0121 | 75.06 | 40.5 | 94.3 | -0.18 | 157.2 | 65.1 | 38.3 |
| 3 – 1 | 2800 | 0.001 | 120.12 | 47.5 | 97.3 | -0.11 | 193.5 | 78.1 | 41.8 |
| 3 – 2 | 2788 | -0.0005 | 119.01 | 56.4 | 97.1 | -0.13 | 198.1 | 79.9 | 41.9 |
| 4 – 1 | 2771 | 0.0018 | 39.98 | 15.4 | 97.1 | -0.10 | 61.2 | 44.9 | 30.8 |
| 4 – 2 | 2792 | 0.0009 | 39.55 | 18.5 | 95.4 | -0.15 | 63.2 | 45.8 | 31.0 |
| 5 – 1 | 4742 | 0.0121 | 75.06 | 40.5 | 94.3 | -0.18 | 157.2 | 65.1 | 38.3 |
| 5 – 2 | 4724 | 0.0120 | 74.9 | 46.5 | 95.2 | -0.20 | 180.4 | 66.6 | 38.9 |
| 6 – 1 | 4689 | 0.0132 | 39.96 | 21.1 | 93.9 | -0.19 | 79.7 | 46.9 | 32.2 |
| 6 – 2 | 4721 | 0.0131 | 39.82 | 26.7 | 93.8 | -0.22 | 94.0 | 48.7 | 32.8 |
| 7 – 1 * | 4724 | 0.0101 | 40.06 | 31.29 | 97.9 | 0.00 | 87.2 | 50.3 | 32.5 |
| 7 – 2 * | 4724 | 0.0101 | 40.06 | 31.29 | 97.9 | 0.00 | 87.2 | 50.3 | 32.5 |
| 8 – 1 | 4724 | 0.0101 | 40.06 | 31.29 | 97.9 | 0.00 | 87.2 | 50.3 | 32.5 |
| 8 – 2 | 4604 | 0.0079 | 40.03 | 31.61 | 98.8 | 0.10 | 89.2 | 50.4 | 32.6 |
| 9 – 1 | 4724 | 0.0101 | 40.06 | 31.29 | 97.9 | 0.00 | 87.2 | 50.3 | 32.5 |
| 9 – 2 | 4783 | 0.0083 | 39.84 | 31.20 | 96.8 | -0.11 | 88.7 | 50.2 | 32.6 |
| 10 – 1 | 4724 | 0.0101 | 40.06 | 31.29 | 97.9 | 0.00 | 87.2 | 50.3 | 32.5 |
| 10 – 2 | 4767 | 0.0076 | 40.29 | 30.59 | 108.9 | 0.00 | 88.0 | 50.2 | 32.6 |
| 11 – 1 | 4724 | 0.0101 | 40.06 | 31.29 | 97.9 | 0.00 | 87.2 | 50.3 | 32.5 |
| 11 – 2 | 4568 | 0.0099 | 40.09 | 31.57 | 91.5 | 0.00 | 92.3 | 50.4 | 32.8 |
| 12 – 1 | 4724 | 0.0101 | 40.06 | 31.29 | 97.9 | 0.00 | 87.2 | 50.3 | 32.5 |
| 12 – 2 | 4677 | 0.0078 | 39.99 | 31.39 | 109.3 | 0.14 | 86.7 | 50.3 | 32.5 |
| 13 – 1 | 4724 | 0.0101 | 40.06 | 31.29 | 97.9 | 0.00 | 87.2 | 50.3 | 32.5 |
| 13 – 2 | 4624 | 0.0088 | 39.73 | 31.73 | 93.7 | 0.03 | 89.5 | 50.3 | 32.6 |
| 14 – 1 | 4724 | 0.0101 | 40.06 | 31.29 | 97.9 | 0.00 | 87.2 | 50.3 | 32.5 |
| 14 – 2 | 4894 | 0.0106 | 40.03 | 30.71 | 101.7 | -0.05 | 87.2 | 50.1 | 32.5 |
| 15 – 1 | 4724 | 0.0101 | 40.06 | 31.29 | 97.9 | 0.00 | 87.2 | 50.3 | 32.5 |
| 15 – 2 | 4668 | 0.0101 | 40.00 | 31.33 | 88.8 | -0.10 | 89.1 | 50.3 | 32.6 |

* Null conditions are identical lighting stimuli presented to evaluate left-right bias (Fotios et al., 2008).

2.3 Experimental Protocol

The experiment took place in a controlled laboratory where neutrally painted, two side-by-side rooms were utilised. The rooms were empty to control the effects of object colourfulness on brightness, such as the Hunt and Helmholtz-Kohlrausch (HK) effects (Hunt and Pointer, 2011), as shown in Fig. 1. Forty-two participants (22 females and 20 males) with an average age of 26 (age ranges between 19 and 51 years), normal colour vision, and good visual acuity were recruited to judge the spatial brightness of two side-by-side neutrally painted rooms in a 2-alternative forced choice (2AFC) simultaneous brightness experiment. Training and null conditions were provided, and trials were randomised and counterbalanced to reduce biases (Royer et al., 2022). A head-chin rest was used to stabilize participants' visual field to control the effects of visual field and retinal position of stimuli on brightness (Mahmoudzadeh et al., 2025). An ethics approval was granted by the local institutional review board (IRB).



Figure 1 – The experiment took place in neutrally painted side by side rooms and a head-chin rest was used to stabilize participants' visual field.

3 Results

The responses to null conditions (pairs 1,2,7) were around 50% suggesting there was no left/right bias, as shown in Fig.2. Melanopsin-based spatial brightness metrics' performance did not exceed 50% (coincidence). Spatial brightness metrics R and B were accurate in predicting subjective responses only 33% of the time, while M_{17} was accurate 50% of the time. The low performance of the metrics can be explained by the developers of the metrics overfitting to data by data generated using a larger range of illuminance, melanopsin response, or chromaticity values. While a model that has an applicability to a wide range of values may be useful for general use, the metrics have low explanatory power that does not provide insight into the role of melanopsin in brightness perception.

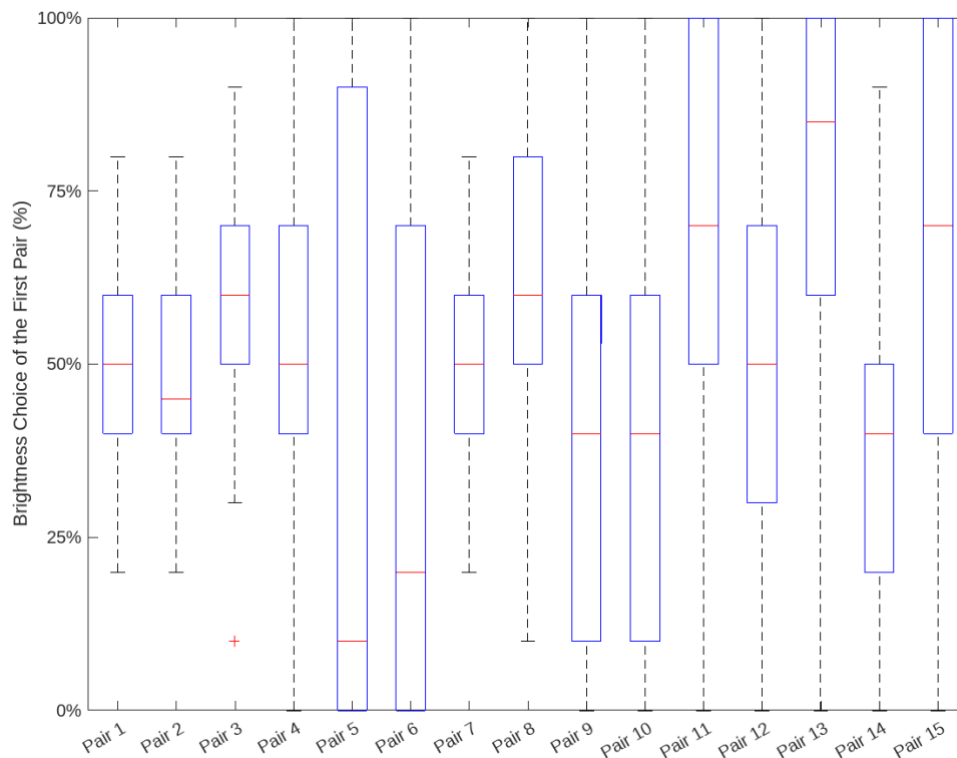


Figure 2 – Brightness responses for 15 pairs where pairs 1, 2, and 7 are null conditions.

4 Conclusions

Spatial brightness, a term more relevant for architectural lighting research and design, is gaining recognition, yet a robust quantification method is still needed. While currently there is no universally agreed spatial brightness model, the term spatial brightness has been championed to overcome the limitations of standard photometry in predicting brightness, especially due to small field of view and exclusion of photoreceptor responses beyond L- and M-cones. More recent studies also indicate melanopsin, a third photoreceptor in the retina, might be contributing to visual pathways. To address this intriguing research questions, a psychophysical experiment was conducted to evaluate the effects of melanopsin and colour gamut on spatial brightness. The experimental data was used to test the performance of specialised spatial brightness models based on melanopsin response.

The results of the experiment suggest that explanatory power of spatial brightness models is low. Future studies should use datasets with large illuminance and CCT ranges to test the predictive power of these models. Future experiments can also utilise stimuli specifically generated to identify the differences between these metrics. Nonetheless, the results suggest the need to develop more robust melanopsin-based spatial brightness models, not necessarily to predict occupants' responses in broad set of conditions, but to expand explanatory breadth of these models (Trafimow and Uhalt, 2015). Such new models can be theory driven rather than data driven to explore the working principles of the integrated human visual and non-visual responses. Such models can also help identify a threshold for the spectral dimension of spatial brightness perception.

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