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THE HELMHOLTZ–KOHLEAUSCH EFFECT ON VIRTUAL REALITY HEAD MOUNTED DISPLAYS

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Abstract

The Helmholtz–Kohlrausch effect is a well-known phenomenon where a colour with constant luminance in the photopic vision range is perceived as having a different brightness if its purity is increased. An increase in colourfulness is often accompanied by an increase in perceived brightness. Some hues display the effect more than others, such as red and magenta as compared to yellow. Many studies on the Helmholtz–Kohlrausch effect have been performed on conventional displays, but the advent of Virtual Reality provides new opportunities to explore the effect in head mounted displays. In this paper, the Helmholtz–Kohlrausch effect is analysed for a commercially available head mounted display, the Meta Quest 2. To this end, a dataset was collected from an experiment with 20 observers and the development of a lightness function for head mounted displays is discussed, based on established models in the literature.

Keywords: Helmholtz–Kohlrausch effect, Virtual Reality, Head Mounted Displays, Colour Science, Psychophysics

1 Introduction

Inside the photopic range of human vision, there is a difference in perception of a colour's brightness if the colour purity is increased. This phenomenon is known as the Helmholtz–Kohlrausch (HK) effect (Nayatani, 1998). The HK effect relates brightness to colourfulness and is prominent when colours with high chroma are compared to achromatic colours with the same luminance (High, Green and Nussbaum, 2023). The fact that a chromatic stimulus appears brighter compared to an equiluminant achromatic stimulus is due to the failure of the additivity law of brightness, and was first noticed by Helmholtz and examined more thoroughly by Kohlrausch (Yaguchi, 2023).

In this work, the HK effect is studied in detail using a commercially available Virtual Reality (VR) head mounted display (HMD). VR has gained unprecedented use in recent years in various scientific fields (Desselle et al., 2020; Delgado et al., 2020; Mäkinen et al., 2022). The developments using VR in neuroscience and psychology especially portray its usability in performing behavioural and psychophysical experiments (Wilson and Soranzo, 2015; Cohen, Botch and Robertson, 2020; Wiesing, Fink and Weidner, 2020; Gil Rodríguez et al., 2022; Elphinston et al., 2023). Moreover, VR offers the ability to perform controlled psychophysical experiments by easily changing the presented stimuli. Recent experiments on colour constancy, for instance, have shown a high degree of performance among observers and revealed results are consistent with scenarios in the real world (Gil Rodríguez et al., 2022).

Initially, the HK effect was modelled using chromaticity diagram-based models (Sanders and Wyszecki, 1963; Hellwig, Stolitzka and Fairchild, 2022). However, due to their limitations formula-based models emerged. These include, amongst others, those defined by Fairchild and Pirrotta (Fairchild and Pirrotta, 1991), and more recently by Hellwig et al. (Hellwig, Stolitzka and Fairchild, 2022) and High et al. (High, Green and Nussbaum, 2023). The stated models can be summarised using Eq. 1.

$$L_{EAL}^* = L^* + k \times C_{ab}^* \quad (1)$$

where

- L_{EAL}^* is defined as the achromatic stimulus that is perceived to have the same lightness as a particular colour stimulus;
- L^* is the lightness of a particular colour stimulus;
- k is a scaling factor;
- C_{ab}^* is the chroma of a particular colour stimulus.

Compared to conventional displays, VR HMDs offer greater immersion, a wider field of view and head tracking, and thus might provide a more naturalistic perception of stimuli. Therefore, in this study, the HK effect is investigated using a calibrated VR HMD (Bhaumik, Van De Perre and Leloup, 2024). Twenty observers performed a magnitude estimation experiment using the Meta Quest 2 HMD, in which the perceived brightness of 60 chromatic stimuli was assessed. From the dataset, the HK effect was modelled based on previously outlined approaches and compared to results from earlier studies with conventional displays.

2 Device under test

The Meta Quest 2, a commercially available HMD, was used to conduct the experiments. The HMD incorporates LCD displays with a screen resolution of 1832 × 1920 pixels. It was driven using an Alienware m15 laptop (16 GB RAM, 64-bit Windows 10 Enterprise, Intel® Core™ i7-8750H CPU at 2.2 GHz, NVIDIA GeForce GTX1060 6 GB Video RAM). The experimental setup is shown in Figure 1.



Figure 1 – The Meta Quest 2 HMD used in the experiment, with white circles representing a circular stimulus displayed to the observer.

3 Dataset

A dataset was generated by designing a series of stimuli, each featuring a circular target displayed on a black background. The circular target subtends a 10-degree field of view to the observer's eye. A reference stimulus is defined, consisting of an achromatic stimulus with a CIELAB L^* value of 50. Six different hues (Red, Green, Blue, Cyan, Magenta, and Yellow) were chosen, each of which was displayed at 10 different L^* levels, as shown in Figure 2, resulting in a set of 60 test stimuli covering the entire luminance range of the HMD.

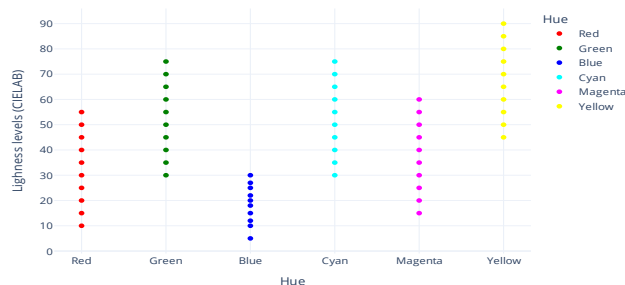


Figure 2 – Distribution of L^* levels for each hue presented at 10 distinct levels.

4 Experiments

Twenty observers (13 male; 7 female) performed a magnitude estimation experiment in which the reference stimulus and test stimuli were presented alternately. The observers were indicated to assign a value of 100 to the perceived brightness of the reference stimulus. Based on this, they had to estimate the brightness of each chromatic test stimulus. The adjudged brightness of the test stimulus could include every value, higher as well as lower than 100, depending on whether the observer estimated the stimulus to be brighter or darker, respectively. A schematic overview of the experimental procedure is shown in Figure 3, where observers viewed the reference and test stimuli in alternating 5-second intervals. All observers were checked to have normal colour vision and all experiments were conducted in accordance with ethical guidelines.

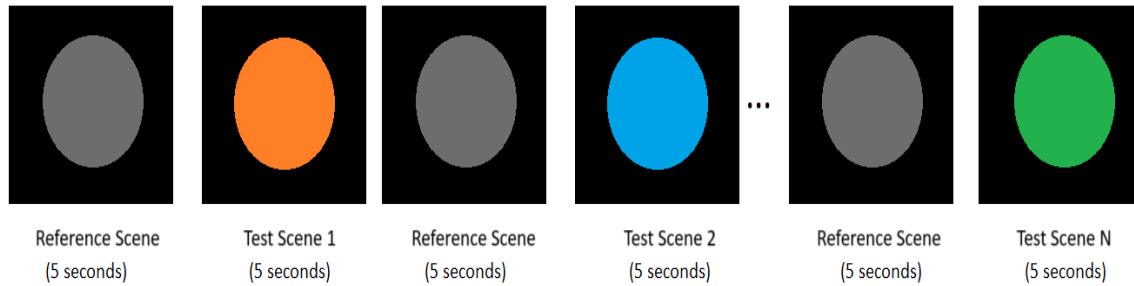


Figure 3 – A schematic of the magnitude estimation experiment, showing alternating presentation of the reference stimulus and test stimuli to observers.

The stimuli were presented in a randomized order to each observer to exclude potential order effects and to allow for an unbiased evaluation. The observers were given a brief acclimatisation period before the start of the experiments. To account for inter- and intra-observer variability, each stimulus was presented twice to each observer, yielding a total of 120 test stimuli. For each observer, the experiment took about 30 minutes. The experiment was divided into four sections, allowing participants to take a break if needed.

5 Modelling the HK effect

The suitability of models derived from experiments on conventional displays was investigated using the visual data derived from the stimuli presented on the HMD. To predict lightness based on hue and chroma characteristics, several established models (High, Green and Nussbaum, 2023; Hellwig, Stolitzka and Fairchild, 2022; Fairchild and Pirrotta, 1991), along with two newer approaches utilizing Fourier-based and Polynomial-based methods, were applied to the dataset gathered from the magnitude estimation experiment. For each model, parameters were optimized using the experimental dataset to minimize the Root Mean Square (RMS) error between the model's predicted lightness and the average observed lightness (defined as the ratio of the brightness of a test stimulus to the brightness of the reference stimulus) from all participants for each stimulus.

6 Results and Conclusion

The results of the experiments highlight the prominence of the HK effect in VR, particularly for blue, red, and magenta, in comparison to yellow hues. These results are consistent with earlier findings from experiments on conventional displays. A model accounting for the HK effect in VR HMDs, based on and similar to that proposed by High et al. (High, Green and Nussbaum, 2023), demonstrated the best fit to the observed data, yielding an R^2 value of 0.94. The model predicts the perceptual lightness of the chromatic stimulus based on its hue and chroma, as defined in Eq. 2. A graphical representation of the average observed lightness against the L^* values predicted from the model, is presented for all 60 stimuli in Figure 4.

$$L_{EAL}^* = L^* + [f(h) + f_r(h)] \times C_{ab}^* \quad (2)$$

$$f(h) = 0.083 \left| \sin\left(\frac{h - 90^\circ}{2}\right) \right| - 0.0314$$

$$f_r(h) = \begin{cases} -0.201|\cos(h)| + 0.347, & \text{for } -90^\circ \leq h \leq 90^\circ \\ 0, & \text{otherwise} \end{cases}$$

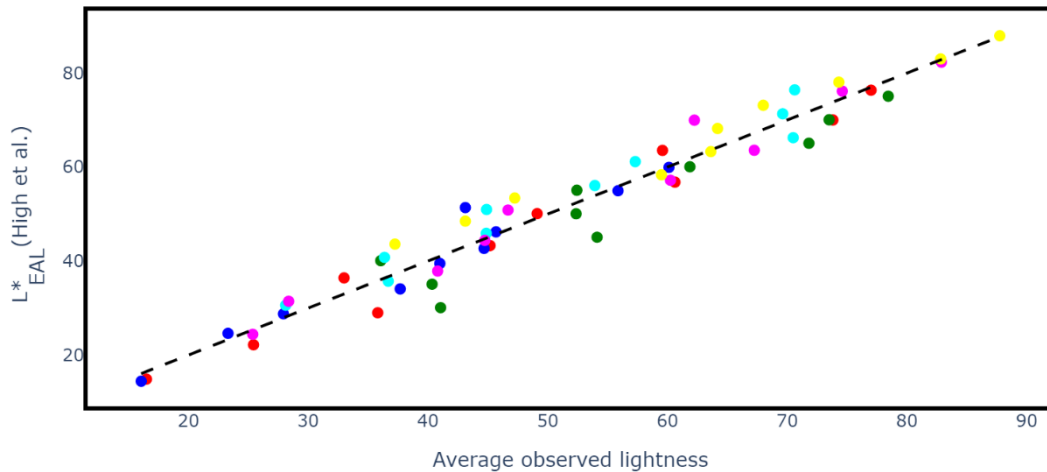


Figure 4 – Representation of the agreement between the average perceived lightness and the predicted L^* values, derived from the High et al. model, for all 60 test stimuli. The diagonal represents perfect agreement between the model predictions and the observed data. Each point, coloured to match its stimulus, represents one test sample.

Although of all the tested models, the High et al. formulation achieved the highest R^2 value, also the Hellwig et al. model, Fourier and polynomial approaches showed good agreement and comparable predictive accuracy. The Fairchild–Pirrotta model is the simplest, with the fewest parameters, but showed somewhat lower performance. In Table 1, a comprehensive comparison of all five tested models is presented, listing each model's RMS error alongside its corresponding R^2 value. Although increasing the number of components in the Fourier and polynomial models could further reduce their prediction errors, such enhancements would introduce a trade-off in terms of greater model complexity and parameter count. Finally, all models were calibrated specifically on data obtained from the Meta Quest 2 headset, and their coefficients therefore embody the colour-gamut characteristics of this device; applying these models to data from other head-mounted displays would likely necessitate re-parameterisation to account for differing gamut profiles.

Table 1 – RMS error and R^2 values for all tested models.

Model	RMS error	R^2
Fairchild and Pirrotta	6.32	0.87
High et al.	4.02	0.94
Hellwig et al.	5.20	0.91
Fourier-based	5.78	0.91
Polynomial-based	5.73	0.91

In conclusion, this study on the HK effect has demonstrated that VR could be a valuable tool for psychophysical experimentation, offering controlled testing conditions for colour science research. In the near future, further experiments will be performed in which observers will be instructed to match the brightness of a chromatic stimulus to that of another chromatic stimulus to validate the derived lightness model.

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