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ON THE INVESTIGATION OF THE CIE 1931 COLORIMETRIC OBSERVER

PhD THESIS

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I. Introduction, aim of the work

The International Commission on Illumination (Commission Internationale de l'Eclairage, CIE) created the first standard trichromatic colorimetric system in 1931: the CIE 1931 standard colorimetric observer [H1], based on three spectral sensitivity curves of human colour vision. These weighting functions were determined in psychophysical experiments, they represent the average of the spectral sensitivity of 17 normal observers.

Since their creation problems were reported on the usability of the standard observer, satisfactory explanations of these errors can be found in the literature.

In the past decade Thornton and co-workers found very large errors [H2] that question the usability of the standard observer, they detected a computed colour difference of up to 70 ΔE^*_{ab} between visually matching metameric sample pairs using nearly monochromatic primaries. They concluded that the magnitude of errors depends on the wavelength range where the spectral power of the stimulus is concentrated.

In my thesis the standard observer is tested in visual experiments modelling applications in information technology. Two additive colour-matching experiments were performed using highly metameric sample pairs.

To be able to define the chromaticity of the white point of display devices and light sources correctly, first I had to deal with the concept of correlated colour temperature (CCT). CCT has been defined based on the smallest colour appearance difference between two colour stimuli [H3]. I could show that this is an ambiguous definition, and according to our proposal, the CIE accepted an objective definition for the determination of CCT [H4].

In the first colour matching experiment the primaries of a CRT monitor were used, observers had to match incandescent lamp illuminated Munsell samples with samples produced on the display. Considerable differences were found in computed chromaticities of the visually matching stimuli, but these differences were not systematic. Inter-observer variances of the colour matches are to be considered in testing colour appearance models. The accuracy of the matches predicted by the standard observer decreased as the metamerism of the samples increased. Based on this I could formulate a colour difference value below of which it is not meaningful anymore to search for colour equality. Next light emitting diodes (LEDs) were used as primaries, the additive mixture of red, green, and blue LEDs were matched to a filtered incandescent source in a Brodhun-type visual photometer. Two LED clusters were constructed, their emission power concentrated at different spectral regions. I could show that the Judd-Vos modification of the standard observer [H5] models more accurately matches set by real observers with narrowband sources. Disagreement was found between the errors found in my experiments and predicted by Thornton. It is shown that the Judd-Vos modification of the standard observer contradicts Thornton’s definition of spectral regions in a mathematical sense.

II. References

[H1] Commission Internationale de l'Éclairage: Colorimetric Observers. ISO/**CIE 10527**-1991

[H2] Thornton W.A.: Toward a more accurate and extensible colorimetry. Part I. – IV. *Color Research and Application* 1992 - 1997

[H3] Grum F., Saunders S.B., MacAdam L.: Concept of correlated color temperature, *Color Research and Application,* 1978, **3** 17-21.

[H4] CIE D1/D2 Symposium, Veszprém, 2002

[H5] Vos J.J.: Colorimetric and photometric properties of a 2° Standard Observer. *Color Research and Application*, 1978, 3/3: 125-128.

III. Theses

1. I have proved experimentally that the visual meaning of the definition of correlated colour temperature – based on the visual finding of observers – can not be confirmed, the determination of its value is uncertain. The visual definition of the term correlated colour temperature has to be abandoned, the definition should be based on the CIE 1960 u,v chromaticity diagram. [2]

2. I have proved experimentally that the accuracy of the CIE 1931 colorimetric observer decreases in case of highly metameric colour stimuli. I have found considerable differences in calculated chromaticities of visually matching metameric stimuli, the magnitude of these errors did not exceed those found in literature.[1,4] Based on the visual experiments I recommend that the errors found be considered when colour appearance model predictions are compared or analysed. If the metameric match prediction is already biased by colour differences of 3-10 ΔE^{*}_{ab} units, it is not worthwhile to search for colour differences on the order of 1-3 ΔE^{*}_{ab} units in case of complex models that use tristimulus values of metameric colour stimuli as an input. [1]

3. W. A. Thornton and co-workers have claimed that using short-, medium- and long- wavelength quasi-monochromatic primaries in additive colour matching experiments, one can select primaries

from the so called Prime Colour (PC), Non-Prime (NP) and Anti-Prime (AP) ‘spectral regions‘, chromaticity coordinates of the visually matching stimuli will deviate from each other depending on whether the prime stimuli were selected from the PC, NP or AP spectral region and the differences will increase in the order PC < NP < AP. I have shown experimentally that subdividing the visible spectrum into PC, NP and AP ‘spectral regions‘ contradicts the usability of the CIE 1931 colorimetric system. [4]

4. I have pointed out, that practical colorimetry and color research may benefit from the introduction of a new standard colorimetric observer, but the replacement of the 1931 standard observer can not be justified based on my experiments using light emitting diodes and CRT displays. In case of LEDs and narrow band stimuli with high values in the wavelength range below 500 nm I recommend using the Judd – Vos modification of the standard observer, as I could show that the modified observer represents real observers more accurately in the short wavelength range. [4]

IV. Publications

In international journals

[1] **Á. Borbély**, J. Schanda: The usability of the CIE colour matching functions in the case of CRT monitors, *Color Research and Application*, **26,** 2001, 436 – 441.

[2] **Á. Borbély**, Á. Sámson, J. Schanda: The concept of correlated color temperature revisited, *Color Research and Application,* **26,** 2001, 450 – 457.

[3] P. Bodrogi, B. Sinka, **Á. Borbély**, N. Geiger, J. Schanda: On the use of the sRGB colour space: the "Gamma" problem. *Displays*, **23**/4, 2002, 165 – 170.

[4] **Á. Borbély**, J. Schanda: Colour matching using LEDs as primaries, *Color Research and Application* **29**, 2004, 360-364.

Conference Papers

[5] **Borbély Á**., Schanda J.: A színinger megfeleltető függvények vizsgálata erősen metamer minták esetén / On the use of colour matching functions in case of highly metameric samples. XXVII. Kolorisztikai Szimpózium, Tata 1999.

[6] Schanda J., Bodrogi P., **Borbély Á**., Kránicz B., Rehák R., Sikné Lányi C., Szolgay P., Schanda J.: Összetett képi információ feldolgozása / Processing of Complex Pictorial Information. Magyar Informatikusok II. Világtalálkozója, Bp. 2000. 859-866.

[7] **Borbély Á.**, Schanda J.: Színmegfeleltetés LED alapszínekkel / Colour matching with LED primaries. Proc. XXVIII. Kolorisztikai Szimpózium, Tata 2001, 148-152.

[8] C. Sik-Lányi, **Á. Borbély**, J. Schanda: Cognitive Effects of White Point Definition on Computer Screens, CIM98, Derby 1998.

[9] C. Sik-Lányi, **Á. Borbély**, J. Schanda: Cognitive Effects in Image Reproduction on Computer Screens, 5th International Symposium „Colour and Colorimetry”, Kranj 1998.

[10] **Á. Borbély**: Kognitive Effekte der Weisspunktdefinition am Komputerbildschirm, Farb-Info ’98, Wien 1998

[11] **Á. Borbély**, J. Schanda: Colour matching using LEDs as primaries, Proc. 2. CIE Expert Symposium on LED Measurement, 2001, Gaithersburgh, MD, USA.

[12] **Á. Borbély**, S.G. Johnson: Prediction of light extraction efficiency of LEDs by ray trace simulation**,** 3. International Conference on Solid State Lighting, SPIE Annual Meeting, 2003, San Diego, CA, USA.

[13] **Á. Borbély**, S.G. Johnson: Performance of phosphor coated LED packages in ray trace simulation**,** 4. International Conference on Solid State Lighting, SPIE Annual Meeting, 2004, Denver, CO, USA.