The Art of Color Science: Individual Differences

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ABSTRACT

The fundamental data of color science are color matching functions, which represent the spectral absorption properties of cone photoreceptors. All colorimetry follows from these functions, which, in standard form, are intended to represent the average sensitivities of the population of human observers with normal color vision. Individuals are, however, individual and have their own color matching functions and other visual responses that naturally vary from the mean. This paper provides a review of the nature and magnitude of individual differences in color matching functions and other mechanisms of color perception along with suggestions for practical systems to account for individual differences in colorimetric practice.

1. The Big Questions

The two big questions discussed in this paper are (1) What do you see? And (2) Do you see what I see? Such questions often cross into the domain of the psychology and philosophy of perception [1] or into the insoluble questions of qualia [2] (*e.g.*, is what you perceive when seeing a stimulus described as red the same is what I perceive when seeing a stimulus described as red).

However, these questions can be addressed to a degree from a more fundamental level. This is accomplished by examining individual differences in the absorption of light by the three cone classes in various observers (individual differences in color matching functions) and the anatomy and physiology underlying them. The phenomena of individual differences in color matching functions is often described under the rubric of observer metamerism (two stimuli that match in color to one observer might mismatch to another). In addition, this paper examines individual differences in the higher-order mechanisms of chromatic adaptation.

2. Color Matching Functions

The CIE standard colorimetric observer was first defined in 1931 (with a second version established in 1964 for larger fields of view) as well understood and utilized in practical colorimetry.[3] These functions were intended to represent the color sensitivities of a mean, or average, observer and they have performed admirably in that role for nearly a century. It has also long been known that individual observers exhibit significant variation about those means in their color matching function data.[4] However, until recently, there were neither resources for, nor interest in, carefully defining individual color matching functions and the variance of the population.

One approach to efficiently defining individual color matching functions has been *Monte Carlo* simulation of the various physiological parameters that make up color matching functions (lens, macula, pigments) in order to synthesize individual functions.[5] Such techniques have proven quite accurate and effective. In addition, the CIE, in 2006, defined more accurate mean functions for variable age and field size [6] and Asano *et al.* refined the *Monte Carlo* techniques to the point that individual observers could be accurately modeled and characterized.[7]

Ultimately, these advances have allowed systems of individual colorimetry to be practically implemented and the first practical system to predict both mean color matches and confidence volumes about such matches representing the spread of the observer population as first suggested by Nimeroff *et al.* in 1961[8] and as pursued by the author for approximately three decades.

3. Chromatic Adaptation

Once cone signals are established through absorption of light according to the cone responsivities (*i.e.* color matching functions), they are subject to the mechanisms of chromatic adaptation to produce signals that ultimately correlate with color appearance. While it is well established that there are individual differences in color matching functions, the question of whether there are additional individual differences in chromatic adaptation mechanisms (not due to the CMFs themselves) remains open. One reason this has not been previously explored in the context of color appearance is that corresponding colors data, required to quantify chromatic adaptation mechanisms, are often very imprecise and any potential individual differences are masked by uncertainty in the results. Once averaged across observers, corresponding colors data are well described using the von Kries hypothesis, and modern implementations of what is now called the von Kries model, that dates back more than a century.[9]

More recently, research has been completed to obtain significantly more precise corresponding colors data.[10] These results indicate that there are very significant individual differences in chromatic adaptation and that it might be necessary to have individual models of chromatic adaptation, in addition to individual CMFs, in order to properly predict appearance.

Additionally, the results indicated that it might be possible that chromatic adaptation is not reversible.[11] In other words, when given a reference color under light source A and asked to select a corresponding color under light source B, the answer might differ from the reverse task when the reference is under source B and the match is selected under source A. Chromatic adaptation might not follow a transitive property across changes in illumination. This result is surprising and requires additional data to be confirmed. Such research is now underway.

Putting this all together allows improvements in a variety of applications such as the potential for individualized color reproduction for high-quality applications and quantifying the individual variability in assessment and specification of the color rendering properties of illumination.[13]

4. A Note On Tetrachromacy

One topic of individual differences that has recently sparked more interest than warranted is the potential for tetrachromacy in female carriers of anomalous trichromacy. The potential for female trichromacy was discussed as early as 1948[14] and speculated upon decades earlier.[15] Because these females, especially if they have one son with normal color vision and another with anomalous trichromacy, have the genetic coding for four distinct classes of cones, it is likely that they have four classes of cones in their retina. However, what seems likely, and perhaps ubiquitous, is that these women still have trichromatic color appearance such that the four cone classes are fed into three color responses at some point in the visual system. No female observer has yet been identified with strong tetrachromacy (a four-dimensional color space) although Jordan *et al.*[16] did manage to find one female carrier out of 24 evaluated that showed some signs of additional discrimination ability. However, the extra dimension was not fully established in that work and there are no indications of observers who cannot function with trichromatic color reproduction (*i.e.* would require a fourth primary in imaging systems) so it is possible there are not functional, or strong, tetrachromats despite the potential being there.

6. Conclusions

Colorimetry has been successful for nearly a decade based on the psychophysical measurement and modeling of average, or mean, observers in terms of color matching functions and chromatic adaptation models. More recent data suggest that individual differences in both can have significant impact on the correlation between predicted matches and appearance and individual visual assessments. Fortunately advances are underway to allow colorimetry to be personalized for individual differences in both aspects of color perception and the promise for an improved future system of colorimetry is strong.

6. REFERENCES

[1] D. Katz, “The World of Colour,” Kegan Paul, London (1935).

[2] D. Dennett,“Quining Qualia,” in Mind and Cognition, W. Lycan (ed.), Oxford: Blackwell, 519–548 (1990).

[3] CIE, “Colorimetry, 4th Ed.,” CIE 015:2018 (2018).

[4] G. Wyszecki and W.S. Stiles, “Color Science, 2nd Ed.” Wiley, New York (1982).

[5] M.D. Fairchild and R.L. Heckaman, “Metameric observers: A Monte Carlo approach,” pp.185-190, IS&T 21st Color & Imaging Conference, Albuquerque (2013).

[6] CIE, “Fundamental Chromaticity Diagram with Physiological Axes - Part 1,” CIE 170:2006 (2006).

[7] Y. Asano, M.D. Fairchild, and L. Blondé, “Individual colorimetric observer model,” e0145671 , PLOS ONE, Vol. 11 (2016).

[8] I. Nimeroff, J.R. Rosenblatt and M.C. Dannemiller, “Variability of spectral tristimulus values,” pp.475-483, J. Research NBS A, Vol. 65A, No. 6 (1961).

[9] J. von Kries, “Chromatic adaptation,” Festschrift der Albrecht-Ludwig-Universität, (Fribourg) (1902) [Translation: D.L. MacAdam, Sources of Color Science, MIT Press, Cambridge, (1970)].

[10] S. Cai and M.D. Fairchild, “Individual corresponding colors data and chromatic adaptation transform,” pp. 248-253, IS&T 24th Color & Imaging Conference, San Diego (2016).

[11] S. Cai and M.D. Fairchild, “Bidirectional individual corresponding colors data,” pp.643-654, Color Research and Application , Vol. 43 (2018).

[12] M.D. Fairchild, “What sets the state of chromatic adaptation?,” in press, OSA Fall Vision Meeting, Washington, D.C. (2019).

[13] M.J. Murdoch and M.D. Fairchild, “Modeling the effects of inter-observer variation on color rendition,” pp.1-18, Lighting Research and Technology, Vol. 49 (2017).

[14] H.L. DeVries, “The fundamental response curves of normal and abnormal dichromatic and trichromatic eyes,” Physica, pp.367-380, Vol. 14 (1948).

[15] G. Jordan and J.D. Mollon, “A study of women heterozygous for color deficiencies,” Vision Res., pp.1495-1508, Vol. 33, No. 11 (1993).

[16] G. Jordan, S.S. Deep, J.M. Bosten, and J.D. Mollon, “The dimensionality of color vision in carriers of anomalous trichromacy,” J. Vision, 12, Vol. 10, No. 8 (2010).