Photoreceptor absorption curves account for human chromatic discrimination ability

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Photoreceptors constitute the first stage in the processing of color information; many more stages are required before humans can consciously report whether two stimuli are perceived as chromatically equal or not. Therefore, although photoreceptor absorption properties are expected to influence the accuracy of conscious discriminability, there is no reason to believe that they should suffice to explain it. However, by means of a simple information-theoretical analysis, here we demonstrate that photoreceptor absorption properties predict the wavelength dependence of human color discrimination ability, as tested by behavioral experiments [1]. The result can be extended beyond the discrimination of pure wavelengths, including also experiments performed with arbitrary spectral profiles [2], for which ~70-80% of the variance of the experimental data can be explained.

The derivation is based in the calculation of the amount of Fisher Information [3] about wavelength (or more generally, about color) contained in the number of photons absorbed by S, M and L cones. The Cramer-Rao bound [4] ensures that any observer attempting to estimate the wavelength of the stimulus from the rates of photon absorption necessarily makes an average estimation error that is at least as large as the inverse of the square root of the Fisher Information.

The analysis requires the knowledge of just two physiological properties: the probability a S, M or L cone absorbs a photon of wavelength λ (which is taken from [5]), and the relative numbers of S, M or L cones in the system under study. In humans, these numbers are approximately 5%, 35% and 60%, respectively, although there is considerable subject-to-subject variability [6]. Such variability in the composition of the photoreceptor layer predicts a certain amount of variability in the wavelength dependence of human discrimination ability, which actually matches the various shapes that have been recorded experimentally. In the framework of our study, hence, the variability in the experimental data does not reflect noise or poor experimental design (as has been sometimes suggested) but rather, subject-to-subject variability in cone relative populations.

The analysis contains a single fitting parameter: the overall luminescence. This parameter constitutes a global scaling factor, and the theory predicts that the discrimination error should diminish as the square root of the total luminescence. The formalism is easily extended to predict the discrimination ability of subjects with atypical photoreceptor absorption characteristics, as in daltonism or tetrachromatism. We are therefore able to show the discrimination ability of subjects (human or not) endowed with arbitrary color-selective sensors.

The Cramer-Rao approach imposes a lower bound to the discrimination error only due to the stochasticity in photon absorption. Since downstream decoding stages need not behave as ideal observers, and since there may well be additional sources of noise, there is no reason to believe that the bound should be tight. The actual error obtained in behavioral experiments can well be expected to be larger than predicted by our analysis, for example, due to additional stochastic elements appearing later on. The agreement between the theoretical and experimental results implies that the bottleneck in chromatic information processing is mainly determined by photoreceptor absorption characteristics and that subsequent encoding stages preserve to a large extent the wavelength dependence of chromatic discriminability at the photoreceptor level. As a consequence, we conclude that downstream processing areas either perform nearly optimality or, if loose information, do so in a color-independent manner.

References

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