ATD Model for Color Vision I: Background

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Abstract

An historical background is provided for the ATD model for color perception and visual adaptation, whose developing variations have appeared over a period of several years, and which is applied to several sets of chromatic adaptation data in the succeeding companion paper.

2. Background

From an historical perspective, the development of the ATD model can be described in two or three sentences. From a personal perspective, a description of the model's evolution requires a review of my entire career in the field of color vision. For example, in regard to an historical perspective, a scholar might write, "In his early models,[1,2,3,4] Guth used what was essentially a Müller/Judd[5] first post-receptor stage, and suggested that the outputs of the three stages represented detection or brightness vectors in Euclidian 3-space. Later, retaining the vector space for a first stage (and adding a line-element discrimination rule to that space) he added a second post-receptor stage that was like that of Hering/Hurvich & Jameson,[6] which meant that he was accepting a complete Müller/Judd[5] model, to which he added, (i) receptor nonlinearities, (ii) receptor "dark light" or constant "noise" signals, (iii) nonlinear von Kries-like receptor gain control, and (iv) neural compression late in the visual pathway.[7,8,9,10,11]

From a personal perspective, the model's development begins with my experiments concerning heterochromatic additivity at threshold levels. (Initial work was described as being in the area of "luminance additivity"—a phrase that was not ideal, since luminance is formally defined as being additive. However, the phrase is appropriate if "luminance" is seen as a conceptual term that can be defined in terms of many different visual responses, such as, detection, direct brightness matching, flicker photometry, visual acuity, etc.) The earliest work included the discovery that spectral lights could actually be mutually inhibitory in the sense that a red-plus-green (or red-plus-blue) mixture could be less detectable than the red alone.[12] Subsequent experiments[13] led to a considerable body of data that showed the extent to which nonadditivity characterized the detectabilities of pairs of monochromatic lights chosen from the entire visible spectrum, and parallel qualitative theoretical developments (all within the framework of opponent colors theory) led to my suggestion (now almost taken for granted by the vision community) that CIE-defined luminance really describes the spectral sensitivity of the nonopponent post-receptor mechanism (because it is the system that is tapped by flicker photometry) whereas apparent brightnesses and threshold visibilities are mediated by neural information from opponent and nonopponent mechanisms.[14,15] A major advance occurred when I found that a three-dimensional vector space, in which just detectable wavelengths were represented as unit-length vectors, well-described a very large body of additivity data.[15] Later, I realized that the 3-dimensional vector configuration that so precisely described my additivity data could be rotated such that its axes represented the 3 post-receptor mechanisms of an opponent colors model. (I did not then realize that the postulated mechanisms were very similar to the first post-receptor stage of Judd/Müller.) Thus was born the initial quantitative ATD vector model.[1,2] The letters A, T and D are abbreviations for, "Achromatic", "Tritanopic" and "Deuteranopic" mechanisms, and it was postulated that the A system signals whiteness, the T system signals redness or greenness, and the D system signals blueness or yellowness. However, the model was not completely satisfactory as an encoder of color appearance (as discussed below) and the main thrust of the model was to predict threshold-level spectral sensitivity and additivity data. It was also applied, with reasonable success, to data concerning differences between the apparent brightnesses and the CIE-defined luminances of colored lights.

Later[3,4] the ATD mechanisms were expressed in terms of the cone receptors, and the idea that many visual phenomena could be modelled using the concept of post-receptor adaptation[16] was very profitably introduced into the theory. I then continued to explore the concept of post-receptor adaptation with both theory and experiment;[17,18] however, the results of what proved to be the last experiment along these lines were not consistent with the hypothesis of post-receptor adaptation, and I began to doubt my own prior interpretations.[19]

In regard to color appearances, the crucial flaw in the model was that there was no red signal in short wavelengths from the T system. That is, according to classical Hering/Hurvich & Jameson opponent colors theory, there is an S cone input to the red/green system, and that input has the same (excitatory or inhibitory) sign as the L input to that system. Therefore, stimulation of the eye with short wavelengths produces a red signal from the red/green system, and that redness combines with blueness from the blue/yellow system to produce the sensation of violet. The consequence for our model was that there was no correlate for violet, and no correlate for the perception of unique blue (which is in the short wavelength region where the response of the T system is at zero (i.e., where its response crosses from one polarity to the other). In the discussion section of Guth, Massof and Benzschawel, we pointed out that the Müller/Judd model solved the problem by introducing a second opponent stage, which received its inputs from the first opponent stage, and whose outputs were like those of the classical Hering/Hurvich and Jameson model. We also pointed out that we could not adopt the Müller/Judd model, because our model suggested that ATD weights changed with luminance level, and that in turn incorrectly implied, within a linear Müller/Judd model, that the spectral locations of the unique hues would vary with intensity level.

I next studied the Abney effect, which pertains to hue shifts that accompany admixtures of white to spectral lights.[20] My initial interpretations of the observed effects were in terms of post-receptor interactions, but the interpretations were overly awkward. Similarly, I found the ATDN model, which postulated different nonlinearities for the outputs of the post-receptor chromatic mechanisms, rather unconvincing.[21] At about this time, my doubts about post-receptor adaptation effects and doubts about post-receptor interactions and doubts about differential post-receptor nonlinearities led me to new modelling directions. In particular, I considered the possibility that what I thought were post-receptor effects were really consequences of nonlinearities at the receptor level.

Accordingly, I decided to discontinue laboratory work until I had explored nonlinear color models. I was fortunate to be able to hire a professional programmer who was to work with me for several years, and who was capable of translating my ideas into a user-friendly computer program that I could use to explore nonlinear theories. My initial goal was to build a model that could explain hue shifts (*and* hue invariances) in the color solid. These shifts are known as (i) Bezold-Brucke intensity-dependent shifts, (ii) Abney hue shifts due to white-plus-chromatic admixtures and (iii) what I call Munsell hue shifts, which are white-plus-chromatic hue shifts in the equal luminance plane. (Actually, the three are not really independent.) I reasoned that these effects reflect very basic visual processes, and that I could not claim to have even a rudimentary nonlinear color model if I could not account for these hue shifts.

I tried countless varieties of nonlinearities at the receptor level, with no success. (This latter sentence describes about a year of work.) I then decided to explore a three-stage model (receptor and two post-receptor stages) like that of Müller/Judd and I examined the consequences of von Kries gain control at the receptor level I soon realized that von Kries' proportionality rule was inappropriate for general modelling purposes, because it implies that neural signals will not increase as intensity increases. As a last resort, I tried a nonlinear gain control rule, which I made to have the property of attenuating receptor signals by an accelerating proportion as intensity increases. (Nonlinear gain control processes in vision have a long history.)

At that point, successful predictions began to emerge, and, with the addition of the final compressive stage (which is ever-present in modern adaptation models) the full power of the model eventually became evident. I say "eventually" because it took thousands of hours (literally) over a period of more than two additional years to test the model against a very large data base, and to arrive at a compromise set of parameters that would allow satisfactory predictions. Especially surprising was the fact that poorly understood contrast and adaptation effects were predicted, even though the model was not developed with those effects in mind. The model also confirmed my suspicion that what seem to be post-receptor effects are really consequences of nonlinear gain control at the receptor level.

To return to the opening paragraph of this paper, what emerged from all of my work was not at all surprising when viewed from an historical perspective. That is, although I many times experienced the pleasure of personal discovery and creative insight during the years of the model's evolution, an impersonal and objective analysis of the model suggests that it offers very little that is new, and that it merely incorporates in one model what many people in the field of color vision know must be there in the first place.

I presented preliminary versions of the model in 1989.[7,8] The first comprehensive description of the model together with additional illustrations of its predictive power was published in 1991,[9,10] and an improvement of that version appears in the 1993 SPIE Proceedings.[11] The major 1993 improvements included a rescaling of the model to allow input with X'Y'Z's (or XYZ's in most cases) in photopic trolands, and, more importantly, the addition of a power function on the initial receptor response. The power function was required to solve the problems that the white point of the model shifted excessively at moderately high luminances and that the overall intensity-response function was too steep to approximate accepted apparent-brightness vs luminance functions.

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