ATD Model for Color Vision II: Applications

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Abstract

Using a slightly modified version of an earlier model, and using a new rule for simulating the effects of simultaneous or successive chromatic adaptation, excellent predictions are made for experimental data that offer especially strong challenges to models for chromatic adaptation.

2. Introduction

The applications considered in this paper are based upon a slight variation of the ATD93p model, which is described in volume 1913 of the 1993 SPE Proceedings.[1] It is also necessary to read the tutorial description that appears in the Journal of the Optical Society of America.[2,3] In writing this paper, I assume that the reader has both of those articles at hand.

At the outset, it must be noted that I could use ATD93p without any parametric modifications and still show predictions that are excellent. However, the variation of ATD93p that I use here allows chromatic adaptation predictions that are somewhat improved. The changes involve an increase in the initial weight for the S receptor, and a compensating decrease in the amount of S that feeds the D_1 system. Specifically, referring to the 1993 Proceedings, in the last paragraph on page 440, and in equation 2c, the initial weighting factor for S is changed from 0.45 to 3.0. Also, in equation 4c on page 442, the coefficient for S' is changed from 1.04 to 0.32. (For illustrative purposes, there is one case where I here show predictions based upon slightly different adjustments of S.)

In regard to how the model is applied, this paper introduces a very important change. In all previous versions of the model, chromatic adaptation effects on color appearances were modelled by changing the gain control parameters in order to exaggerate the attenuations of the receptor responses. The new procedure, which is intuitively more appealing, is to weight the adapting stimuli by factors that presumably relate to display characteristics such as their size and duration. (This change also produces a major conceptual improvement in the model, because the gain control system remains always fixed, which means that the entire model is now completely "hard wired".) For example, in many cases, an adapting light covers a relatively large portion of the visual field, whereas a "target" light, whose appearance is of concern, is quite small. Within the model, it is then assumed that, *in regard to its effect on gain control for the receptors associated with the target light*, the luminance of the adaptation light must be multiplied by a factor, now called α, that can be at least as high as 50. It is as if there is a retinal flooding of neural information from surrounding areas that affects gain control in center areas. Similarly, in cases of successive contrast, a long duration, and intensely fixated adapting light might also be associated with large α's. It should be noted that, within the model, no conceptual distinction is made between successive and simultaneous (spatial) contrast, in the sense that both phenomena are produced by gain control changes.

Consider now the general procedure for making predictions about chromatic adaptation effects on a target light. In this section, frequent reference will be made to equations in the 1993 Proceedings.) The most straightforward case is when it can be assumed that gain control for the target light is determined solely by the adapting light. (This is the assumption for all predictions made in the present paper.) The assumption is probably reasonable for situations in which there are large adapting fields and small target lights (unless the target light is intensely fixated) and/or long duration adaptation lights and briefly viewed target lights.

First, to evaluate the color appearance of the target light as it would appear in the dark, the X'Y'Z' values (in trolands) for the light are put through the model in the usual way in order to obtain the light's $A_2T_2D_2$ values. [It is probably true that XYZ's, rather than X'Y'Z's, can be used in most situations, and I do just that for the MacAdam[4] and McCann[5] *et.al.*/Land[6] data that I consider below. Also, I have noticed that log trolands are linearly related to log luminance, and I *tentatively* suggest the following equation to convert luminance (in cd/m²) to trolands (td):]

$$\text{td} = 18\ L^{0.8}.$$

Referring to the 1993 Puddings, note that the factor by which gain control attenuates a receptor response, for example the attenuation of L, is given in equation 3a as, $1-[L/(\sigma+L)]$. This quantity is called an "*attenuation factor*". [As pointed out to me by Mr. Mark Wolski, it is better written as $(\sigma/\sigma + L)$.]

Second, the X'_a, Y'_a, Z'_a, values of the adapting light are multiplied by α (α ranges from 15 to 50 in this paper) and the associated L_a, M_a & S_a receptor responses are determined using equations 2a, 2b and 2c. Third, the attenuation factors, $(\sigma/\sigma + L_a)$ and $(\sigma/\sigma + M_a)$ and $(\sigma/\sigma + S_a)$ are determined, and they are substituted for the LMS attenuation factors that were previously determined for the target light, itself. (i.e., they are substituted for the attenuation factors associated with "self adaptation" of the target light.) After this substitution, new L', M' and S' values are used in equations 4a, 4b and 4c, and the rest of the model is then applied in the usual fashion to yield the $A_2T_2D_2$ values for the target light viewed under adaptation by the adapting light. Alternatively stated, L_a, M_a & S_a (for $\alpha X_a'$, $\alpha Y_a'$ and $\alpha Z_a'$) are substituted for the L, M and S values *inside* the square brackets of equations 3a, 3b and 3c, and the model is then applied as usual to obtain the $A_2T_2D_2$ values for the target light viewed under adaptation conditions.

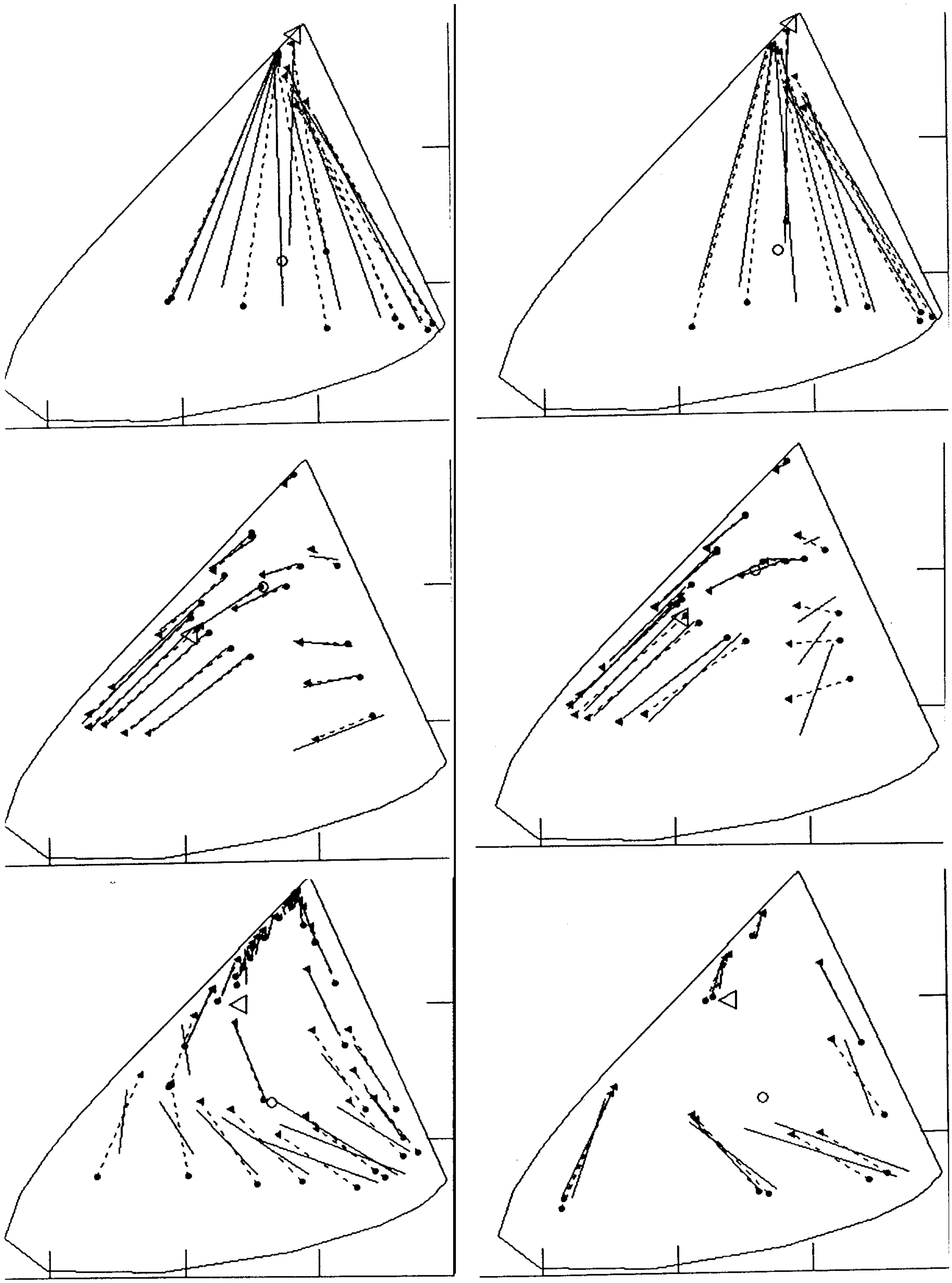


Figure 1. Data (end points of solid lines) and model predictions (filled circles and triangles at end points of dotted lines) showing xy coordinates of pairs of test lights that appear identical after preadaptation of each pair member with lights shown by either open circles or open triangles. Top row for subject DLM, and bottom for EJB.

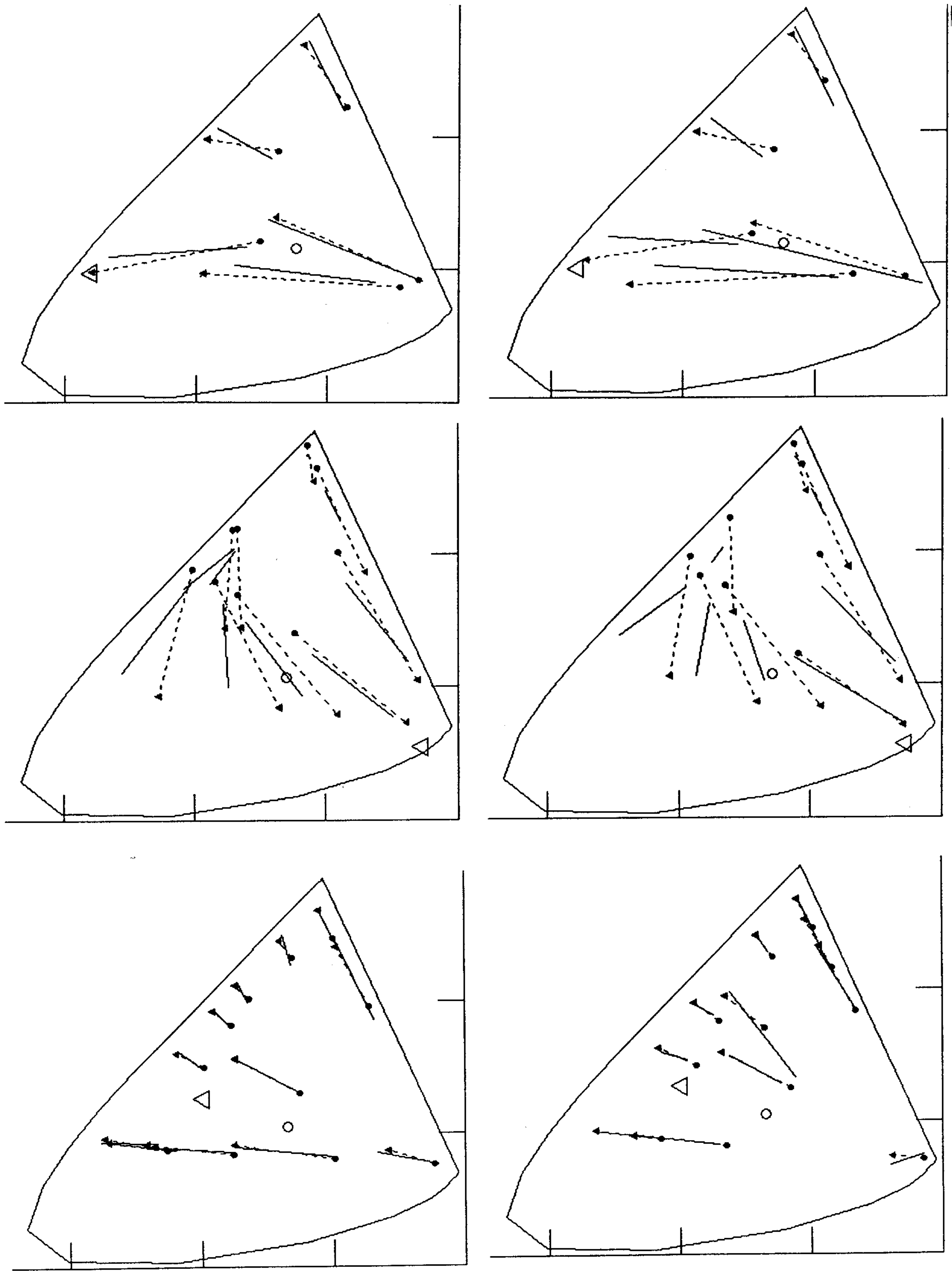


Figure 2. Same as Figure 1.

If it is of interest to know the X'Y'Z' values of an unadapted light that would have the same $A_2T_2D_2$ values as the adapted target light, then the model's equations (of course, without any substituted attenuation factors) can be reversed to solve for the X'Y'Z's given those $A_2T_2D_2$'s.

If it is assumed that the target light as well as the adapting light, contributes to gain control for the target light, then the X'Y'Zs for the two lights must be appropriately weighted, summed, and then used to determine L_a, M_a & S_a. (For example, if α is assumed to be 5.0 and the test light is given its "self adaptation" weight of 1.0, then X'Y'Z's should be determined for a light mixture of 5.0 times the adaptation light plus 1.0 of the target light, and the resulting X'Y'Z's should be used to calculate the L_a, M_a & S_a values that will determine the adaptation attenuation factors.)

It might also be of interest to determine the X'Y'Z's for a light which, when viewed under a particular adaptation light, will have some specified $A_2T_2D_2$ value. For example, in some of the predictions that appear below, I solve for the xy chromaticity coordinates for a light that will appear achromatic (i.e., that will have a specified A_2, and $T_2 = D_2 = 0$). If gain control is determined completely by the adapting light, then a solution is straightforward and exact; however, if gain control is partially from the target light and partially from the adapting light, then it is necessary to search X'Y'Z' space in order to approximate the answer. (As mentioned above, the assumption that gain is mainly from the adapting light is often quite reasonable.)

3. Applications

3.1 MacAdam's Chromatic Adaptation Data

In what should be considered to be as classic as his color discrimination study, MacAdam[4] determined the chromaticity coordinates of pairs of lights that appeared identical after each member of the pair was intensely adapted to a very different chromatic light. Successive adaptation was involved in the sense that adaptation lights and test lights appeared successively in the same fields.

Rather than duplicating an earlier description of the application of the model to MacAdam's data, I here refer the reader to p. 987 of my JOSA paper.[2,3] The only change to that description is that I here apply ATD93p, with the modifications that I described above, using $\alpha = 15$. (As mentioned above, predictions no longer involve a change in gain control parameters.)

Figures 1 and 2 show MacAdam's data for subjects DLM and EJB as well as predictions made by the here-modified ATD93p. Note that all predictions for both subjects were made with no parameter changes.

3.2 McCann, McKee and Taylor/Land's Chromatic Adaptation Data

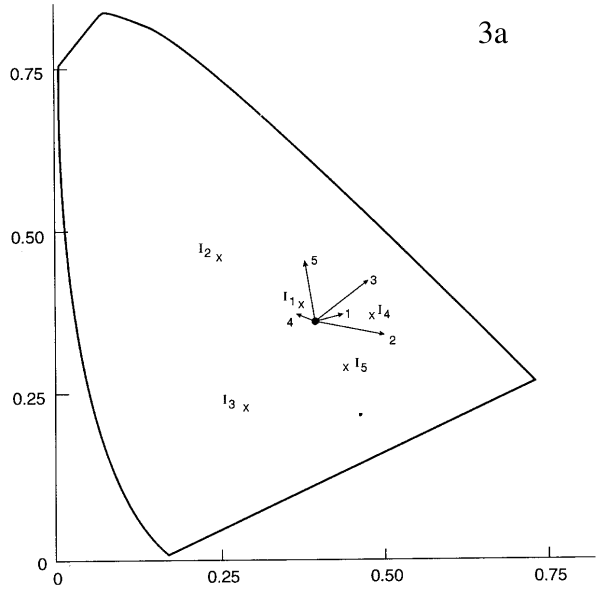
McCann, McKee & Taylor[5] and Land[6] reproduced classic simultaneous contrast effects by demonstrating that chromatic surrounds tend to induce approximately complementary hues into nominally gray target areas (that is, into areas that would appear approximately gray when viewed in neutral surrounds). For example, they show that a surround area that is illuminated by a greenish light will induce redness in a nominally grey target chip, and that a surround area that is illuminated by a reddish light will induce greenness in that same nominally grey target chip. They also used approximately whitish, bluish and yellowish lights to illuminate the surrounds, and for each of the total of five illuminants, they determined Munsell chips that best-matched (under whitish illumination) the nominally gray target chip that appeared colored by induction.

> I purposely deemphasize that the surrounds consisted of a Mondrian pattern of variously colored Munsell chips, because the predictions made below require no reference at all to the characteristics of those chips or even to the fact that a Mondrian pattern was involved. This is not to say that there never exist local induction effects on a target area, or that the spectral reflection characteristics of surrounding chips are always irrelevant.
>
> Neither of those possibilities is tenable, because it is perfectly obvious that it does matter, say, whether a chromatic inducing area surrounds a target or appears far distant in the visual field. And it must matter whether, say, a greenish inducing illuminant falls on a surround of a large number of variously colored Munsell chips or on a large number of identically colored chips, each of the same imaginary pigment that reflects only a narrow band of long wavelengths (in which case the surround might appear as uniformly black). However, in the case of the experiment considered here, the successful predictions imply that local effects due to the particular arrangements of the Mondrian chips in relation to the target chip were small, and that any effects due to the particular reflectance characteristics of the Mondrian chips were also small.

For unexplained reasons, the two above-cited reports of this experiment give substantially different results. I here choose to model the data that are reported in the *Scientific American* article, which is the more recent (and which, in contrast to the 1976 paper, provides complete information about the essential-to-know spectral distributions of the illuminants). The chromaticity coordinates of the chips that were chosen to match the nominally gray chip under the five different illuminants summarize the results of the experiment. These points are shown with filled circles in Fig 3b.

> Within the current model, the McCann,et.al./Land experiment is conceptually identical to that of MacAdam (1956) as considered above. That is, McCann, *et.al.*/ Land determined the chromaticity coordinates of lights (i.e., chips) that appeared identical (approximately) while each member of the pair was adapted to different lights (i.e., surround illuminants). Therefore, it would be possible to show their data and the model's predictions using the same kind of diagrams as are shown in Figs. 1 and 2. However, a somewhat different approach is used here.

* erratum shown in shaded box;
original paragraph should now be disregarded



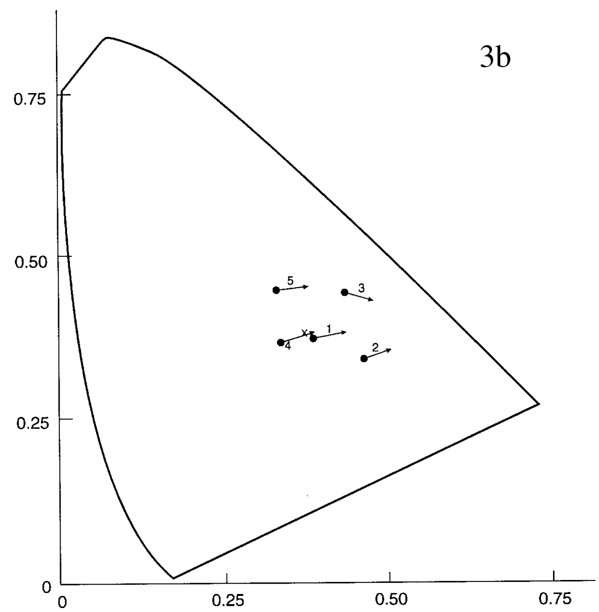


Figure 3a. (above top) Isolated X's show xy coordinates of illuminants of Mondrian surrounds, which, according to model predictions, will induce roughly complementary hues (shown with arrow-tips with corresponding numbers) into the Mondrian's nominally-grey test areas, coordinates for which are shown with the filled circle.

Figure 3b. (above bottom) Filled circles are xy coordinates of comparison chips that matched the hues of nominally-grey test areas within a variously-illuminated surrounding Mondrian pattern. Arrow-tips show predicted hue-shifts of the comparison chips, as expected from induction by their whitish surround, whose chromaticity coordinates are shown with the small X that is almost on arrow number 4.

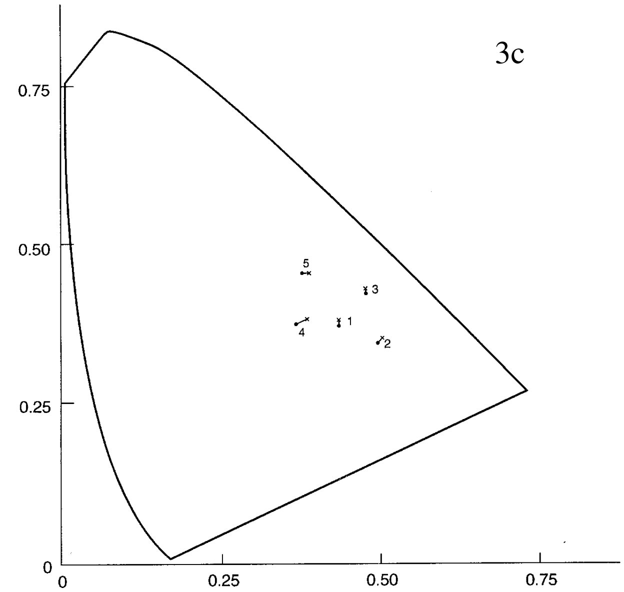


Figure 3c. Coordinates of corresponding arrow-tips from Figs. 3a and 3b transferred to a common diagram.

In using the model to account for an appearance shift due to a particular illuminant, the illuminant was assigned an $\alpha = 50$ (presumably reflecting the relatively large field covered by the illuminant) and (as explained above) the associated receptor attenuation factors were substituted for those associated with the relevant target chip. Then the model was applied as usual to determine the $A_2T_2D_2$ values for the chip as it would appear under the illuminant. For a particular Mondrian illuminant, the prediction can be summarized by showing the xy chromaticity coordinates of the nominally gray chip as well as the xy chromaticity coordinates of an unadapted chip that would have the same $A_2T_2D_2$ values as those predicted by the model for the adapted chip. An arrow connecting the former to the latter is directly related to the color shift predicted by the model. Such arrows are shown for each of the five Mondrian illuminants in Fig. 3a, which also shows the chromaticity coordinates of the illuminants that produced the shift that is identified with the corresponding number. However, Fig. 3a represents only part of the theoretical analysis of the experiment. It is also necessary to predict the shift in appearances of the matching chips under their (whitish) illuminant. These shifts are shown in Fig. 3b. If the xy coordinates of an unadapted light that would match an adapted nominally gray target patch are the same as the equivalent xy coordinates of the whitish-adapted matching patch, then the model would perfectly predict the data. That is, if the tips of corresponding arrows in Figs. 3a and 3b were coincident, then the predictions would be perfect. The coordinates of those corresponding arrow-tips are shown in Fig. 3c.

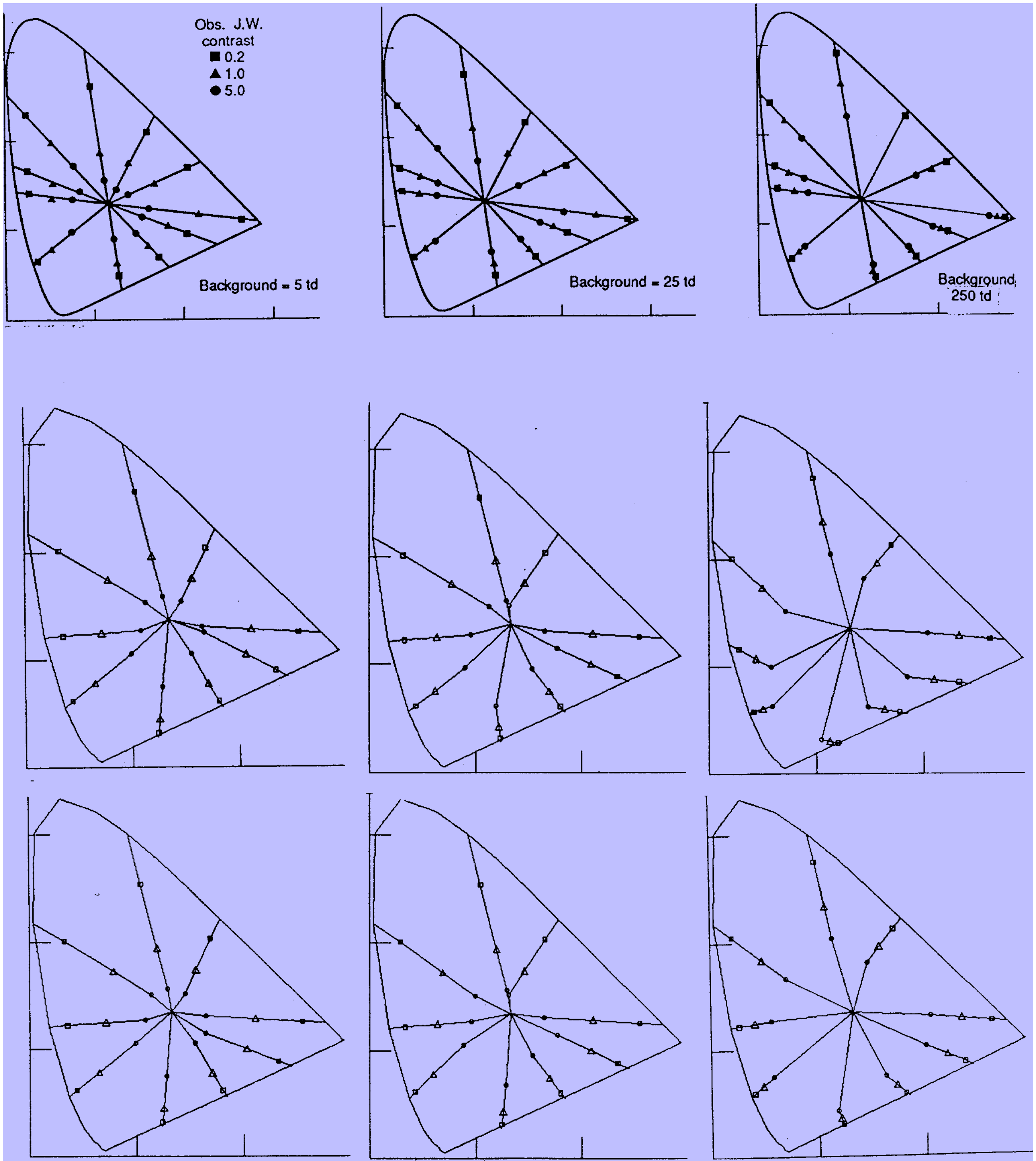


Figure 4. Top row: data showing coordinates of target lights that appear achromatic when surrounded by spectral (or purple) backgrounds of chromaticity indicated by intersections of radial lines with edge of xy space. Target lights were mixtures of the background light plus increments with luminances of 0.20, 1.0, or 5.0 times the background luminance. Middle row: predictions by revised ATD93p model. Bottom row: predictions by a slightly modified revised version, illustrating model's ability to predict nearly straight lines as loci of achromatic points.

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* erratum shown in shaded box;
The model's predictions are incorrect and should now be disregarded.

3.3 Werner and Walraven's Chromatic Adaptation Data

Both of the experiments considered above require matching responses from subjects, rather than judgments of hue appearance. Werner and Walraven[7] completed an experiment that provides an exceptionally rich body of data concerning the effects of chromatic simultaneous contrast on color appearance. In particular, they determined the chromaticity coordinates of centrally located target lights that appeared achromatic in the presence of a wide variety of chromatic surrounds of three different luminances. The luminances of the target lights were also varied. A more complete description of the experiment and its results, as well as a detailed explanation of how the model is applied to the data, appears in the JOSA paper[2] on pp. 987-991) and the reader is referred to that article. Of course, in the present case, I apply the heremodified ATD93p (with an $\alpha = 15$). Note that, in the case of the model used in the 1991 JOSA article, parameter changes were required to account for the effects and to illustrate the predictions; however, no such change is required using ATD93p, or its present modification. I merely apply the model to find the chromaticity coordinates of lights of the required luminances that will have $T_2 = D_2 = 0$ under the prevailing adaptation conditions.

The top row of Fig. 4 shows the data for one subject of Werner and Walraven. Note, for example, that, because a bright red surround will induce considerable greenness in a more neutral center area of only slightly higher luminance, much red light will have to be added to the center to produce apparent whiteness; therefore, achromatic-appearing lights will plot near the red corner of chromaticity space, as the data show. Predictions by the modified ATD93p are shown in the middle row of Fig. 4. In evaluating the predictions, it will be noted that they do not all fall on straight radial lines, as do the data. In considering this fact, it should be understood that Werner and Walraven constrained their data to fall on straight lines. They carefully tried to confirm that coordinates of truly achromatic target lights fell on those lines, but it remains possible that some curvature might have been observed had the data not been constrained. However, the issue does not unduly stress the model, for, as shown in the bottom row of Fig. 4, a slight change in the initial weight for S (to 1.5) and the amount of S into D_1 (0.5) can produce predictions that are nearly straight radial lines.

4. References

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2. S. L. Guth, Model for color vision and light adaptation," *J. Opt. Soc. Am. A*. Vol. **8**, pp. 976-993, 1991.
3. S. L. Guth, "Erratum for 'Model for color vision and light adaptation," *J. Opt. Soc. Am. A*., Vol. **9**, p. 344, 1992.
4. D. L. MacAdam, "Chromatic adaptation," *J. Opt. Soc. Am*., Vol. **46**, pp. 500-513, 1956.
5. J. J. McCann, S. P. McKee and T. H. Taylor, "Quantitative studies in rednex theory," *Vis. Res*., Vol. **16**, pp. 445-458, 1976.
6. E. H. Land, "The retinex theory of color vision," *Sci. Amer,* Vol. **237**, p. 108-128, 1977.
7. J. S. Werner and J. Walraven, "Effect of chromatic adaptation on the achromatic locus: the role of contrast, luminance and background color," *Vis. Res*., Vol. **22**, pp. 929-943, 1982.

published previously in SPIE, Vol. 2170, page 153

* erratum shown in shaded box;
The original predictions of the Werner and Walraven data were in error and this section should now be disregarded.