When do We Assimilate in Color?

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Abstract

Color Assimilation is a very obvious effect, in which two identical stimuli appear very different hues. This paper studies the hypothesis that the broad spectral sensitivity functions of human vision are the cause of these spatial effects. The results show that the long-wave response to middle-wave light, and the middle-wave response to long-wave light introduce spatial effects consistent with observed colors.

Introduction

Color effects caused by assimilation are highly variable. At times they are impressively large[1-3]; at other times there is a complete absence of a chromatic effect. The chromatic effects are generated by spatial interactions between equal test areas and surrounds. This paper studies the conditions and mechanisms leading to the presence or absence of chromatic assimilation.

Presence and Absence of Color Assimilation

Figure 1a (top) is a dramatic example of chromatic assimilation. The color rendition, in the top row, shows red squares on the left with a blue tint, while the red squares on the right have an orange tint. The next lower row shows the red (left), green (middle) and blue (right) separations for the above image. Figure 1b (bottom) shows lightness assimilation and fails to exhibit chromatic effects. The bottom row shows red, green and blue separations for 1b. The red separations and the blue separations are the same in Figure 1a and 1b. The only difference is in the green separations. In the non-chromatic (lower image) the green separation is the same as the red separation. In the chromatic (top image) the green separation is the same as the blue separation flipped horizontally. This paper presents a systematic study of color effects found in color assimilation displays.

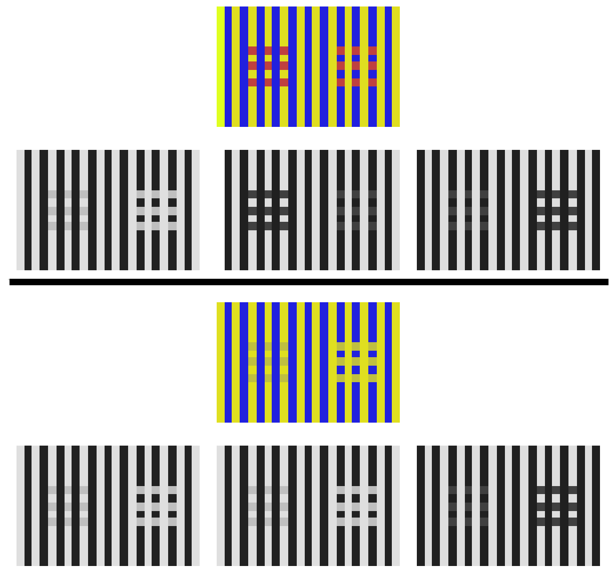

Figure 1a (top) shows an example of color assimilation, composed of red squares on a blue-yellow striped background. The nine red square on the left are identical stimuli to the nine on the right. The spatial nature of surround causes the large shift in appearance. The three colorless images below are the red (left), green (middle), and blue (right) color separations used to make the colored image. Figure 1b. The lower color image is an example of lightness assimilation. The change in appearance here shows no chromatic shift. The bottom row shows its red, green and blue separations.

Color patches

Figure 2a shows two sets of nine squares (red, green and blue) in a white surround. The digital values of the nine squares are constant in all the versions of Figure 2. They are red (225,50,50), green (50, 225, 50), blue (50, 50, 225). The assimilation effects are created by adjusting the values of the surround.

Figure 2b shows all combinations of red-cyan, green-magenta, blue-yellow stripes beneath red, green and blue sets of nine squares. Figure 2b shows the effect of alternating colored stripes replacing the white surround. The surrounds are limited to digital values 255 and 50 [red (225,50,50), green (50, 225, 50), blue (50, 50, 225), yellow (225, 225, 50), magenta (225, 50, 225), cyan (50, 225, 225)]. Except for the white surround all areas in Figure 2 are permutations of digital values 225 and 50 in red green and blue separations. The top row of Figure 2b shows no color assimilation effect. The middle and bottom rows show strong effects.

Figure 3 shows the parallel experiments using yellow, magenta and cyan sets of nine squares. Figure 3a shows two sets of nine squares (yellow, magenta and cyan) in a white surround. The digital values of the nine squares are constant in all the versions of Figure 3. They are yellow (225,225,50), magenta (225, 50, 225), yellow (225, 225, 50). The assimilation effects are created by adjusting the values of the surround.

Figure 2a shows sets of red, green, and blue squares used as the test areas throughout Figure 2. Here, they are shown with a white surround.

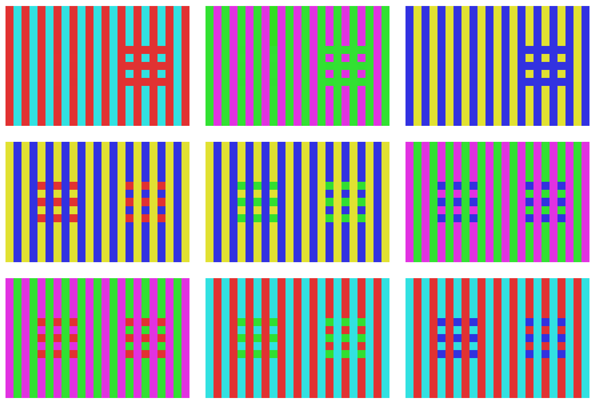

Figure 2b adds striped surrounds. The top row shows no color shifts while dramatic effects of the surround are seen in the lower two rows.

Figure 3a shows the sets of cyan, magenta, and yellow squares used as the test areas throughout figure 3. Here they are shown with a white surround.

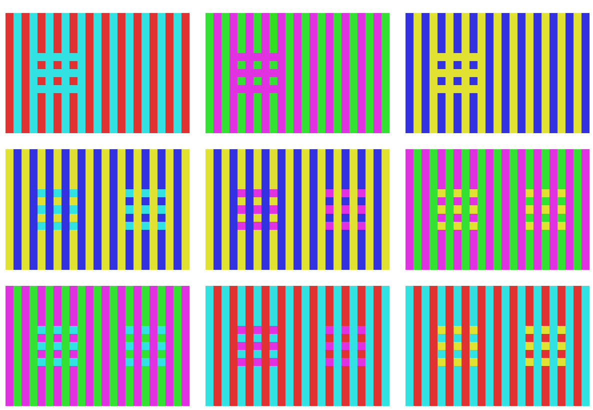

Figure 3b add the same surround stripes as Figure 2b. Again the top row shows no color shifts, while dramatic effects are seen in the lower two rows.

Figure 3b shows all permutations of red-cyan, green-magenta, blue-yellow stripes beneath yellow, magenta and cyan sets of nine squares. The squares and surrounds are limited to digital values 255 and 50, as in Figure 2.

The top row of Figure 3b shows no color assimilation effect. The middle and bottom rows show strong effects. In an attempt to describe the rules for when assimilation occurs we can look at the separations of each of the permutations. In top rows of both 2b and 3b the color of the patch is the same as one of the background stripes. In these displays there are no chromatic effects. In the middle and bottom rows of both 2b and 3b the color of the patch is different from the background stripes. In all of these displays there are strong chromatic effects.

From these displays we can observe that color assimilation effects are observed for red, green, blue, yellow, magenta and cyan test patches in red-cyan, green-magenta and blue-yellow stripes. Any test color (squares) in any complimentary color stripe pattern can show chromatic assimilation. When the test color matches one of the surround stripes there is no effect.

Human Spectral Sensitivity Responses

Colorless assimilation is a complex phenomenon in which appearance is dependent on the population of surrounding areas.[4] Gray test patches can change from looking darker, due to contrast, to looking lighter, due to assimilation by changing the outer surround.[5] Before trying to unravel the many different parameters found in Figures 2b and 3b, it is extremely valuable to identify the human spectral responses to these chromatic displays. There are two obvious choices, cone absorption data and CIE Tristimulus Values. Smith and Pokorney[6] showed that cone measurements and psychophysical data were in agreement when other absorptions were considered. In this paper we will uses the 1964 X, Y and Z Tristimulus values as the human visual spectral response.[7]

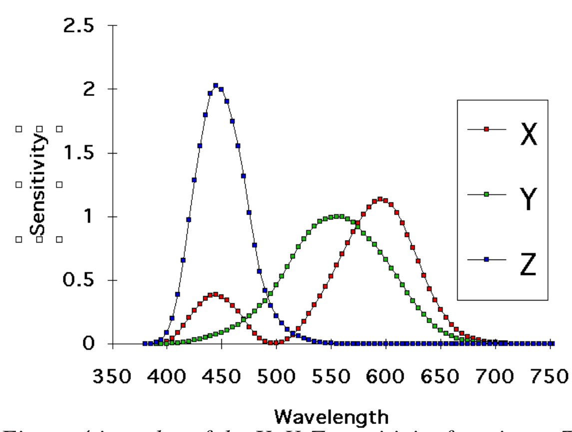

Figure 4 is a plot of the X, Y, Z sensitivity functions. The X responds to light over a range of wavelengths from 400 to 700 nm. The Y responds to light over a range of wavelengths from 425 to 675nm. The Z function responds to wavelengths from 400 to 525nm. The X and Y sensitivity functions respond to all of the red, green and blue phosphors and filters in displays and the yellow, magenta and cyan dyes in prints. The X response to middle-wave light and the Y response to long-wave light constitute crosstalk. Crosstalk degrades the color separation of the appearance of the reproduced image. Imaging systems attempt to convey the red separation image undiluted to the long-wave receptors. The fact that visual response is sensitive to both long- and middle-wave light is the source of a variety of visual phenomena.

Voglesong[8] points out that the evaluation of many color reproduction systems has led to an ideal spectral response used in status A densitometry. In this combination of many different media he identifies the wavelength limits for optimal color separation. He divides the spectrum into three spectral regions with zero crosstalk. His ideal spectral response for optimal color separation has zero response at 493 and 595 nm. Using this information we can divide the spectrum into long- middle- and short-wave stimuli. Long wave light is defined as 595 nm and above. Short-wave light is 495 nm and below. Middle-wave light is the region from 500 to 590 nm.

We can use CIE Tristimulus Values to represent the eye's spectral sensitivity. We can use Voglesong's minima to divide the visible spectrum into long-, middle-, and short-wave segments. We can evaluate crosstalk by calculating the X, Y, Z separation images for the long-, middle-, and short-wave stimuli used in Figures 2 and 3.

This paper looks at the effect of unwanted absorptions by the human visual pigments, or crosstalk. To improve colorfulness and saturation color imaging systems minimize color separation crosstalk, for example, minimize the red response to green light . This analysis requires that we look at the red, green, and blue responses to response to red, green and blue light. We will assume white is a stimulus with an equal-energy spectrum. Ordinarily in colorimetry one would use a real illumination such as daylight or tungsten. An equal energy spectrum falls between daylight and tungsten. Further, we will assume that the long-wave stimulus has equal energy for all wavelengths from 595 to 780 and zero at all other wavelengths; the middle-wave stimulus has equal energy for all wavelengths from 500 to 590 and zero at all other wavelengths; the short-wave stimulus has equal energy for all wavelengths from 380 to 495 and zero at all other wavelengths. By using Voglesong's division of the spectrum we can arrive at a general understanding of the response that is media independent. All photographic, printing and display technologies observe the general rule described by Voglesong.

We begin by combining the effects of the illumination and the sensitivity functions. The first step is to segment the X response into long-, middle- and short-wave components. The integral of X's sensitivity to an equal energy spectrum (380-780nm) is 23.33. The integral of the response from 595 to 780 nm is 11.027, or 47.3% X's response to long-wave light. Analogously, we can calculate that 35.8% of X's response to an equal-energy spectra is from the region from 500 to 590; 16.9% from below 495 nm. (Table 1).

Corresponding calculations for the Y response are: 24.5% to long-wave light; 66.6% to middle-wave light; 8.9% to short-wave light. Calculations for the Z response are: 0.00% to long-wave light; 4.5% to middle-wave light; 95.5% to short-wave light. This provides a 3x3 matrix to calculate and evaluate the X, Y, Z images.

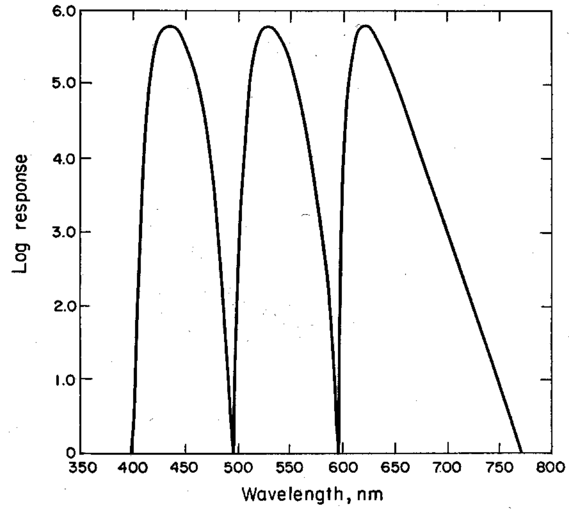

Figure 5 is taken from Voglesong. The curves represent the ideal spectral response for densitometry. They were used to optimize color reproduction systems by specifying the spectral distributions for optimal color separation.

Since we have stimuli that are limited to digital values of permutations of 50 and 225, we can evaluate the crosstalk for all areas in Figures 2c and 3c by multiplying the per-

	longLight	midLight	shortLight	Sum
X	0.473	0.358	0.169	1.000
Y	0.245	0.666	0.089	1.000
Z	0.000	0.045	0.955	1.000
	Rin	Gin	Bin	
RED	225	50	50	
CYAN	50	225	225	
GREEN	50	225	50	
MAG	225	50	225	
BLUE	50	50	225	
YEL	225	225	50	
	Rout	Gout	Bout	
RED	133	93	50	
CYAN	142	182	225	
GREEN	113	167	58	
MAG	162	108	217	
BLUE	80	66	217	
YEL	195	209	58	

*Table 1 is a lookup table for generating the red, green, blue separation values of all colors used in the display. The top shows the proportions of 1964 CIE Tristimulus Values X, Y and Z sensitivity to long-, middle, and short-wave light as identified by Voglesong. The middle section list the digital values of used to create Figures 2 and 3. The bottom section lists the calculated values of all colors, including crosstalk between input separations and the sensitivity of human vision. For example, the Rout response 133 is the sum of (0.473*225) + (0.358*50) + (0.169*50).*

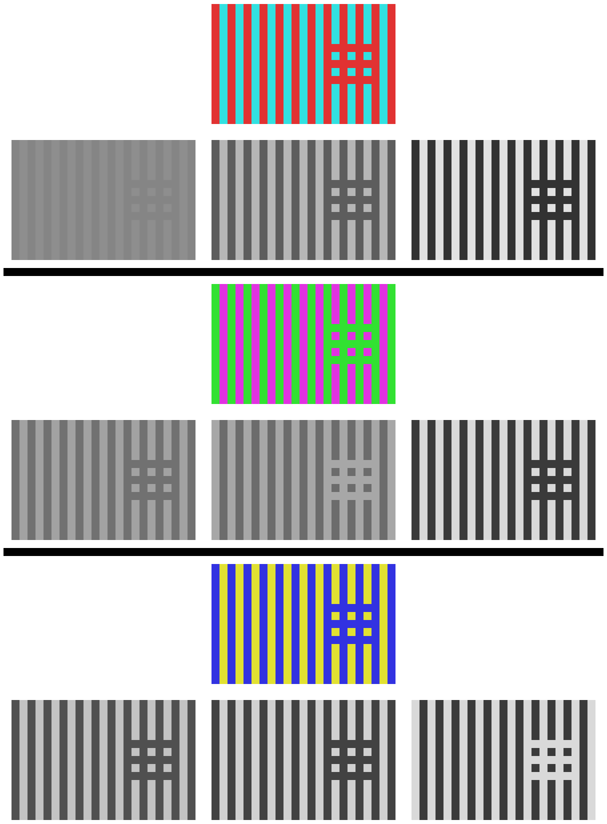

Figure 2 c shows the three targets in the top row of Figure 2b with their X, Y, Z separation images. The digital value of each pixels was determined by the data in Table 1. In each case the square on the left (indistinguishable from the stripes) appear equal to those on the right. There are no color assimilation affects in these displays.

mutations of 50 and 255 by the X, Y, Z sensitivity matrix[9]. The results are shown in Table 1. We can use this table to look up the red, green, and blue response values for all colors used in these displays. Since we are looking at many permutations of complex spatial patterns, this lookup greatly simplifies the analysis and allows us to pay attention to the spatial properties of the images..

We can display the calculated X, Y, Z separation images corresponding to the displays in Figures 2b and 3b. Figure 2c shows the displays from the top row of Figure 2b with X, Y, Z separations. The crosstalk caused by the X's response to middle-wave light and Y's response to long-wave light has reduced the contrast in these separations. This can be seen clearly by comparing the X, Y, Z separation images to the ordinary RGB separations. Here the surround stripes are the permutations of 50 and 225. They are all high contrast stripes. The X, Y, Z separation images show significant change in contrast due to crosstalk. For example, the red changed from (225, 50, 50) to (133, 93, 50). The cyan changed from (50, 225,225) to (142, 182, 225). The appearace of the test squares are the same in each separation. Furthermore, the crosstalk has not introduced chromatic assimilation; the nine squares on the left have the same appearance as the nine on the right.

The displays that exhibit color assimilation in the middle and bottom rows of Figure 2b have more interesting X, Y, Z separations (Figure 2d). The first display has red squares on blue-yellow stripes. The crosstalk in the long-wave cone separation has converted the red square from (225, 50, 50) to (133, 93, 50 (a major change)); the yellow stripe from (225, 255, 50) to (195, 209, 58); and the blue stripe from (50, 50, 225) to (80, 66, 217 (minor changes)). The interesting effect is that the crosstalk has changed the spatial pattern. As shown in figure 6, the RGB color separations are limited to the values of 255 and 50. The red squares have adjacent areas in each separation with equal values. The effect of crosstalk, as shown in the X image, is to cause the central square to break away from having the same digital value as the stripes. The red is now a distinct area with intermediate lightness. The crossover introduces edges on all four sides of the squares. The equal intermediate grays no longer appear equal. The spatial pattern on the left makes the square on the left appear darker; the pattern on the right makes the square look lighter in the X image separation (See Figure 6).

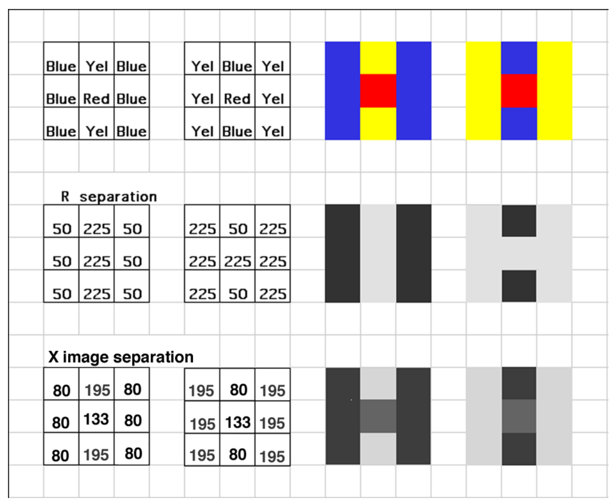

Figure 6 shows the effect of stimulus crosstalk between X, Y, Z separations. Think of this as a magnified diagram of a red square and its eight nearest neighbors. The top row shows the color names and the shows the color pattern. The next row lists the digital values of the original image in the red record on the left. It also shows a display of these sets of nine pixels. The central gray test patches appear the same. The bottom row shows the values for these pixels in the X separation images (from Table 1) along with its display. The effect of crosstalk is to change the value of the central pixel from being equal to one of the background stripes to being intermediate between their values. The visual effect of this separation crosstalk is that the intermediate grays no longer look alike. The 133 on the left appears darker than the 133 on the right. The implication is that crosstalk can account for color assimilation. The effect seen here for one display is seen in all the other displays.

The shift in lightness of the red squares in blue-yellow stripes can be seen in the top section of figure 2d. The color image of the display is in the center. Just below are the long-, middle-, and short-wave cone separation images. The red squares are darker on the left in both the long and middle separations than in the square on the right. That correlates with less yellow on the left than on the right.

In other words, the crosstalk caused by the extremely broad spectral response of the Tristimulus Values accounts for the color shift in red squares on blue-yellow stripes. The three X, Y, Z separation images show the set of lightness shifts in two of the separations. The green squares have more yellow on the right and they have higher lightnesses in both the X and Y separations. Again, the color shift correlates with the lightness shifts in the X and Y separation images.

The third set of images in Figure 2d has blue squares on green-magenta stripes with X, Y, Z separations. The blue squares have more yellow on the right and they have higher lightnesses in both the X and Y separations. As with the remaining three displays in Figure 2d show color shifts that correlate with the lightness shifts in the X, Y, Z separation images.

Figure 3c and 3d shows yellow, magenta and cyan squares in the same backgrounds used in figure 2c and 2d. Here, as well, the color shift correlates with the lightness shifts in the separation images.

The results are summarized in Table 2. In all 12 cases the color shifts correlate with the lightness shifts observed in each X, Y, Z separation image. In all of the permutations the dramatic shifts in appearance were found in the X and Y separations. The lack of overlap in spectral sensitivity between Z and Y, compared to X and Y, limits the size of the effect. Although there are strong effects involving blue colors, the direction of the changes are generally associated with X and Y responses.

Discussion

Land reported similar results using the Cornsweet effect to make different colors from identical stimuli. His analysis used color separations with film-filter combinations with cone sensitivities. He reported the same results; color shifts correlate with lightness shifts found in cone separation images.[10]

The above experiments used as input a very limited set of digital values (225 and 50). These values were close to those found as very effective examples of color assimilation. These examples often have values in the square very close to those in the stripes. By making the value the RGB separation images equal to those of the stripes eliminates an hypothesis that color assimilation is associ-

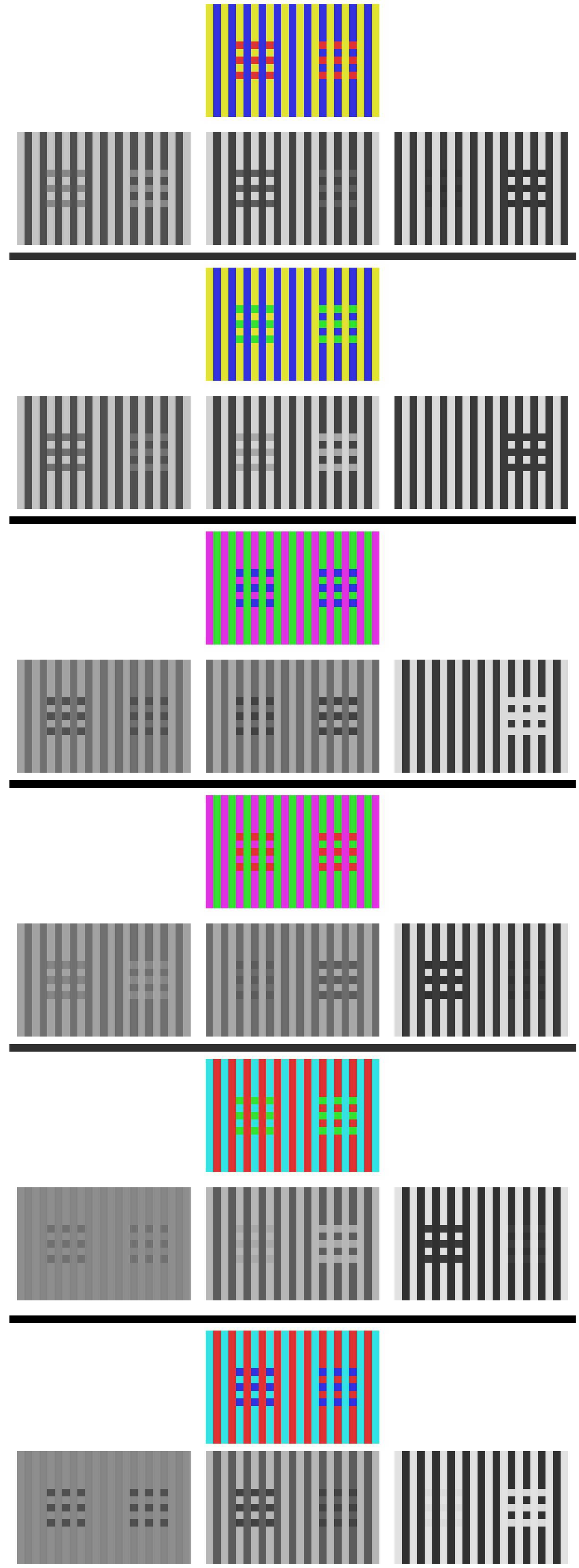

Figure 2d shows the color displays from Figure 2b middle and bottom rows) along with their X, Y, Z separation images. The color shifts are consistent with the lightness shifts caused by crosstalk seen in the separation.

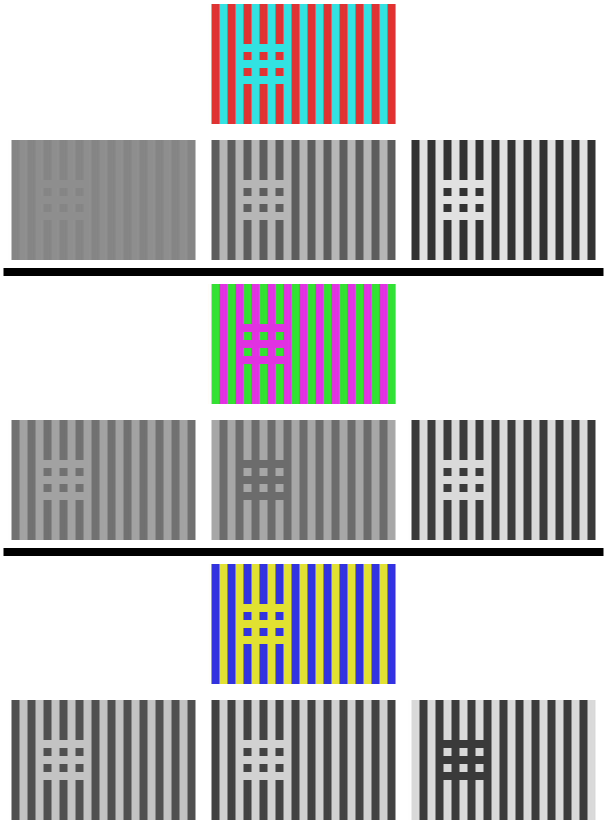

Figure 3c shows the three targets in the top row of Figure 3b with their X, Y, Z separation images. The digital value of each pixel was determined by the data in Table 1. In each case the squares on the left (indistinguishable from the stripes) appear equal to those on the right. As in Figure 2c there are no color assimilation affects in these displays.

ate with crispening effects in the RGB separation images. It is highly likely that the crispening effect plays an essential role in the appearance of the individual X, Y, Z separation images.

Conclusion

This study looked at the influence of the broad spectral absorption characteristics of human visual system on color assimilation displays. Using Vogelson's division of the spectrum into long- middle- and short-wave segments, we were able to calculate relative illumination/sensitivity responses. These showed that the X sensitivity function response is composed of 47% long-wave light; 36% middle-wave light and 17% short-wave light. The Y sensitivity function response is composed of 24% long-wave light; 67% middle-wave light and 9% short-wave light. The Z sensitivity function response is composed of 0% long wave light; 4% middle-wave light and 96% short-wave light. These crossover absorptions introduce spatial edges in the output images. These edges generate assimilation effects, similar to those seen in black and

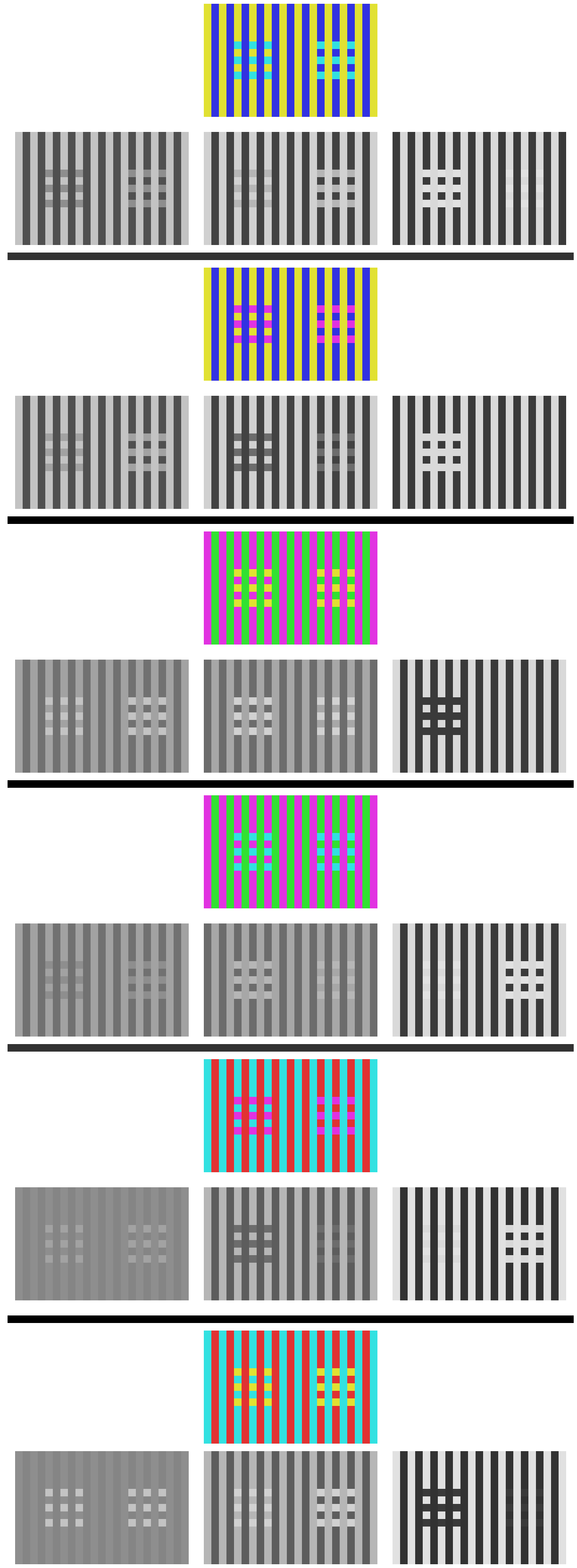

Figure 3d shows the color displays from Figure 3b (middle and bottom rows) along with their X, Y, Z separation images. The color shifts are consistent with the lightness shifts caused by crosstalk seen in the separations.

Figure	Squares	Stripes		Left Squares				Consistent
	color	colors	X image	Y image	Z image	Color	Color	with
			appears	appears	appears	appears	appears	Crosstalk
2c	red	red/cyan	equal	equal	equal	equal		yes
2c	green	grn/mag	equal	equal	equal	equal		yes
2c	blue	blue/yel	equal	equal	equal	equal		yes
2d	red	blue/yel	darker	darker	equal	lessR-lessG	less yellow	yes
2d	green	blue/yel	darker	darker	equal	lessR-lessG	less yellow	yes
2d	blue	grn/mag	darker	sl lighter	equal	lessR-moreG	less red	yes
2d	red	grn/mag	darker	lighter	equal	lessR-moreG	less magenta	yes
2d	green	red/cyan	sl darker	darker	equal	sl lessR-lessG	less green	yes
2d	blue	red/cyan	sl lighter	darker	sl darker	less G	more magenta	yes
3c	cyan	red/cyan	equal	equal	equal	equal		yes
3c	magenta	grn/mag	equal	equal	equal	equal		yes
3c	yellow	blue/yel	equal	equal	equal	equal		yes
3d	cyan	blue/yel	darker	darker	equal	lessR lessG	bluer	yes
3d	magenta	blue/yel	darker	darker	equal	lessR lessG	bluer	yes
3d	yellow	grn/mag	lighter	lighter	equal	more R more G	yellower	yes
3d	cyan	grn/mag	darker	lighter	equal	more G	greener	yes
3d	magenta	red/cyan	equal	darker	sl darker	less G	more magenta	yes
3d	yellow	red/cyan	equal	darker	equal	less G	more orange	yes

Table 2 lists the lightness shifts introduced in the displays by crosstalk. The first two columns list the figure and description of the display. The next three columns list the appearance of the left set of squares compared with the right set in the X, Y and Z separation images. The next columns list the color shifts observed in the display in terms of changes in redness and greenness. The next column describes the color shifts in terms of common color names. The final column lists whether the observed color shift was consistent with the triplet of lightness shifts. In each case the color shift is consistent with the triplet of lightness shifts seen in the X, Y, and Z separation images.

white displays. Color assimilation correlates with the appearance of X, Y, and Z separation images. The shifts in lightness seen in each output separation image are consistent with color effects observed.

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Biography

John McCann received his B.A. degree in Biology from Harvard University in 1964. He managed the Vision Research Laboratory at Polaroid from 1961 to 1996. His work concentrated on research in human color vision, large format instant photography and the reproduction of fine art. He is a Fellow of the IS&T. He is a past President of IS&T and the Artists Foundation, Boston. He is currently consulting and continuing his research on color vision.