Further studies of the McCollough effect¹

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Following prolonged viewing of black and white striped patterns in colored light, red and green aftereffects that lasted as long as 3 days were seen on the patterns, illuminated with white light. Alternate exposures of a vertical pattern of stripes in green light and a horizontal in white light (or a vertical in white light and a horizontal in red light) produced a red aftereffect on the vertical pattern and a green on the horizontal. The red and green aftereffects were also produced with a single vertical pattern. Adaptation colors that were at all greenish produced a red aftereffect on a vertical pattern and a green on a horizontal, whereas colors that were at all reddish produced a green aftereffect on a vertical pattern and a red on a horizontal. Colors near pure blue and pure yellow, which had little red or green content, produced weak aftereffects. The saturation of the aftereffects on the vertical grating varied in proportion to the red or green content of the adaptation color. Vivid red and green aftereffects were frequently obtained with the vertical and horizontal adaptation patterns paired with colors that closely bracketed pure yellow or pure blue. In all cases, the aftereffects gradually desaturated as the head was gradually tilted down to the side; the colors on each test pattern, vertical and horizontal, vanished at 45-deg head tilt and reversed beyond 45 deg.

McCollough (1965) demonstrated a color aftereffect that depended on the orientation of stationary edges. The aftereffect was built up by alternately viewing, for example, a pattern of black and white vertical stripes in orange light and a pattern of horizontal stripes in blue light. After adaptation, the vertical pattern appeared blue-green; the horizontal, orange. Pairs of other colors that differed considerably in wavelength produced distinguishable aftereffects on both patterns, vertical and horizontal. The aftereffect depended on the retinal orientation of the edges, for the colors switched patterns when the head was tilted 90 deg down to the side.

The present study indicates that the aftereffects are basically red and green. Red and green aftereffects were produced either by (1) alternate presentations of a pattern of vertical or horizontal stripes in red or green light and an orthogonal pattern in white light, or by (2) a constant presentation of a pattern of vertical stripes in one of a large variety of colors. A pattern presented in light that was at all greenish produced a red aftereffect on a pattern with the same orientation and a green aftereffect on the orthogonal pattern, whereas a pattern that was presented in a light that was at all reddish produced a green aftereffect on a pattern with the same orientation and a red aftereffect on the orthogonal pattern. When only the vertical pattern was used for adaptation, the saturation of the aftereffect on the vertical grating varied with the redness or greenness of the adaptation color. Colors near pure blue and pure yellow produced very weak aftereffects. In every case, the colors desaturated as the head was tilted gradually down to the side; the colors vanished at 45 deg and reversed beyond 45 deg.

EXPERIMENT 1

Red and green aftereffects were built up with alternating exposures of a pattern of vertical stripes and a pattern of horizontal stripes. One pattern was presented in red or green light and the other in white light.

Apparatus

Gratings of alternating black and white stripes with a 4:3 black-white ratio (visual angle 24 and 18 min) were projected on a screen by projectors with 300-W bulbs. A green filter (Wratten 55, dominant wavelength in Illuminant A, 524.1 nm) or a red filter (Wratten 26, 620.6 nm) was placed on one projector; the other projector, without a filter, illuminated the black and white stripes at 91 and 76 dB re 10^{-10} L. One adaptation grating had 25 vertical stripes, the other, 25 horizontal stripes. The test grating was made of two patterns projected side-by-side a pattern of 15 vertical stripes and a pattern of 25 horizontal stripes.

Subjects

Subjects throughout these experiments were male and female Harvard students and staff.

Procedure

The S sat 8 ft from the screen and for 10 min simply viewed the vertical and horizontal patterns, which were interchanged every 10 sec. Five Ss viewed the vertical pattern in green light and the horizontal in white light. And another five Ss viewed the vertical pattern in white light and the horizontal in red light. Following adaptation S inspected the test pattern, illuminated in white light, and reported the colors seen on both sides with the head held upright and tilted 45 deg and 90 deg down to the side. Then each side of the test pattern was covered, to eliminate effects of simultaneous contrast, and S reported the color on the exposed side.

Results

Table 1 shows that the vertical test pattern (v) frequently appeared pink or red (r) and the horizontal (h), green (g). The colors desaturated as the head was gradually tilted down to the side; they vanished at 45 deg and reversed beyond 45 deg. Each side of the pattern was covered without modifying the colors on the exposed side.

Discussion

Both a red and a green aftereffect were produced with alternating exposures of a grating in colored light, red or green, and an orthogonal grating in white light. The aftereffects were most saturated on test gratings with the same retinal orientation as the adaptation gratings; the aftereffects were least saturated (actually vanished) on test gratings with a retinal orientation 45 deg relative to the adaptation gratings. Both a red and a green aftereffect might not have occurred without the use of the adaptation grating shown in white light. Also, other adaptation colors might not have produced both a red and a green aftereffect. To answer both these questions, aftereffects were next produced with only a vertical grating illuminated with one of a large variety of colors.

EXPERIMENT 2

To determine the colors of the aftereffects, Hajos (1967) tested the colors, red, yellow, green, and blue (Wratten filters with dominant wavelengths, 660, 580, 520, and 470 nm). All pair combinations of these colors were tested. During adaptation one

Table 1
Aftereffects in Experiment 1

	Filters used with vertical (v) and horizontal (h) adaptation gratings	Colors seen with head upright and eyes freely moving	Colors seen with head tilted 90 deg	45 deg
S				
1	v-green h-no filter	v-pink h-green	reverses	none
2	v-green h-no filter	v-pink h-white	reverses	none
3	v-green h-no filter	v-pink h-weak green	reverses	none
4	v-green h-no filter	v-pink h-green	reverses	none
5	v-green h-no filter	v-pink h-yellow	reverses	none
6	v-no filter h-red	v-pink h-green	reverses	none
7	v-no filter h-red	v-weak pink h-weak green	v-green h-white	none
8	v-no filter h-red	v-pink h-green	reverses	none
9	v-no filter h-red	v-pink h-yellow	reverses	none
10	v-no filter h-red	v-red h-green	reverses	none

member of a pair was presented with a vertical grating and the other member with a horizontal grating. The proportions of the names of the colors seen on the vertical and horizontal test gratings were: red, 45%; green, 28%; yellow, 13%, and blue, 5%. Hajos thus concluded that the aftereffect was not the mixture complement of the adaptation color.

Experiment 1 demonstrated that when one adaptation grating was presented in colored light and the orthogonal grating in white light, colored aftereffects were seen on each orthogonal test grating. Hajos' experiment, which employed two colored orthogonal gratings, undoubtedly produced a mixed aftereffect on each test grating. Thus his study does not indicate the color of the aftereffect produced by a given color, nor does it prove that the aftereffect is not the mixture complement of the adaptation color.

Apparatus

Gratings of alternating black and white stripes were projected on a screen 2 m from S by projectors with 1000-W bulbs. The black and white stripes subtended 20 and 15 min and were illuminated at 78 and 93 dB re 10^{-10} L. A 55 x 55-cm pattern of 36 vertical stripes was used for adaptation. The test grating was made of two 45 x 45-cm patterns projected side-by-side—a pattern of 28 vertical stripes and a pattern of 28 horizontal stripes. Bausch and Lomb interference filters and Wratten filters, described in Table 2, were used in projecting the adaptation grating. The filters were not equated for luminosity.

Subjects

The two Ss, one male and one female, had excellent color vision according to the H-R-R Plates and the Farnsworth 100-Hue Test.

Procedure

The S simply viewed the vertical grating projected on the screen through one of the filters for 10 50-sec periods. Each period was separated by 10 sec of darkness. Several minutes were allowed after adaptation for afterimages to fade, and then the test

grating was viewed. S reported the colors seen on both sides of the grating with the head held upright and tilted 45 deg and 90 deg down to the side. Aftereffects were recorded only when they reversed with the 90-deg head tilt. S also gave magnitude estimates of the saturation of the aftereffects, disregarding hue differences. An arbitrary number was assigned to the saturation of the first aftereffect; numbers were then assigned to succeeding aftereffects in proportion to the first number. In this manner a rough idea of the saturation of the aftereffects was gained, even though the sessions extended several weeks.

After adaptation to each color the aftereffects were usually neutralized. Hajos (1967) was able to neutralize rapidly the aftereffects produced by colored orthogonal gratings by readapting to the same gratings each rotated 90 deg. Neutralization required about one-fourth the time needed to build up the aftereffects. Immediately after neutralization, the aftereffects could be built up again in the same time as the original aftereffects. In the present experiment neutralization was achieved by rotating the colored vertical grating so that the stripes were horizontal and readapting until the test gratings appeared colorless.

One through five colors were used in a single sitting. All Ss first adapted with the BL 520 and 620 filters, for these produced vivid aftereffects and thus served to initially demonstrate the aftereffects. The other filters were used in a random sequence. Corrective lenses were worn to focus the grating projected with light in the 405-478 nm range.

Results

Table 3 shows the hue and saturation (magnitude estimates) of the aftereffects on the vertical and horizontal test gratings. Sometimes S did not want to estimate the saturation of very weak aftereffects.

The aftereffects produced by light in the region 490-620 nm (blue-green through red) were predominantly red and green. Greenish adaptation colors generally produced red aftereffects on the vertical grating and green aftereffects on the horizontal, whereas reddish adaptation colors generally produced green aftereffects on the vertical grating and red aftereffects on the horizontal. As in the first experiment, the colors weakened as the head was gradually tilted down to the side; they vanished at 45 deg and reversed beyond 45 deg. Ss' responses were not

Table 2

Type	Filters Approximate transmission peak (nm)	Approximate half-width (nm)
B and L 405	406	
B and L 420	425	18
B and L 450	448	15
B and L 486	485	15
B and L 490		
B and L 500	500	16
B and L 520	521	
B and L 530 + Wratten 4	534	20
B and L 546 + Wratten 4	547	15
B and L 560 + Wratten 4	560	16
B and L 570 + Wratten 4	573	15
B and L 578 + Wratten 4	576	16
B and L 589 + Wratten 15	588	15
B and L 600 + Wratten 15	600	16
B and L 610 + Wratten 15	615	17
	Dominant wavelength in illuminant A	Excitation purity
Wratten 47a	477.5	91.7%
Wratten 47b	452.7	99.0%

Table 3
Aftereffects in Experiment 2 (Aftereffects Produced with a Vertical Colored Grating and Seen on a Vertical (v) and Horizontal (h) Test Grating). The Magnitude Estimates of the Saturation of the Aftereffects are Indicated by the Numbers.

		405	420	450	47b	47a	486	490	500	520	530	546	560	570	578	589	600	610	620
S	1	v	red-yellow .9	red-yellow 2	orange-yellow 1.5	gold-yellow 4	yellow-red 7	yellow-red 5	red 15	red 2	v red 18	pink 6	red 6	pink 2	pink .15	none	greenish-blue .5	bluish-green 1.8	bluish-green 1.7
			h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h
2	v	green .7	green .9	orange-yellow 1.9	yellow	none	pinkish-purple 1.6	pink 1.75	pink 3	pinkish-purple 2	v pinkish-purple 2.5	pinkish-purple 1.1	pinkish-purple 1.8	purplish-pink 1	pink 1.4	bluish-green 1.3	green 1.75	bluish-green 2.5	bluish-green 2.25
		h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h
3	v	green 1	green	yellow-green 3	green .75	green	none	pink 3	pink 6	pink 10	v pink .5	pink 4	pink 2	none	pink 1.5	green 4	green 8	green 2	green 7
		h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h

entirely consistent. S3 reported only pink and green. S2 often stated that the pink aftereffect contained a trace of purple and the green aftereffect a trace of blue. S1 likewise occasionally reported a blue tint in the green aftereffect.

The aftereffects produced by light in the region 405-486 nm (violet through blue-green) were generally weak and ambiguous. Nevertheless, a fairly definite reversal of the aftereffect appears to have occurred as the adaptation light was varied from blue-green to violet. S2 and S3 reported that the 490 filter (blue-green) produced a red aftereffect on the vertical grating, whereas the 405 and 420 filters (violets) produced a green aftereffect. S1 did not report the reversal—the 420 and 405 filters produced a reddish-yellow aftereffect, not green, on the vertical grating. The proportion of red in the reddish-yellow was estimated to be only 5 to 20%. These very yellowish aftereffects might easily have been confused with very weak green aftereffects.

The aftereffects were neutralized by readapting to the original color with the adaptation grating rotated so that the stripes were horizontal. Neutralization required only 3 min on the average. The vertical grating had originally produced a stronger aftereffect on the vertical grating than on the horizontal. Yet, surprisingly, neutralization of the strong aftereffect on the vertical grating was readily achieved with the horizontal grating. Undoubtedly the aftereffects could also have been neutralized with a green vertical grating if the original grating had contained red and with a red vertical grating if the original grating had contained green.

When the test grating was projected through the interference filters, the aftereffects appeared as though strongly colored glasses were being worn. The aftereffects could be seen without the test grating on roughly drawn patterns of stripes oriented in or near the vertical or horizontal meridians of the eye. The spacing, color, and thickness of the stripes appeared quite unimportant.

Discussion

The aftereffects show a sharp reversal of color in the yellow region of the spectrum and a more gradual reversal in the blue region. The 578 filter, a slightly greenish yellow, produced a red aftereffect on the vertical grating and a green aftereffect on the horizontal; the 589 filter, a slightly reddish yellow, produced a green aftereffect on the vertical grating and a red aftereffect on the horizontal. If the aftereffects depend on redness or greenness then pure yellow would produce no aftereffects, for it is neither reddish nor greenish. Filter 490, a greenish blue, produced a red aftereffect on the vertical grating and a green aftereffect on the horizontal, whereas Filter 420, a reddish blue, produced a green aftereffect on the vertical grating and a red aftereffect on the horizontal. The reversal in the blue region appears to be more gradual, for colors near pure blue produced aftereffects with a yellowish component. The spectral regions near pure blue and pure yellow will be further investigated.

EXPERIMENT 3

Aftereffects were built up with alternating exposures of the vertical and horizontal gratings paired with colors that closely bracketed either pure yellow or pure blue. Consider, for example, adaptation to an alternating reddish-yellow vertical grating and greenish-yellow horizontal grating. Each grating alone would produce a green aftereffect on the vertical grating and a red aftereffect on the horizontal. When both gratings are used, the aftereffects produced on each test grating may simply add or otherwise reinforce each other.

Dimmick and Hubbard (1939) had Ss set a monochromator so that just noticeable redness or greenness was seen in a yellow or in a blue. Pure yellow and pure blue lay between the jnd points at 476 and 582 nm.

Table 4
Aftereffects Produced with Yellow Filters

S	Filters used with the vertical (v) and horizontal (h) adaptation gratings		Aftereffects on the vertical and horizontal test gratings	
	(v)	(h)	(v)	(h)
1	none	578	white	white
	none	589	white	white
	589	578	white	pink
2	578	none	white	white
	589	none	white	white
	578	589	white	white
3	none	589	white	white
	none	578	white	white
	578	589	pink	yellowish-green
4	578	none	pink	white
	589	none	very pale blue	white
	578	589	red	green
5	578	none	pink	pale green
	589	none	pale green	pink
6	none	589	white	white
	none	578	white	white
	578	589	pink	white
7	578	none	red	white
	589	none	green	weak pink
8	none	589	weak red	weak green
	none	578	white	white
	none	570	white	weak red
	578	589	pink	weak green
9	578	none	white	yellow
	589	none	white	white
	578	589	pink	green
10	578	589	pink	white

Apparatus

Same as Experiment 2.

Procedure

The S first viewed a single grating for 10 50-sec periods. The grating was oriented vertically or horizontally and projected through one of the following filters: BL 570, 578, and 589 (yellows with peaks at 573, 576, and 588 nm, as described in Table 2); Wratten 47b and 47a (blues with dominant wavelengths in Illuminant A at 452.7 and 477.5 nm). The aftereffects were observed on the vertical and horizontal test gratings a few minutes after adaptation.

Some Ss later adapted to alternating vertical and horizontal gratings. One grating was projected through the BL 578 filter and the other through the BL 589 filter—yellows that bracketed pure yellows. The blues were used in an equivalent manner. The gratings were interchanged every 10 sec for a 10-min period.

Results

Tables 4 and 5 show, respectively, the aftereffects produced with the yellow filters and the blue filters. The greenish yellow filter, BL 578, used alone, occasionally produced a pink aftereffect on the grating with the same orientation as the adaptation grating; the reddish yellow filter, BL 589, used alone, occasionally produced a green aftereffect. Both filters used with the orthogonal gratings frequently produced vivid red and green aftereffects, even when either filter alone had produced no aftereffects. The aftereffects produced with the blue filters are less clear. When both filters were used with the orthogonal gratings, a reddish aftereffect was sometimes seen on the grating that had been paired with the 47a filter (a blue with very slight green) and a greenish aftereffect on the grating that had been paired with the 47b filter (a violet).

Discussion

The orthogonal adaptation gratings often produced strong red and green aftereffects. Each orthogonal adaptation grating used alone would produce an aftereffect on both test gratings. (This was demonstrated in Experiment 2 with a vertical adaptation grating.) When both orthogonal gratings are used, the aftereffects may simply represent an addition of the aftereffects produced by each grating. The neutralization procedure of Experiment 2, however, appears to rule out a simple additive process. The vertical grating produced considerably stronger aftereffects on the vertical grating than on the horizontal. Yet the aftereffects were readily neutralized with a horizontal grating illuminated with the original adaptation color. The horizontal grating by itself would presumably produce considerably stronger aftereffects on the horizontal grating than on the vertical. These latter aftereffects added to the original aftereffects would not produce neutralization—neutralization of the original strong aftereffect on the vertical grating could not be accomplished without simultaneously building up a strong reversed aftereffect on the horizontal grating. Thus the interaction of processes due to orthogonal gratings is probably not additive.

GENERAL DISCUSSION—COLOR OF THE AFTEREFFECTS

Adaptation to a colored vertical grating produces an aftereffect on the vertical grating (Experiment 2) that is clearly not the mixture complement of the adaptation color, for the straight line joining the aftereffect color and adaptation color on the chromaticity diagram does not pass through the white point. Nor is the aftereffect color equivalent to the negative afterimage of the adaptation color.

Edridge-Green and Porter (1914) demonstrated that the negative afterimage of a light is not always equivalent to the mixture complement. Tschermaek-Seysenegg (1929) observed that the afterimage contained more blue and red than the mixture complement. Bohnenberger (1920) showed that the afterimage of yellow, orange, blue, and blue-green deviated toward red. Aubert (1865) found that the red and blue tendencies were absent from the complementaries, green and magenta. Wilson and Brocklebank (1955) have recently confirmed these observations.

Table 5
Aftereffects Produced with Blue Filters

S	Filters used with the vertical (v) and horizontal (h) adaptation gratings		Aftereffects on the vertical and horizontal test gratings	
	(v)	(h)	(v)	(h)
1	47a	none	white	white
	47b	none	yellow-green	dark red
	47a	47b	bluish-red	dark green
2	47a	none	white	white
	47b	none	white	white
3	47a	none	pink	yellow
	47b	none	pink	white
	47a	47b	pink	green-yellow
4	47a	none	yellow	white
	47b	none	yellow	red
	47a	47b	dark pink	cream
5	47a	47b	pink	cream yellow
6	47a	47b	pink	cream yellow
7	47a	none	white	white
	47b	none	white	white
	47a	47b	white	white
8	47a	none	pink	pink
	47b	none	pink	pink
	47a	47b	pink	weak pink

Fig. 1. Arithmetic means of magnitude estimates of the saturation of the aftereffects on the vertical and horizontal test gratings produced by the vertical grating paired with various filters. Filters up to about pure blue, 476 nm, and beyond pure yellow, 582 nm, typically produced green aftereffects on the vertical grating and red on the horizontal, whereas filters between blue and yellow typically produced red aftereffects on the vertical grating and green on the horizontal. The red-green valence curve shows the proportions of red and green light energies needed to match an equal-energy spectrum. Red light is needed up to pure blue and beyond pure yellow; green light is needed between these colors. The maximal green value, at 530 nm, is set equal to the maximal red aftereffect.

Orange and yellow and also cyan, blue, and violet produced afterimages that deviated toward red. Green and magenta, mixture complements, produced afterimages equivalent to the mixture complements. When any mixture complements were gradually added together, each color changed in hue in the direction of the negative afterimage.

The aftereffects on the vertical grating in Experiment 2 are clearly not equivalent in color to negative afterimages. Adaptation colors beyond yellow in the red direction of the spectrum produced a green aftereffect; the negative afterimage varied, violet-blue-cyan. Colors between blue and yellow produced a red aftereffect; the negative afterimage varied, orange-red-magenta-purple-violet. The aftereffects contain little blue, yet a good blue afterimage can be obtained with an orange light. The same orange light would produce a green aftereffect.

The aftereffects appear to depend on a red-green mechanism. Hering (1878) believed that a colored light affected both a red-green and a blue-yellow mechanism. The short and long

wavelength regions of the spectrum, up to pure blue and beyond pure yellow, cause a red response in the red-green mechanism; the middle wavelength region, between pure blue and pure yellow, cause a green response. In Experiment 2, colors that caused a red response produced green aftereffects on the vertical grating and red aftereffects on the horizontal; colors that caused a green response produced red aftereffects on the vertical grating and green aftereffects on the horizontal. Pure yellow and pure blue are neither reddish nor greenish and thus do not affect the red-green mechanism. They would likely produce no aftereffects.

Hurvich and Jameson (1955) calculated a red-green valence curve for the tristimulus mixtures used in matching an equal-energy spectrum. They used Judd's transformation equation, $r - g = 1.0X - 1.0Y$, to convert the CIE tristimulus values for the Standard Observer into an opponent red-green valence curve. Positive values represent a red response; negative values, a green response. The curve has been roughly reproduced in Fig. 1. The negative values were converted to positive values.

The maximal green value (at 530 nm) was set at the ordinate value of the maximal red aftereffect, and the other points were made proportional to the maximal value.

The valence curve represents the proportions of red and green light energies used in matching an equal-energy spectrum. The interference filters have nearly equal energy transmission peaks and thus approximate an equal-energy spectrum. Hence the valence curve roughly describes the proportions of red and green light energies needed to match the adaptation lights. The saturation of the aftereffects on the vertical grating (Experiment 2) roughly parallels the valence curve; the saturation appears to vary with the color and not the luminosity of the adaptation light. When the intensity of a monochromatic source is widely varied, the color changes only slightly, and hence the proportion of red and green energies needed to match the source changes only slightly. The saturation of the aftereffects may not vary with the luminosity of the adaptation light, providing the color remains constant—but this remains to be tested.

Two properties of pure yellow and pure blue, the spectral points where the aftereffects presumably reverse color, may be noted. Pure yellow and pure blue are the only colors without redness or greenness, and they are the only psychologically unique colors that are mixture complements. Pure yellow and pure blue, at 582 and 476 nm (Dimmick & Hubbard, 1939), can be connected on the chromaticity diagram by a straight line that approximately intersects the white point. The other unique or pure colors, red and green, are not mixture complements; they will only produce yellow, yellow-green, or orange when mixed in a nearly equal energy ratio (Walls, 1952). The red and green of the Hering theory are mixture complements, but they are not pure colors, for the colors become complementary only when the red is made very bluish (a purple) or the green made a full blue-green (Ladd-Franklin, 1929). Hurvich and Jameson (1951) claimed to have gotten a yellowless, achromatic color by fusing a "pure red" presented to one eye and a "pure green" presented to the other eye. But Walls (1952) has remarked that the "pure"

greens were 489.4 and 498.1 nm—close to Hering's *Urgrün*, a pure blue-green at 495 nm.

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NOTES

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