An Investigation of the Role of Perceived Spatial Frequency in Pattern-Contingent Color Aftereffects

by

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Dedication

I would like to dedicate this work to my brother, Dr. Jim Jordan, and my mother, Catherine Jordan, who have helped me to continue to learn; to Dr. Wayne Herschberger, who told me to continue to learn; and to the memories of my two fathers, James Jordan and Martin Loughney, who knew I could continue to learn.

Introduction

The modifiability of perception has been a source of a great deal of investigation in the attempt to delineate the processes involved in human form perception. Prolonged exposure (adaptation) to a patterned stimulus often produces a change in the perception (aftereffect) of a subsequently viewed (test) stimulus. This change in perception is known as a pattern-contingent aftereffect when the aftereffect is contingent on some spatial parameter of the adapting pattern.

McCollough (1965) reported a demonstration of an orientation-contingent color aftereffect. Observers were alternately adapted to a horizontal square-wave grating consisting of blue and black bars and a vertical square-wave grating consisting of orange and black bars. Subsequent presentation of achromatic horizontal and vertical test gratings resulted in reports of desaturated hues complementary to the hues paired with each orientation of the gratings during adaptation. McCollough suggested that this aftereffect revealed the existence of color sensitive, orientation-specific edge-detecting mechanisms in the human visual system.

Spatial frequency, which is the number of grating cycles per degree of visual angle, is another parameter known to produce contingent color aftereffects. Stromeyer (1972) produced spatial frequency-contingent color aftereffects by alternately adapting observers to a high spatial frequency grating (e.g., narrow black bars and green slits) and a low spatial frequency grating (e.g., wide black bars and red slits). Achromatic test gratings were reported to appear desaturated red in the light slits of the high spatial frequency test grating and desaturated green in the light slits of the low spatial frequency test grating. In order to produce a spatial frequency-contingent color aftereffect the spatial frequencies of the two adapting gratings must be separated by at least one octave (Lovegrove & Over, 1972). Furthermore, achromatic test gratings which have spatial frequency intermediate to the adapting grating (octave scale) appear colorless (Stromeyer, 1972). There have been numerous studies demonstrating that the closer the match between the spatial parameters of the adapting and test gratings the greater the magnitude of the color aftereffect. For example, Stromeyer (1972) reported that the magnitude of a spatial frequency-contingent color aftereffect was greatest when the spatial frequency of the test grating matched that of the adapting grating.

However Uhlarik, Pringle, and Brigell (1977) reported a color aftereffect contingent on perceptual organization. Specifically, they showed that an orientation-contingent color aftereffect could be either present or absent without accompanying changes in any physical parameters of the test stimulus. Uhlarik et al. utilized a reversible figure as a test stimulus which could be organized as a diamond-shaped horizontal grating surrounded by a background of a vertical grating, or as an upward and downward nested series of incomplete three-sided rectangles. Color aftereffects were generally reported in the former organization and rarely in the latter. In addition, Mikaelian (1976) induced an orientation-contingent color aftereffect subsequent to prolonged exposure to prismatic tilt. In the test phase observers adjusted the orientation of achromatic test gratings until the saturation of the color aftereffect was maximal. The results indicated that the observers matched the perceived, rather than the retinal, orientation of the adapting gratings.

Many of the findings with pattern-contingent color aftereffects have been hypothesized to be the result of color adaptation of pattern-specific units or channels in the visual system and that these units are specifically tied to the spatial parameters of the stimulus. For example, McCollough (1965) reported that color aftereffects appear to reverse when the observer's head is rotated 90° from vertical and that the aftereffects do not show interocular transfer. Similarly, Harris (1970) investigated the specificity of spatial frequency-contingent color aftereffects by inducing red and green aftereffects each tied to a different spatial frequency of vertical gratings. When viewing distance was varied the aftereffects seemed to be tied to the retinal spatial frequencies of the gratings. Both results support the hypothesis that the color aftereffects are bound to the spatial parameters of the stimulus. The results of Uhlarik et al. (1977) and Mikaelian (1976) however suggest that under the appropriate testing conditions color aftereffects can be shown to be contingent on parameters that are not bound to the stimulus.

The goal of the present research was to further examine the role of cognitive factors[1] on color aftereffects. Specifically, the present experiment examined the possibility that cognitive factors can influence the nature of a spatial frequency-contingent color aftereffect by demonstrating changes in the nature of the effect contingent on changes in the perceived spatial frequencies of test gratings. The results of Uhlarik et al. (1977) suggested that perceived depth relations mediate color aftereffects to some extent in that color aftereffects were generally observed in only one of the two predominant organizations of a reversible test figure. Secondly, the organization in which the color aftereffects were observed is characterized by differences in perceived depth; i.e., a center horizontal diamond figure appears in front of a background of vertical bars (Lawson, Packard, Lawrence, & Whitmore, 1977). This suggests that the presence of the color aftereffects reported by Uhlarik et al. might be gated by higher-order factors mediating perceived depth relations.

Proximal size (and hence spatial frequency of a grating) is the visual angle subtended on the retina by a stimulus. However, perceived size seldom depends solely upon retinal size. Rather, some approximation to size constancy typically obtains where constancy is defined as perception of the distal (objective) rather than the proximal values of the stimulus. The present research investigated the role of perceived size on spatial frequency-contingent color aftereffects. This was accomplished by inducing color aftereffects tied to different spatial frequencies of adapting gratings. In the test phases of the present series of experiments, perceived spatial frequency of test gratings varied due to pictorial cues to depth. Emmert's law states that for a constant retinal size, variations in perceived depth or distance result in variations in perceived size. Two pictorial arrays which produce such variations are the Necker cube[2] and a receding corridor array which are shown in Figures 1 & 2. These arrays were chosen as a context in which to present test gratings of identical retinal spatial frequency in the attempt to demonstrate color aftereffects contingent on perceived spatial frequency. For example, both gratings in Figure 2 are of identical retinal spatial frequency. However, the depth cues in a receding corridor array make the upper grating appear to be more distant than the lower grating, which gives rise to differences in perceived size and also perceived spatial frequency.

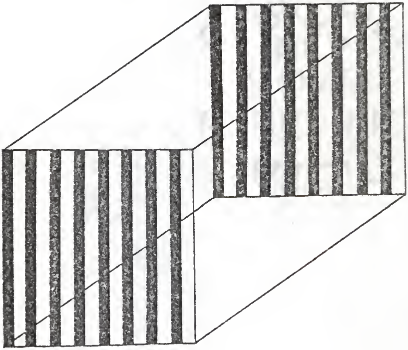
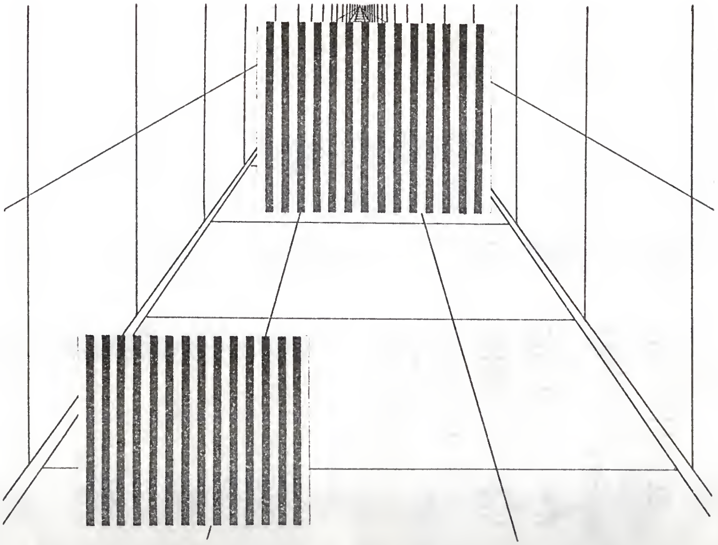


Figure 1. Example of a Necker cube which manifests Emmert's law. The two gratings are of identical retinal spatial frequency.

Figure 2. Example of a receding corridor array which manifests Emmert's law.

The two gratings are of identical retinal spatial frequency.



Experiment 1

Stromeyer (1972) investigated the strength of color aftereffects as a function of the degree of match between the spatial frequencies of the adapting and test gratings. Observers were adapted to a single grating of a fixed color and spatial frequency. After adaptation observers matched the saturation of the aftereffect color to a comparison display for test gratings of various spatial frequencies. The aftereffects were strongest for test gratings that matched the retinal spatial frequency of the adapting grating and progressively weaker for test gratings of higher and lower spatial frequencies.

In the present experiment individual observers were adapted to a grating of a single color (magenta or green) and spatial frequency (3 or 6 cycles/deg). Observers were then tested for a color aftereffect contingent on perceived spatial frequency using two-dimensional arrays in which the retinal spatial frequency of the achromatic test gratings was 4.2 cycles/deg, which was either 0.5 octaves higher or lower than the adapting grating.

For example, adaptation to a grating consisting of green and black bars with a spatial frequency of 3 cycles/deg should produce a red aftereffect on an achromatic test grating of the same spatial frequency. A Necker cube (Figure 1) and a corridor array (Figure 2) each containing two achromatic 4.2 cycles/deg gratings were used as test figures. If the aftereffects are contingent only on retinal spatial frequency the strength of the aftereffects should be identical (i.e., appear to be equally saturated) for both of the gratings on the Necker cube and for both of the gratings on the corridor array because even though there is a slight mismatch between the adapting and test spatial frequencies, the aftereffect is typically reported over four octaves of spatial frequency (Stromeyer, 1972). However, if the Necker cube is perceived in depth and the lower face is organized as the front, the upper face should be perceived as larger (i.e., lower spatial frequency) since it is perceived as more distant yet subtends the same retinal expanse (Emmert's law). The color aftereffect evoked by the grating on the upper face should then be perceived as stronger or more saturated than the grating on the lower face because the perceived spatial frequency of the upper grating would be a closer match to the spatial frequency of the adapting grating. Similarly, although both gratings on the corridor array are of identical retinal spatial frequency, in this example (adaptation to a 3 cycles/deg grating) the perceived spatial frequency of the grating in the upper region of the array would be a closer match to the spatial frequency of the adapting grating. Thus, the finding of a difference in the reported magnitude of the aftereffect for two gratings of identical retinal spatial frequency would indicate that the perceived spatial frequency of the test gratings influenced the aftereffect.

Measurement of the changes in organization of the Necker cube were obtained before and after adaptation in order to assess the effect of an interpolated adaptation period, and the resulting color aftereffects, on perceptual organization.

Method

Observers

Twenty-four undergraduate students participated in the experiment in order to fulfill a psychology course requirement. None of the observers were familiar with pattern-contingent color aftereffects. Normal red-green color vision, as determined by pseudoisochromatic plates (Hardy, Rand, & Rittler, 1946), was a criterion for participation in the experiment.

Stimuli and Design

All stimuli were 35 mm slides that were rear projected on a transluscent screen. Presentation of adaptation stimuli was controlled by a two-channel projection tachistoscope (Marietta #15-5-C). The adaptation stimuli consisted of square wave gratings photographed on Kodak High-Contrast (#5069) copy film. The projected image of the adaptation and test slides subtended a visual angle of 4 deg horizontally and 2.6 deg vertically at a viewing distance of 2.5 m. There were four different adaptation conditions determined by the factorial combination of two spatial frequencies of the adapting grating (3 or 6 cycles/deg) projected through either a magenta (Wratten #34a) or green (Wratten #53) gelatin filter. Adaptation condition was a between-subjects factor. Observers were randomly assigned to one of the four adaptation conditions with the restriction that there were six observers in each condition. The adaptation gratings were always oriented vertically. In the conditions where the adapting gratings were projected through the magenta filter the luminances of the black bars and magenta slits were 1 and 100 ft-L respectively. When the adapting gratings were projected through the green filter the luminances of the black bars and green slits were 1.3 and 100 ft-L respectively.

The preliminary pattern used to test for the presence of a spatial frequency-contingent color aftereffect contained achromatic vertical square wave gratings 3 cycles/deg on the left and 6 cycles/deg on the right (Figure 3). In addition, three figures were used to test for the presence of color aftereffects contingent on perceived spatial frequency. These test figures consisted of (a) a Necker cube with identical achromatic vertical 4.2 cycles/deg square wave gratings on each face (Figure 1), (b) a Necker cube with a vertical 4.2 cycles/deg grating on only the upper face (Figure 4), and (c) a corridor array with identical 4.2 cycles/deg gratings in both the lower and upper region of the corridor (Figure 2). The luminances of the black bars and white slits of all test gratings were 6.3 and 100 ft-L respectively.

Procedure

Preadaptation. Each observer was familiarized with the phenomenon of a reversible perspective figure by viewing a line drawing of a Necker cube (with no gratings) and asked to allow two predominant organizations (lower face front and upper face front) to reverse spontaneously. The Necker cube with identical gratings on each face was then displayed on the viewing screen. Observers were given a pushbutton switch that activated an event recorder and instructed to fixate a point in the center of the screen. They were then told to report any changes in the perceived organization of the cube by depressing the switch whenever the lower face was perceived as the front of the cube, and releasing the switch whenever the upper face was perceived as the front. These changes in organization were recorded for 2 min.

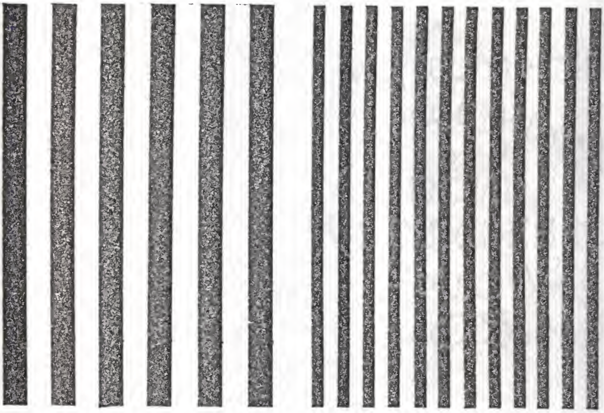


Figure 3. Preliminary pattern used to test for the presence of a spatial frequency-contingent color aftereffect. The bars on the left are twice as thick as those on the right.

Adaptation. After assignment to an adaptation condition, each observer was adapted for 30 min to the particular grating of a single color and spatial frequency for that condition. The adaptation grating was presented for 25 sec at a time alternating with 5 sec dark periods. Observers were instructed to maintain a constant upright body position with as little head movement as possible and to allow their gaze to wander over the projection area.

Postadaptation. The observers were allowed to rest for 10 min after adaptation. Then changes in organization of the Necker cube containing two gratings (Figure 1) were measured for 2 min in the same manner as in the preadaptation phase. Subsequently, observers were systematically questioned to determine (a) if spatial frequency-contingent color aftereffects obtained, (b) whether these color aftereffects were contingent on perceived or retinal spatial frequency, and (c) if the perceived sizes of the test gratings on the Necker cube (Figure 1) and the corridor array (Figure 2) were consistent with Emmert's law. With the exception of the first question, all of the questions were specified as two-alternative forced choices to the observer. Specifically, the following questions were asked (each question is followed by the definitions of responses consistent with the manifestation of an aftereffect contingent on perceived spatial frequency or responses consistent with the manifestation of Emmert's law):

A. Preliminary test for a spatial frequency-contingent color aftereffect (Figure 3).

1. Do you see any trace of color on this slide? If so, what color?

2. If you had to say that either the left or the right side of this slide contained more of the color, which would it be, <u>left</u> or <u>right</u>?

In order to be included in the test phase of the experiment, each observer had to meet the prerequisite of responding to preliminary questions 1 & 2 in a manner which would indicate the presence of a spatial frequency-contingent color aftereffect. Specifically, each observer had to report a color that was approximately complementary to the particular adaptation color in that region of the test grating (Figure 3) that had the same spatial frequency as the adapting grating. For example, after adaptation to a 3 cycles/deg grating projected through a green color filter, the appropriate response to question 1 would be "red" or "pink" and the appropriate response to question 2 would be "left" (i.e., the 3 cycles/deg grating). Eleven observers failed to meet these prerequisites and were replaced in the appropriate adaptation condition in order to complete the experimental design.

B. Tests for color aftereffects contingent on <u>perceived</u> spatial frequency:

CUBE WITH A SINGLE GRATING (Figure 4).

1. I would like you to allow this cube to reverse organizations a few times. Which face of the cube has to be in the front in order for the face with the grating on it to appear to contain the most color, <u>lower left</u> or <u>upper right</u>?

The definition of a response to this question consistent with an aftereffect contingent on perceived spatial frequency depended on the spatial frequency of the adapting grating. The perceived size and hence spatial frequency of the 4.2 cycles/deg grating could vary if the changes in organization alter perceived depth relations, because Emmert's law would state that when the lower face is organized as the front of the cube the upper face would be perceptually larger. (The manifestation of Emmert's law was examined by the test questions in part C.) For example, the appropriate response would be "lower left" for the 3 cycles/deg adaptation conditions because when the lower face is organized as the front, the perceptually enlarged 4.2 cycles/deg grating on the upper face would appear to be a closer match to the low spatial frequency adapting grating and thus the aftereffect should be more saturated. The opposite response (i.e., "upper right") would be expected for the 6 cycles/deg adaptation conditions because when the upper face is organized as the front of the cube, the test grating on the upper face would then appear to be a closer match to the adapting grating.

CUBE WITH TWO GRATINGS (Figure 1).

2. Which face of this cube appears to be the front, lower left or upper right?
3. While the cube is in this organization, if you had to say that one of the gratings contained more color than the other, which would it be, lower left or upper right?

The particular organization of the cube reported in question 2 at any point in time is arbitrary. Therefore, the definition of a response to question 3 consistent with an aftereffect contingent on perceived spatial frequency depended on both the spatial frequency of the adapting grating and the particular organization of the test cube. Regardless of the observer's response to question 2 ("lower left" or "upper right"), that face that was organized as the front would be perceived as smaller (i.e., higher spatial frequency) than the other face due to implied depth relations. Similarly, the face of the cube organized as the back would be perceptually larger (lower spatial frequency). Therefore, the low spatial frequency adaptation conditions

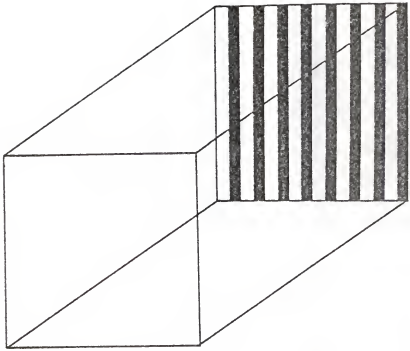


Figure 4. Necker cube containing a single grating on the upper face which was used in Experiment 1.

(i.e., 3 cycles/deg) should produce the most saturated aftereffect on the grating contained on the face of the cube which appears to be the lower spatial frequency, and the high spatial frequency adaptation conditions (i.e., 6 cycles/deg) should produce the most saturated aftereffect on the grating which appears to be the higher spatial frequency. Thus if an observer in the 3 cycles/deg adaptation condition responded to question 2 that the lower left face was organized as front, the definition of a response to question 3 consistent with an aftereffect contingent on perceived spatial frequency would be "upper right" which is the grating which would be perceived to have the lower spatial frequency. Alternatively, if an observer in the 3 cycles/deg adaptation condition responded "upper right" to question 2 the definition of a response to question 3 consistent with an aftereffect contingent on perceived spatial frequency would be "lower left" which is the grating which would be perceived to have the lower spatial frequency. Similarly, if an observer in the 6 cycles/deg adaptation condition responded "lower left" to question 2, the definition of a response to question 3 consistent with an aftereffect contingent on perceived spatial frequency would be "lower left."

4. Now try to reverse the organization of the cube. Which face of the cube appears to be the front, <u>lower left</u> or <u>upper right</u>?
5. While the cube is in this organization, if you had to say that one of the gratings contained more color than the other, which would it be, <u>lower left</u> or <u>upper right</u>?

The response to question 4 should be, by definition, the opposite of that given to question 2. Thus if the observer responded "upper right" to question 4, the definition of a response to question 5 consistent with an aftereffect contingent on perceived spatial frequency would be the opposite of that given to question 3. In the example given above this would be "lower left" for the 3 cycles/deg adaptation conditions and "upper right" for the 6 cycles/deg adaptation conditions.

CORRIDOR ARRAY WITH TWO GRATINGS (Figure 2).

6. If you had to say that one of the gratings on this slide contained more color than the other, which would it be, lower left or upper right?

If the corridor array gives rise to depth relations, then Emmert's law holds that the upper grating should be perceived as larger (i.e., lower spatial frequency) than the lower grating since they both subtend the same retinal expanse and have identical spatial frequency (4.2 cycles/deg) yet the upper grating is perceived as more distant. Thus, for the 3 cycles/deg adaptation conditions the perceived spatial frequency of the upper test grating should be a closer match to that of the adapting grating and the definition of a response to question 6 consistent with an aftereffect contingent on perceived spatial frequency would be "upper right". Similarly, the perceived spatial frequency of the lower test grating would be a closer match to that of the adapting grating for the 6 cycles/deg adaptation conditions and the definition of a response to question 6 consistent with a perceived spatial frequency contingent color aftereffect would be "lower left".

C. Test for perceived size differences between the gratings on the test stimuli:

CORRIDOR ARRAY WITH TWO GRATINGS (Figure 2).

1. If you had to say that one of the gratings on this slide was larger than the other, which would it be, lower left or upper right?

If the corridor array gives rise to depth relations, then Emmert's law holds that the upper grating should be perceived as larger than the lower grating since both gratings subtend the same retinal expanse, yet the upper grating is perceived as more distant. Therefore, for all adaptation conditions the definition of a response to question 1 consistent with perceived size differences in accord with Emmert's law would be "upper right".

CUBE WITH TWO GRATINGS (Figure 1).

2. Which face of this cube appears to be the front, lower left or upper right?
3. While the cube is in this organization, if you had to say that one grating was larger than the other, which would it be, lower left or upper right?

Again, the particular organization reported in question 2 is arbitrary and the perceived size of the gratings on the cube should vary depending on the organization of the cube. If the changes in organization alter depth relations, then Emmert's law holds that when a particular face is organized as the front, the other face would be perceptually larger since it is perceived as more distant yet subtends the same retinal expanse as the front face. Thus, for all adaptation conditions, a response to question 3 consistent with Emmert's law would be the opposite of that given by the observer to question 2. For example, if the observer responded "lower left" to question 2, a response of "upper right" to question 3 would be consistent with Emmert's law.

Results and Discussion

Color and Size Judgments

Table 1 presents the number of responses to the questions in parts B and C of the postadaptation phase of Experiment 1 for each adaptation condition which were consistent with the definition of a color aftereffect contingent on perceived spatial frequency (part B postadaptation) or with the definition of perceived size differences between the gratings on the Necker cube and the corridor array predicted by Emmert's law (part C postadaptation). There were no systematic differences among adaptation conditions so the column labelled "total" in Table 1 represents the data pooled across the four adaptation conditions.

If the observers responded solely to the retinal parameters of the test stimuli, it would have been reflected by chance responding to all of the two-alternative forced-choice questions included in Table 1. Chance performance was defined as 12 of 24 in the "total" column and was based on the fact that the spatial frequency of the two gratings on the test stimuli were identical. Furthermore, this spatial frequency was intermediate (i.e., one half octave) between the two adapting spatial frequencies so responding between the two alternative test gratings would be expected to be random if based solely on physical parameters of stimulation. However the color and size judgment data in Table 1 indicated that observers were responding to the perceived, rather than solely the retinal, parameters of the test stimuli. Eighteen of the 24 observers gave a response to question B3 regarding the differential strength of the aftereffect on the Necker cube with two gratings (Figure 1) that was consistent with the definition of a color aftereffect contingent on perceived spatial frequency. This differed significantly from what would be expected due to chance ($p < .05$)[3]. Question B6 tested for differential strength of the aftereffect on the two gratings contained on the corridor array

Table 1

Number of responses consistent with the definitions of responding to the perceived properties of test stimuli for each adaptation condition.

COLOR JUDGMENTS

Question	Test Figure	Adaptation Condition				
		3 cycles/deg		6 cycles/deg		
		magenta	green	magenta	green	total (n=24)
B1	cube -one grating	4	4	5	3	16
B3	cube - two gratings	3	5	6	4	18 *
B5	cube - two gratings	3	3	2	2	10
B6	corridor-two gratings	4	5	6	4	19 **
SIZE JUDGMENTS						
Question	Test Figure					
C1	corridor - two gratings	4	5	6	6	21 **
C3	cube - two gratings	5	3	5	5	18 *

* $p < .05$

** $p < .01$

(Figure 2) and 19 of 24 observers ($p < .01$) gave responses that were consistent with the definition of an aftereffect contingent on perceived spatial frequency. However, only 16 of 24 observers gave responses consistent with the definition of a perceived spatial frequency-contingent color aftereffect for question B1 concerning the Necker cube with one grating (Figure 4) which did not differ significantly from chance ($p > .05$). Similarly, when observers were asked to reverse the Necker cube with two gratings (Figure 1) the number of responses to question B5 consistent with the definition of an aftereffect contingent on perceived spatial frequency also did not differ significantly from chance (10 of 24; $p > .05$).

Twenty-one of 24 observers ($p < .01$) gave a response to question C1 regarding perceived size differences between the two test gratings on the corridor array (Figure 2) that was consistent with size differences predicted by Emmert's law. In addition, 18 of 24 observers ($p < .05$) gave a response to question C3 regarding perceived size differences between the two test gratings on the Necker cube (Figure 1) that was consistent with Emmert's law. These size judgment results indicate that perceived size differences between the gratings on the test stimuli obtained in a manner consistent with Emmert's law and provide validation for the underlying assumption on which the questions in part B were based.

Reversal data

If color aftereffects of differential saturation were present on the two gratings on the Necker cube, it might have been anticipated that the cube would have been more stable in one or the other of the two predominant organizations. This would have been indicated by a greater mean amount of total time spent in one of the two organizations of the cube during postadaptation relative to preadaptation, an increase in the mean duration of one or the other, or of both, organizations during postadaptation relative to preadaptation, and a decrease in the mean number of reversals from pre- to postadaptation.

The reversal data however did not meet any of these criteria of stability. Table 2 presents the mean reversal data obtained from observers during the pre- and postadaptation phases of the experiment for the Necker cube containing two gratings (Figure 1). There were no significant differences between the mean total amount of time spent in each of the two predominant organizations (lower face front and upper face front) in either the pre- or the postadaptation phases, $t_{dep}(21) \leq 0.30$, $\underline{p} > .05$. In addition, there were no significant differences between the mean durations of each of the two organizations in either the pre- or postadaptation phases, $t_{dep}(21) \leq 1.37$, $\underline{p} > .05$. Finally, there was no significant difference between the mean number of reversals in the pre- and postadaptation phases of the experiment, $t_{dep}(21) \leq 1.64$, $\underline{p} > .05$.

Table 2

Mean preadaptation and postadaptation reversal

data for each organization of Figure 1 (N=22*).

	total time in each organization (sec)		duration of each organization (sec)		number of reversals
	lower face front	upper face front	lower face front	upper face front	
preadaptation	63.9	56.1	9.3	6.1	21.1
postadaptation	60.2	59.8	6.8	6.8	28.5

*Data for two observers lost due to human and mechanical error.

Experiment 2

In Experiment 1 observers were adapted to a single chromatic grating. In the second experiment spatial frequency contingent color aftereffects were examined by alternately adapting observers to two different chromatic gratings (magenta and green) separated by one octave of spatial frequency (3 and 6 cycles/deg). Observers were then tested for color aftereffects contingent on perceived spatial frequency using test stimuli that were similar to those used in Experiment 1. In all cases, the spatial frequency of the gratings in the test stimuli was one half octave intermediate (4.2 cycles/deg) between the adapting gratings.

If the two faces of the Necker cube are characterized by differences in perceived depth, it is not possible to describe a priori the location of these faces in space relative to the picture plane (the viewing screen). When inspecting a receding corridor array an observer may first assess overall depth in the array and then (a) choose the most distant object as being of zero value and underestimate all other objects in relation to its size, (b) choose the closest object as being of zero value and overestimate all other objects in relation to its size, or (c) choose any of a number of possible midpoints in the array as being of zero value and judge all other objects in relation to that point (cf. Coren & Girgus, 1977). In order to control for the possibility that observers utilized different zero points of perceived depth in the two-dimensional pictorial arrays during the test phase of Experiment 2, observers were allowed to adjust the distance between themselves and the viewing screen by moving forward or backward which would, of course, alter the retinal spatial frequency of the test gratings. This should maximize the reports of differences between the aftereffect colors associated with the perceived spatial frequency of the test gratings even though the retinal spatial frequencies of these gratings are identical at any given viewing distance. The rationale for the previous statement is that if the cube and the corridor array give rise to perceived depth relations and observers are allowed to move, the observer should be able to choose a zero point where one grating in the test stimulus is perceived as more similar in spatial frequency to one of the adapting gratings and the other test grating is perceived as more similar to the other adapting grating.

An additional measure obtained in Experiment 2 was similar to a neutral or null point procedure described by Harris (1970). As an example of the neutral point procedure, if a green aftereffect color is made contingent on wide bars and a red aftereffect color is made contingent on narrow bars, there should be a crossover distance or "null point" where a test grating appears green if the observer moves any closer to and red if the observer moves any further from the viewing screen. To determine this neutral point in Experiment 2 observers were shown corridor arrays with only one test grating of an intermediate spatial frequency relative to the adapting gratings. This single test grating was located in either the lower or upper region of the corridor array (Figures 5a & b). For each of these test arrays, observers were instructed to move to the neutral point. If the aftereffect depends solely on retinal spatial frequency, the neutral point settings for a grating in the lower region of the array would not differ significantly from settings for a grating in the upper region.

Figure 5a. A receding corridor array containing a single grating in the lower region used to assess the null point of the aftereffects in Experiment 2.

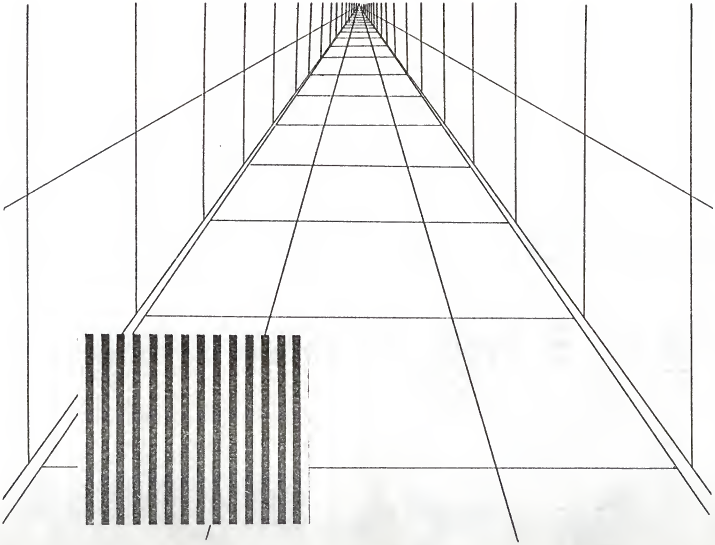
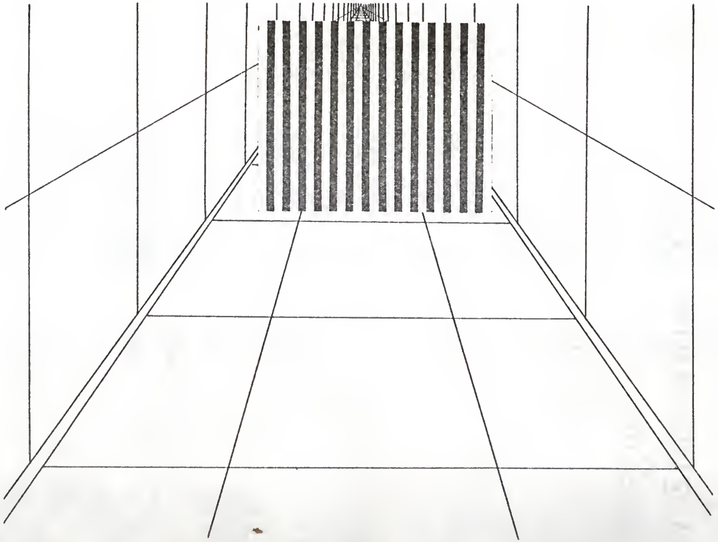


Figure 5b. A receding corridor array containing a single grating in the upper region used to assess the null point of the aftereffects in Experiment 2.



However, if perceived spatial frequency is involved in the aftereffect, and a grating in the upper region of the array is perceived as larger than a grating in the lower region, the neutral point settings for a grating in the upper region of the array would be significantly further from the viewing screen than the settings for a grating in the lower region of the array.

Measurements of the changes in organization of the Necker cube (Figure 1) were also obtained before and after adaptation in order to assess the effect of an interpolated adaptation period, and the resulting color aftereffects, on perceptual organization.

Method

Observers

Twelve undergraduate students participated in the experiment in order to fulfill a psychology course requirement. None of the observers had participated in Experiment 1, nor were they familiar with pattern-contingent color aftereffects. Normal red-green color vision, as determined by pseudoisochromatic plates (Hardy, Rand, & Rittler, 1946), was a criterion for participation in the experiment.

Stimuli and Design

All stimuli were 35 mm slides that were rear projected on a transluscent screen. Presentation of adaptation stimuli was controlled by a two-channel projection tachistoscope (Marietta #15-5-C). The adaptation stimuli were square wave gratings photographed on Kodak High-Contrast (#5069) copy film. The projected image of the adaptation and test slides subtended a visual angle of 4 deg horizontally and 2.6 deg vertically at a viewing distance of 2.5 m. Adaptation consisted of alternately presenting a 3 cycles/deg and a 6 cycles/deg grating projected through a magenta (Wratten #34a) and a green (Wratten #53) gelatin filter. Color and spatial frequency of adapting gratings was counterbalanced across observers resulting in two between-subjects adaptation conditions. Observers were randomly assigned to one of the two adaptation conditions with the restriction that there were six observers in each condition. The adapting gratings were always oriented vertically. The luminance of the gratings projected through the magenta filter was 1 and 100 ft-L for the black bars and for the magenta slits, respectively. When the adapting gratings were projected through the green filter, the luminances of the black bars and green slits were 1.3 and 100 ft-L, respectively.

The preliminary pattern used to test for the presence of a spatial frequency-contingent color aftereffect was the same as in Experiment 1 which consisted of achromatic vertical square wave gratings 3 cycles/deg on the left and 6 cycles/deg on the right (Figure 3). Two test figures from Experiment 1 were used to test for the presence of color aftereffects contingent on perceived spatial frequency. These figures were (a) the Necker cube with identical achromatic vertical 4.2 cycles/deg gratings on each face (Figure 1) and (b) the corridor array with identical 4.2 cycles/deg gratings in both the lower and upper regions of the array (Figure 2). In order to determine the neutral point of the aftereffects two additional corridor arrays with a single achromatic 4.2 cycles/deg grating in either the lower or upper region of the array (see Figures 5a & b) were included as test stimuli in Experiment 2. The luminances of the black bars and white slits of all test gratings were 6.3 and 100 ft-L, respectively.

In order to allow the observer to move along the line of sight relative to the viewing screen during the test phase of the experiment a chair with wheels was substituted for the immobile chair used in Experiment 1. The wheels of the chair were restricted to tracks which extended 1.2 m either side of the 2.5 m adapting distance. During the preadaptation, adaptation, and the initial part of the postadaptation phases of the experiment, the wheels of the chair were locked in order to keep the observer a constant 2.5 m distance from the viewing screen.

Procedure

Preadaptation. Each observer was familiarized with the phenomenon of a reversible perspective figure by viewing a line drawing of a Necker cube (with no gratings) and asked to allow the two predominant organizations (lower face front and upper face front) to reverse spontaneously. The Necker cube with identical gratings on each face (Figure 1) was then displayed on the screen. Observers were given a pushbutton switch that activated an event recorder and instructed to fixate a point in the center of the screen. They were then told to report any changes in the perceived organization of the cube by depressing the switch whenever the lower face was perceived as the front of the cube and releasing the switch whenever the upper face was perceived as the front. These changes were recorded for 2 min.

Adaptation. After assignment to an adaptation condition, each observer was adapted for 60 min to the alternate presentation of the two adapting gratings. The two adapting gratings were alternately presented for 25 sec with intervening 5 sec dark periods. Observers were instructed to maintain a constant upright body position with as little head movement as possible and to allow their gaze to wander over the projection area. There was a 2 min rest period after 20 and 40 min of adaptation.

Postadaptation. The observers were allowed to rest for 10 min after adaptation. Then changes in the organization of the Necker cube containing two gratings (Figure 1) were measured for 2 min in the same manner as in the preadaptation phase. Observers were then tested for a spatial frequency contingent color aftereffect by presenting Figure 3 on the viewing screen and asking the following questions:

1. Do you see any trace of color on this slide? If so, where?
2. What color?
3. If you had to say that the left side of this slide appeared either pink or green, which would it be, pink or green?
4. If you had to say that the right side of this slide appeared either pink or green, which would it be, pink or green?

In order to be included in the test phase of the experiment, each observer had to meet the prerequisite of responding to questions 3 & 4 in a manner which would indicate the presence of a spatial frequency contingent color aftereffect. Specifically, each observer had to report colors that were complementary to the particular adaptation color in that region of the test grating (Figure 3) with the same spatial frequency as the adapting grating. For example, after alternate adaptation to a magenta 3 cycles/deg grating and a green 6 cycles/deg grating, a response of "green" to the low spatial frequency region of the test grating (question 3) and "pink" to the high spatial frequency region of the test grating (question 4) would be consistent with a spatial frequency-contingent color aftereffect. Four observers were replaced in the appropriate adaptation condition for failing to meet this prerequisite.

Observers meeting the aforementioned criterion were then tested for color aftereffects contingent on perceived spatial frequency. The lock on the wheels of the chair was released and the Necker cube containing two gratings (Figure 1) was presented on the screen. The observers were instructed (a) to move forward (or backward) until both gratings on the cube appeared to contain the same aftereffect color, (b) to move backward (or forward) until both gratings on the cube appeared to contain the other aftereffect color, and (c) to move to an intermediate distance where the aftereffect colors began to switch. Allowing the observer to adjust this intermediate point should maximize the reports of differences between the aftereffect colors associated with the perceived spatial frequency of the test gratings. When the observer indicated that step (c) had been completed, the observer was asked to indicate which face of the cube was perceived as the front and while the cube was in that organization if there were any aftereffect colors on the two test gratings. These questions were all free response rather than forced choices. Observers were then asked to reverse the organization of the cube and to report the presence of any aftereffect colors on the two test gratings.

The observers were then shown the corridor array containing two 4.2 cycles/deg gratings (Figure 2) and steps (a) through (c) were repeated. Again the observers were questioned to determine the presence of any aftereffect colors on the two test gratings after the completion of step (c).

The null point for the color aftereffects was obtained by displaying a corridor array containing a single 4.2 cycles/deg grating in the _lower_ region of the array (Figure 5a) on the screen and asking the observer to move to a crossover distance where the test grating appeared green if they moved any closer to and pink if they moved any further from the viewing screen. The direction of the movement necessary to yield the specified aftereffect color depended, of course, on the adaptation condition. The neutral point procedure was repeated using a corridor array containing a single 4.2 cycles/deg grating in the _upper_ region of the array (Figure 5b). Order of presentation of Figures 5a & b was counterbalanced across observers.

Finally each observer was questioned to determine if there were perceived size differences between the gratings contained on the test stimuli (Figures 1 & 2) which were consistent with Emmert's law by asking questions C1, C2, and C3 from Experiment 1.

Results and Discussion

Color reports, size judgments, and distance settings

For the Necker cube containing two 4.2 cycles/deg gratings (Figure 1) 11 of 12 observers were able to complete postadaptation step (c). The twelfth observer did not report the presence of any aftereffect colors at any distance to which the chair could be moved along the tracks. Table 3 contains a summary of the color reports of these 11 observers who were able to move to a distance where the aftereffect colors on the test stimuli gratings began to switch. Of the 11 observers who completed step (c), nine reported different aftereffect colors on the two gratings (i.e., one test grating on the cube appeared pink and the other grating appeared green). The other

Table 3

Summary of color reports obtained from observers in Experiment 2 who moved to a distance where the aftereffect colors on the test gratings on the Necker cube (Figure 1) and on the test gratings on the corridor array (Figure 2) began to change (step c postadaptation).

	Adaptation condition	
	3 cycles/deg green 6 cycles/deg magenta	3 cycles/deg magenta 6 cycles/deg green
COLOR REPORTS FOR CUBE (Figure 1)		
a. number of reports of two different aftereffect colors	5	4
b. number of reports of one aftereffect color on one grating and no aftereffect color on the other grating	1	1
total	6 (M=2.9 M)*	5 (M=2.8 m)
COLOR REPORTS FOR CORRIDOR (Figure 2)		
a. number of reports of two different aftereffect colors	2	1
b. number of reports of one aftereffect color on one grating and no aftereffect color on the other grating	2	2
total	4 (M=3.1 m)	3 (M=2.9 m)

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[*] The numbers in parentheses are the mean distances in meters at which the color reports were obtained.

two observers reported one aftereffect color on one of the test gratings and no aftereffect color on the other test grating (i.e., the other test grating appeared achromatic). The hues of these color reports for all 11 of these observers were consistent with definitions of perceived spatial frequency-contingent color aftereffects based on the assumption that the test stimuli would yield perceived size differences consistent with Emmert's law. Not included in this table are the results obtained when observers were asked to reverse the cube and report the presence of aftereffect colors. Of the 11 observers who gave color reports associated with the initial organization of the cube, five were unable to reverse the cube long enough to make color judgments, four reported that the aftereffect colors remained unchanged with reversal of the cube, and two reported that with a reversal both test gratings now contained the same aftereffect color (i.e., both gratings appeared pink or both appeared green).

Table 3 also presents the results obtained with the corridor array containing two 4.2 cycles/deg gratings (Figure 2). Five of the twelve observers failed to report the presence of any aftereffect color at any distance to which the chair could be moved along the runners. The remaining seven observers were able to move to a distance where the aftereffect colors on the test stimuli gratings began to switch (step c postadaptation). When asked to report the presence of any aftereffect colors at this distance, three of the seven reported that each test grating on the array contained a <u>different</u> aftereffect color. The remaining four observers reported that one grating in the test array contained one aftereffect color and the other test grating appeared achromatic. The hues of these color reports for six of these seven observers were consistent with definitions of perceived spatial frequency color aftereffects based on the assumption that the test stimuli would yield perceived size differences consistent with Emmert's law.

It is interesting to note the mean distance settings at which the color reports were obtained for the cube and the corridor. If observers were responding solely to retinal spatial frequency of the test gratings the mean distance settings would have been approximately 2.5 m, since the adapting distance was 2.5 m and the spatial frequency of the test gratings was the intermediate (octave scale) of the adapting spatial frequencies. However, the distance settings all exceed 2.5 m and it thus seems that observers were responding to perceived distance relations. Specifically, it seems that observers chose the closest point in the array as being of zero depth and systematically overestimated all other objects in the array relative to this zero point (see introduction Experiment 2).

Eleven of the 12 observers gave a response to question C1 regarding perceived size differences between the two test gratings on the corridor array (Figure 2) that was consistent with Emmert's law. In addition, 11 of the 12 observers gave a response to question C3 regarding perceived size differences between the two test gratings on the Necker cube (Figure 1) that was consistent with Emmert's law.

There was a significant difference between the null point settings for the test grating in the lower region of the array (M=267 cm) and those for the test grating in the upper region of the array (M=295 cm), $t_{dep}(10) = 3.89$, $\underline{p} < .01$, when observers were shown corridor arrays containing a single 4.2 cycles/deg grating (Figures 5a & b).

The color report, size judgment, and neutral point data for Experiment 2 taken together again support the hypothesis that under the appropriate conditions color aftereffects can be made contingent on perceived spatial frequency of test gratings. This finding is especially evident under the conditions of the present experiment where two different aftereffect colors were induced and observers generally reported one aftereffect color on one achromatic test grating and the other aftereffect color on another achromatic grating contained in a test array in which the retinal spatial frequencies of the test gratings were identical.

Reversal data

Table 4 presents the mean reversal data obtained from observers during the preadaptation and postadaptation phases of the experiment for the Necker cube containing two 4.2 cycles/deg gratings (Figure 1). The mean total amount of time spent in each of the two predominant organizations did not differ significantly in either the pre- or postadaptation phases, $t_{dep}(11)$ 2.03, $p > .05$. In addition, there were no significant differences between the mean durations of each of the two predominant organizations of the cube in either the pre- or postadaptation phases, $t_{dep}(11) > 1.24$, p .05. Finally, the mean number of reversals of the cube during preadaptation did not differ significantly from the mean number of reversals during postadaptation. It had been anticipated that if aftereffect colors of different hue were present on the two gratings on the Necker cube, the cube might have been more stable in one of the two organizations due to the salience added by differential hue. By the criteria of stability of the cube outlined in Experiment 1 increased stability was not indicated

Table 4

Mean preadaptation and postadaptation reversal data for each organization of Figure 1 (N=11*).

	total time in each organization (sec)		duration of each organization (sec)		number of reversals
	lower face front	upper face front	lower face front	upper face front	
preadaptation	64.9	55.1	7.2	5.6	21.8
postadaptation	69.8	50.2	11.1	5.0	22.4

[*] Data for one observer lost due to human and mechanical error.

statistically, although there was a tendency towards stability in terms of mean total amount of time and mean duration of each organization.

Experiment 3

In Experiment 2 observers were alternately adapted to two different chromatic gratings (magenta and green) separated by one octave of spatial frequency (3 and 6 cycles/deg) in order to induce spatial frequency-contingent color aftereffects. One of the dependent measures in Experiment 2 involved varying viewing distance to determine a null point setting for the color aftereffects on a test grating presented in the context of a pictorial corridor array. The null point viewing distance for a grating in the lower (closer) region of the test array was significantly shorter relative to the viewing screen than the settings for the same grating in the upper (farther) region of the array. This finding suggests that the color aftereffects were contingent, at least to some extent, on the perceived spatial frequency of test gratings.

The purpose of Experiment 3 was to quantify this effect by determining the null point of color aftereffects for test gratings that varied over a range of retinal spatial frequencies. This was done in order to determine the contribution of perceived spatial frequency to the nature of spatial frequency contingent color aftereffects. Color aftereffects contingent on spatial frequency were induced by alternately adapting observers to two different chromatic gratings (magenta and green) separated by two octaves of spatial frequency. To determine the neutral point observers were shown corridor arrays with a single test grating in either the lower or upper region of the array (see Figures 5a & b). There were four levels of cycle width (bar and slit) of the test gratings on the viewing screen. Varying cycle width has the effect of altering retinal spatial frequency.

Also, if viewing distance is varied retinal spatial frequency changes while cycle width on the viewing screen remains the same. However, for any given cycle width the perceived spatial frequency of the test gratings varied due to depth relations resulting from placing the grating in either the lower or upper region of the receding corridor array. If the aftereffects depend solely on retinal spatial frequency, at a given level of cycle width the null point settings for a test grating in the lower region of the array would not differ significantly from settings for a test grating in the upper region of the array. However, if a test grating in the upper region of the array is perceived as larger than a test grating in the lower region and perceived spatial frequency is involved in the aftereffects, systematic effects on null point settings would be expected. Specifically, at a given level of cycle width the null point settings for a grating in the upper region of the test array would be significantly further from the viewing screen than the settings for a grating in the lower region of the array. In summary, if the observers' null point settings vary solely with cycle width, this would indicate that the color aftereffects are contingent solely on retinal spatial frequency. However, if the null point settings vary with position on the array (lower or upper region), this would indicate that perceived spatial frequency is involved in the color aftereffects.

Method

Observers

Eight undergraduate students participated in the experiment in order to fulfill a psychology course requirement. None of the observers were familiar with pattern-contingent color aftereffects.

Normal red-green color vision, as determined by pseudoisochromatic plates (Hardy, Rand, & Rittler, 1946), was a criterion for participation in the experiment.

Stimuli and design

All stimuli were 35 mm slides that were rear projected on a transluscent screen. Presentation of adaptation stimuli was controlled by a two-channel projection tachistoscope (Marietta #15-5-C). The adaptation stimuli were square wave gratings photographed on Kodak High-Contrast (#5069) copy film. The projected image of the adaptation slides subtended a visual angle of 4 deg horizontally and 2.6 deg vertically at a viewing distance of 2.5 m. Adaptation consisted of alternately presenting a 3 cycles/deg grating and a 12 cycles/deg grating projected through a magenta (Wratten #34a) and a green (Wratten #53) gelatin filter. Color and spatial frequency of adapting gratings was counterbalanced across observers resulting in two between-subjects adaptation conditions. Observers were randomly assigned to one of the two adaptation conditions with the restriction that there were four observers in each condition. The adapting gratings were always oriented vertically. In the conditions where the 3 or 12 cycles/deg gratings were projected through the magenta filter, the luminances of the black bars and green slits were 1 and 100 ft-L respectively. When the adapting gratings were projected through the green filter the luminances of the black bars and green slits were 1.3 and 100 ft-L respectively.

The preliminary pattern used to test for the presence of a spatial frequency contingent color aftereffect contained achromatic vertical square wave gratings 3 cycles/deg on the left and 12 cycles/deg on the right (Figure 6). The test stimuli were sixteen 35 mm slides. The projected image of the slides subtended a visual angle of 8 deg horizontally and 5.2 deg vertically at a viewing distance of 2.5 m. Of the sixteen test slides eight were experimental slides and eight were control slides. The eight experimental slides consisted of test gratings of four different cycle widths (3.7, 5.6, 7.5, and 11.2 mm) contained in either the lower or upper region of the corridor array (see Figures 5a & b for examples). The corresponding spatial frequencies of these gratings at the 2.5 m adapting distance were 12, 8.5, 6, and 4.2 cycles/deg. The eight control slides consisted of the same four gratings placed in either the lower or upper region of the slide without the context of the receding corridor array and the accompanying cues to depth. The purpose of these control slides was to control for the possibility of position on the slide affecting the nature of the aftereffect. The luminances of the black bars and white slits of all test gratings were 6.3 and 100 ft-L respectively.

In order to allow the observer to move along the line of sight relative to the viewing screen during the test phase of the experiment, the wheels of a wheelchair were restricted to tracks which extended 2.4 m either side of the 2.5 m adapting distance. During the adaptation phase of the experiment, the wheels of the chair were locked in order to keep the observer a constant 2.5 m distance from the viewing screen.

Procedure

Adaptation. After assignment to an adaptation condition, each observer was adapted for 30 min by alternately presenting the two adapting gratings for 25 sec with intervening 5 sec dark periods.

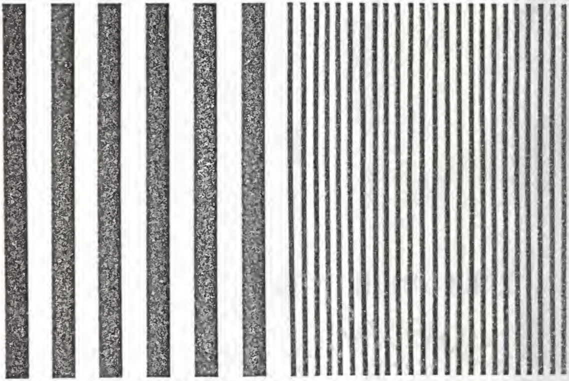


Figure 6. Preliminary pattern used to test for the presence of a spatial frequency-contingent color aftereffect. The bars on the left are four times thicker than those on the right.

Observers were instructed to maintain a constant upright body position with as little head movement as possible and to allow their gaze to wander over the projection area.

Postadaptation. Ten minutes after adaptation, observers were tested for spatial frequency contingent color aftereffects by presenting Figure 6 on the viewing screen and asking the following questions:

1. Do you see any trace of color on this slide? If so, where?
2. What color?
3. If you had to say that the left side of this slide appeared either pink or green, which would it be, pink or green?
4. If you had to say that the right side of this slide appeared either pink or green, which would it be, pink or green?

In order to be included in the test phase of the experiment, each observer had to meet the prerequisite of responding to questions 3 and 4 in a manner which would indicate the presence of a spatial frequency contingent color aftereffect. Specifically, each observer had to report colors that were complementary to the particular adaptation color in that region of the test grating (Figure 6) with the same spatial frequency as the adapting grating. For example, after alternate adaptation to a magenta 3 cycles/deg grating and a green 12 cycles/deg grating, a response of "green" to the low spatial frequency region of the test grating (question 3) and "pink" to the high spatial frequency region of the test grating (question 4) would be consistent with spatial frequency contingent color aftereffects. Two observers were replaced in the appropriate adaptation condition for failing to meet this prerequisite.

Subsequently, the locks on the wheelchair were released and one of the 16 test slides was presented on the viewing screen. The observer was instructed to move forward or backward to a crossover distance where the grating on the test slide appeared one aftereffect color if they moved any closer to the screen and the other aftereffect color if they moved any further away. Each observer was instructed that this procedure would be repeated for a number of different slides and that their task was to be the same for each slide. In all, observers were given 24 trials consisting of two presentations of each of the eight experimental slides and one presentation of each of the eight control slides.[4] Order of presentation of the test slides was randomly determined for each observer.

Results and Discussion

There were no significant differences between the neutral point settings for the two counterbalanced adaptation conditions so the settings were pooled across this between-subjects factor for purposes of analysis. The null point settings obtained from observers for the control slides, the first replication of the experimental slides, and the second replication of the experimental slides were subjected to separate 2 (position on the slide) x 4 (cycle widths) by 8 (subjects) within-subjects analyses of variance. The results of these analyses are presented in Table 5. In all three analyses the effect of cycle width (retinal spatial frequency) was significant, $F(3,21) \geq 47.24$, $p < .01$. In addition, the main effect of position on the slide (lower or upper region) was significant for each replication of the experimental slides, $F(1,7) \geq 13.18$, $p < .01$, but not for the control slides, $F(1,7) < 1$. The critical difference between the experimental

Table 5

Summary of the separate analyses of variance

CONTROL SLIDES

Source	df	MS	F
Position on slide (P)	1	75.47	<1
Observers (O)	7	3039.47	
P x O	7	197.73	
Cycle width (C)	3	17835.90	46.75*
C x O	21	381.53	
C x P	3	28.93	<1
C x P x O	21	112.91	

EXPERIMENTAL SLIDES (Replication 1)

Source	df	MS	F
P	1	1064.41	13.18*
O	7	1317.55	
P x O	7	80.73	
C	3	16081.02	127.80*
C x O	21	125.87	
C x P	3	130.25	1.5
C x P x O	21	87.94	

EXPERIMENTAL SLIDES (Replication 2)

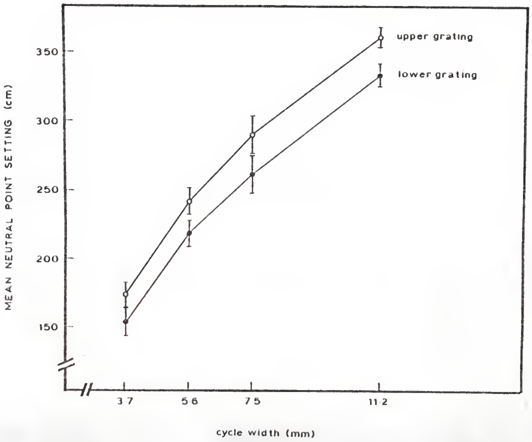
Source	df	MS	F
P	1	1985.82	24.27*
O	7	1631.17	
P x O	7	81.82	
c	3	14249.42	90.89*
C x O	21	156.78	
C x P	3	13.42	<1
C x P x O	21	45.64	

$^*p < .01$

and control slides was the presence or absence of the context of a receding corridor array. The results indicate that only retinal spatial frequency affected the neutral point settings for the control slides. However, the neutral point settings for the experimental slides indicated that both perceived and retinal spatial frequency systematically influenced the pattern-contingent color aftereffects. The interaction of position on the slide and cycle width was not statistically significant for the control slide null point settings or for either replication of the experimental slides. Assuming that a null point setting is a linear function of factorial effects and experimental error, this absence of an interaction indicates that, for the experimental slides, perceived and retinal spatial frequency are additive components of the color aftereffects (Winer, 1971, Chapter 5).

Since the pattern of results was similar for the first and second replications of the experimental slides, the null point settings were pooled across replications and are shown in Figure 7.

Figure 7. Mean neutral point settings pooled over the first and second replications of the experimental condition. Bars indicate ±1 standard error.



General Discussion

The results of the present series of experiments indicate that under the appropriate testing conditions color aftereffects can be made contingent on the perceived, as well as the retinal, spatial frequency of test gratings. In most previous studies of spatial frequency contingent color aftereffects perceived and retinal spatial frequency have covaried. For example, Teft and Clark (1968) displayed test gratings of various spatial frequencies at a fixed viewing distance, thus changes in retinal width of the bars on the test gratings entailed changes in perceived width. Murch (1969) held the physical width of a test grating constant and varied the viewing distance, which resulted in varying retinal width. However, it is possible that perceived size could have varied with retinal size since size constancy is seldom perfect. The present experiments separated these factors by constructing test stimuli in which retinal spatial frequency was held constant while perceived spatial frequency varied due to pictorial cues to depth.

Feature extraction model of contingent color aftereffects

Most explanations have postulated that selective chromatic adaptation of neurophysiological feature detectors underlies contingent color aftereffects. This feature extraction hypothesis postulates that there are individual neurons in the visual system which selectively extract certain basic features from stimuli in the visual environment. That parameter to which a neuron is optimally sensitive is termed its "trigger" feature in that a specific value of any given parameter activates a commonly sensitive population of cells, and a different value gives rise to the activation of another population of cells. Form or pattern can then be identified on the basis of the most active population of cells. Orientation contingent color aftereffects, then, are contingent on the similarities of the trigger features of neural units and the physical parameters of the adapting stimuli. For example, McCollough (1965) suggested that color sensitive edge-detectors which have been described in cat and monkey (Hubel & Wiesel, 1962, 1968) could account for orientation contingent color aftereffects. Alternatively, May and Matteson (1976) suggest that orientation contingent color aftereffects involve color adaptation of spatial frequency specific mechanisms rather than edge specific feature detecting mechanisms. Both of these explanations have in common the notion that simple feature extraction underlies human form perception and that the contingent color aftereffects indicate the involvement of these mechanisms. Similar kinds of explanations have been advanced to account for a variety of kinds of contingent color aftereffects.

The findings that color aftereffects can be made contingent on perceptual organization (Uhlarik et al., 1977) or on perceived orientation (Mikaelian, 1976) point to the problems associated with any model of contingent aftereffects which is strictly tied to the physical parameters of the adapting and test stimuli (i.e., stimulus bound). According to Uhlarik et al. (1977), in order for a feature extraction model to hold it must be assumed that the mechanisms which perform the feature extraction process can be mediated by cognitive organizational factors. For example, it could be the case that each of the organizations of the test figure used by Uhlarik et al. activated different feature extraction mechanisms and adaptation might affect only one of these mechanisms. In addition, Mikaelian (1976) states that the result that color aftereffects can be made contingent on perceived orientation "supports the argument that the McCollough effects are not retinally locked, and that the phenomenon may be mediated by central processes; a view that places severe limitations on the commonly proposed explanation in terms of selective chromatic adaptation of simple edge-detectors" (p. 462).

The effects due solely to differences in perceived size in the present research also indicate that spatial frequency contingent color aftereffects might not be as dependent on the similarities of the trigger features of neural units and the physical parameters of adapting stimuli as simple feature extraction models would suggest. For example, for any given cycle width in Experiment 3 the retinal spatial frequency of the grating in the lower region of the test array was identical to that of the grating in the upper region of the array, yet the neutral point settings were systematically different for these two gratings.

In an attempt to speculate on the relation of the present findings to underlying neurophysiology, it is interesting to note that Richards (1967, 1968) presented both neurophysiological and psychophysical evidence implying that there is spatial remapping in the primate visual system which leads to changes in apparent size with alterations of depth. He suggested that this remapping was correlated with changes in convergent eye movements and thus that accomodation and convergence might be responsible for size scaling. Since the size scaling affects binocular rivalry, Richards concluded that size scaling occurs before the first site of binocular combination of input from the two eyes, possibly at the lateral geniculate nucleus. However, Humphrey and Weiskrantz (1969) reported that lesions in inferotemporal cortex of monkey produced a marked effect on size constancy in that monkeys could no longer discriminate objects in a nonstimulus bound manner although they could still discriminate size when distance was equal. This finding suggests that the inferotemporal cortex plays an important role in size constancy scaling. However, Pollen and Taylor (1974) have pointed out that:

> ...the normal temporal lobe may contain a mechanism that scans or zooms over the representation of visual space at a finite number of sizes, so that a number of different object sizes may be cross-correlated with the memory. Whether such zooming occurs within the temporal lobe or via temporal efferent influences on other levels of the visual system...is unknown. (p. 245)

Although the results of Richards (1967, 1968) and Humphrey and Weiskrantz (1969) offer a neurophysiological basis for size constancy scaling, these results were obtained by varying viewing distance to produce size transformations. Therefore, it is unclear whether perceived size varied or remained constant due to "constancy scaling". Additionally, accomodation and convergence could have served as peripheral mechanisms involved in size scaling in those studies. The present results, however, were obtained using stimuli in which size varied due to pictorial cues to depth and as such accomodation and convergence presumably would not be involved in size scaling of these stimuli.

Evidence that size scaling of stimuli takes place after visual cortex in humans is presented by Blakemore, Garner, and Sweet (1972). In this study, a spatial frequency contingent size aftereffect (Blakemore, Nachmias, & Sutton, 1970) was induced and in the test phase the aftereffect was measured at various viewing distances. The results indicated that the observers matched the retinal spatial frequency of the adapting gratings. Blakemore et al. intepret this result as indicating that size scaling occurs after visual cortex, possibly at inferotemporal cortex. However, in this study also size transformations were produced by varying viewing distance and again accomodation and convergence might have served as peripheral mechanisms involved in size scaling. In a study which allows comparison between size constancy scaling involved in three-dimensional viewing and constancy scaling invoked by pictorial cues to depth, Weiskrantz (1974) reports training monkeys to discriminate between two novel three-dimensional objects of a fixed shape, size, and orientation. In the test phase, the monkeys had to identify the discriminant stimulus under a variety of transformations of size, color, and orientation, including presenting two-dimensional photographs of the object. Weiskrantz (1974) found that with the exception of the two-dimensional photographs the monkey unhesitatingly recognized the correct object. This finding implies that there was some sort of size scaling process operating, but that it might not be the same in kind for three-dimensional and two-dimensional stimuli.

Associative model of contingent color aftereffects

The observation that pattern-contingent color aftereffects can last for hours (McCollough, 1965) or even months (Jones & Holding, 1975) suggests that the effects may be more than just fatigue of neural units. In addition, the failure of orientation (McCollough, 1965) and spatial frequency-contingent color aftereffects (Stromeyer, 1972) to show interocular transfer whereas orientation contingent tilt aftereffects (Lovegrove & Over, 1973) and spatial frequency contingent size aftereffects (Stromeyer, 1972) do show transfer suggests that color and pattern information are processed at different levels of the visual system. These observations have led Murch (1972, 1976) to propose an associative model of contingent color aftereffects. This model postulates that selective adaptation of opponent process color receptors of the lateral geniculate nucleus which feed into feature extracting mechanisms in visual cortex results in the contingent color aftereffects. The specific construct proposed to produce the association is classical conditioning. According to Murch (1976):

> In this view, the lined grid in inspection functions as the conditioned stimulus (CS) while the color functions as the unconditioned stimulus (UCS). As the result of the pairing of the CS (lined grid) with the UCS (color) a conditioned response (CR) develops so that the adaptive response of the visual system to the color is evoked by the lined grid.... Via the mechanism of conditioning, the result of the pairing is that the lined grid takes on the capability of creating the same shift in chromatic sensitivity that the color stimulus produced in inspection. The presentation of the lined grid in testing then elicits the adaptive state allowing the achromatic test pattern to appear tinged with a color roughly complementary to the adapting hue. (p. 615)

This model also involves the fatigue of feature extracting mechanisms although populations of cells at two different levels of the visual system (color sensitive units at the lateral geniculate nucleus and form sensitive units at visual cortex) are hypothesized to be involved rather than populations of cells at a single level of the visual system (color and form sensitive units at visual cortex). As such, this model is subject to some of the same limitations as the feature extracting models. However, Murch (1976) considers the usual establishment of pattern-contingent color aftereffects, in which opponent red-green aftereffect colors are induced each contingent on one parameter of the inducing pattern, to be a case of conditioned discrimination because "antagonistic conditioned responses are developed to two conditioned stimuli" (p. 616). In Experiment 2, when observers were shown a Necker cube containing identical square wave gratings on each face (Figure 1), nine of the 12 observers moved to a distance at which one of the gratings appeared green and the other grating appeared red, yet the gratings were of identical retinal size. In this case, the associative model leads to the implausible conclusion that two different "antagonistic" conditioned responses (green and red aftereffect colors) can be elicited by the *same* conditioned stimulus (a lined grid).

A cognitive-decision approach to form perception

The present research suggests that stimulus bound feature extracting mechanisms, while they may be important, cannot be completely descriptive of human form perception. Rock (1975) argues that feature extraction mechanisms are neither a necessary nor a sufficient explanation of form perception. The contention that feature extracting mechanisms are not a necessary explanation of form perception is supported by Rock's examination of studies of selective visual deprivation during rearing. For example, Rock cites Hirsch and Spinelli's (1971) report that if a kitten is exposed only to vertical contours during development, only units responsive to vertical contours on the retina can be found in visual cortex. It would therefore be expected that cats reared in such a manner could not discriminate contours to which they have not been previously exposed (such as horizontal contours) since there would presumably be no neural units responsive to such contours. However, Hirsch (1972) found that cats reared in this manner could discriminate among contours to which they had not been exposed almost as well as among contours to which they had been exposed.

A simple example which demonstrates that feature extracting mechanisms are not a sufficient explanation of form perception is the phenomenon of a reversible figure such as the Necker cube used in the present research (Figure 1). In the case of the Necker cube there are at least two distinct perceptions (i.e., lower face front and upper face front), yet the pattern of retinal stimulation extracted by feature detecting mechanisms is identical.

In order to account for the more or less veridical perception of orientation, size, and shape, and the resulting constancies, Rock (1975) proposes that the perceptual system "takes into account" various information to complement the information present on the retina. For example, size constancy may be the result of the perceptual system taking perceived distance information into account in addition to the proximal stimulation. Conceivably, and as evidence presented above would suggest, accomodation and convergence information could function as a physiological substrate of the "taking into account" process under three-dimensional viewing conditions. The question then remains as to what, if any, kind of neurophysiological mechanism could function to take into account perceived distance information under two-dimensional viewing conditions in which perceived size varies due solely to pictorial cues to depth. Rock (1975) proposes a cognitive decision explanation of form perception. According to Rock this model proposes that the incoming stimulus information is first registered centrally and then cognitively evaluated on the basis of "what entity or entities in the objective world are most likely producing this stimulus distribution?" (p. 286).

The proposal advanced by Rock (1975) that the perceptual system, although possibly unconsciously, takes perceived distance information into account to arrive at the perception of size could provide a possible description of the present pattern of results. Unfortunately, Rock has not specifically dealt with how a cognitive-decision model of form perception would account for spatial frequency- or orientation-contingent color aftereffects. However, since the aftereffects are thought to reveal properties of size and orientation specific processes in the human visual system, Rock's model may be applicable. In line with Rock's proposal, for any of the explanations presented above, whether they be based on edge-specific, spatial frequency-specific, or associative mechanisms, to adequately describe contingent color aftereffects it must be assumed that higher order, cognitive factors (such as "taking-into-account" perceived distance information) can influence the underlying mechanisms involved in form perception.

Conclusions

A useful analogy to place the central issues involved in the study of contingent color aftereffects into perspective is provided by Holway and Boring's (1941) investigation of size constancy. Holway and Boring had observers match the size of a variable disk of light to a standard disk under a number of viewing conditions. In one condition, monocular viewing with no depth cues, observers' settings approached a retinal size match. However, under full cue monocular and binocular viewing conditions, observers' settings approached size constancy. The analogy is that studies of contingent color aftereffects are invariably conducted under reduced cue conditions in that a context-free grating is presented on a two-dimensional viewing screen in a dimly lit room. Given these conditions, it is not surprising that the nature and magnitude of the observed effects have been contingent on the retinal parameters of the stimuli. Indeed, this situation is descriptive of the control condition in Experiment 3 in which the results indicated that the observers were responding to the retinal properties of test gratings. However, when test gratings are presented in a more cue-laden context, such as a receding corridor array, observers begin to respond more to the perceived objective properties of stimuli. The implication of this analogy is that as long as form perception is investigated using stimuli whose perception is more or less bound to the retinal stimulation (reduced cue conditions), human form perception, which is usually veridical under normal viewing conditions, will be left unexplained. Future investigations of contingent color aftereffects, and of the processes involved, should attempt to use more cue-laden stimuli in order to investigate the effects of higher order transformations of the proximal stimulation.

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Footnotes

[1] The term "cognitive factors" as used in this paper is best defined as a higher-order process that is not stimulus bound (cf. Howard, 1974). It should be noted that this definition does not preclude neurophysiological description, nor does it say anything about the location of the processes involved in cognition.

[2] There has been some disagreement in the literature as to whether there are perceived size differences between the two faces of the Necker cube given a particular organization. Gregory (1963) has argued that a Necker cube, as represented in a drawing, does not manifest perceived size differences. However, Hotopf (1966) and Robinson (1972) have disputed this claim and Hotopf's data clearly indicate that perceived size differences do obtain in a manner consistent with Emmert's law. Nevertheless, Experiments 1 & 2 checked for perceived size differences using a forced-choice questionnaire technique.

[3] All of the two alternative, forced-choice data were analyzed using a binomial sampling distribution having the following characteristics: $n=24$; $p=q=.5$.

[4] Pilot work had indicated that observers began to fatigue after approximately 25 settings. It was decided to collect as much data as possible in the experimental condition since the control condition was simply a replication of Harris (1970).

The role of perceived spatial frequency in pattern-contingent color aftereffects was examined in the present series of experiments. Spatial frequency-contingent color aftereffects were induced by adaptation to a single chromatic grating of a fixed spatial frequency (Experiment 1) or alternate exposure to two different chromatic gratings of two different spatial frequencies (Experiments 2 & 3). The test stimuli for Experiments 1 and 2 consisted of gratings placed in two-dimensional pictorial arrays (e.g., Necker cube and corridor array) such that while the physical (retinal) spatial frequencies of the test gratings were identical, the perceived spatial frequencies were different due to implicit depth relationships. The results indicated that under these conditions the color aftereffects were contingent on perceived rather than retinal spatial frequency. Test stimuli for Experiment 3 consisted of a single grating placed in either the lower or upper region of a corridor array. Under these conditions the nature of the color aftereffects was different for a grating in the lower region of the array than for a grating in the upper region even though the gratings were of identical retinal spatial frequency. The implications of these findings for models of pattern-contingent color aftereffects based on the fatigue of selectively tuned neural "units" are discussed. It is concluded that selective extraction of features in the visual environment by these units, while possibly important, is not completely descriptive of human form perception.

An Investigation of the Role of Perceived Spatial Frequency in Pattern-Contingent Color Aftereffects

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