Perception & Psychophysics
1991, 50 (3), 249-257

Characteristics of the indirect McCollough effect

LORRAINE G. ALLAN and SHEPARD SIEGEL
McMaster University, Hamilton, Ontario, Canada

Induction of contingent color aftereffects with a single chromatic grid sometimes results in an illusory color on a grid different from the one presented during induction. Such illusory color, contingently elicited by a noninduced grid, has been termed the indirect McCollough effect (indirect ME). We show that the indirect ME occurs only when the color complementary to the grid color is present during induction (either physically present or as a color afterimage), and that the indirect ME is seen only on gratings that are orthogonal to the induction orientation. These findings are in accord with the account of the indirect ME proposed by Humphrey, Dodwell, and Emerson (1989). We also show that characteristics of the indirect ME (seen following one-grid induction), both on induced and orthogonal orientations, are similar to those observed with the direct ME (seen following the usual two-grid induction procedure). Both procedures result in contingent aftereffects that display substantial retention and that do not display interocular transfer.

The orientation-contingent color aftereffect originally reported by McCollough (1965) can be demonstrated easily. The McCollough effect (ME) may be seen by presenting an observer with two chromatic grids that alternate every few seconds. For example, one grid could consist of alternating black and green horizontal bars and the other grid could consist of alternating black and magenta vertical bars. Following such induction, complementary color aftereffects contingent on grid orientation are noted—black and white test grids appear chromatic. In this example, the white space between black horizontal bars appears pinkish, and the white space between black vertical bars appears greenish.

In fact, two chromatic grids are not necessary for the induction of orientation-contingent color aftereffects (e.g., Ambler & Foreit, 1978; Humphrey, Dodwell, & Emerson, 1989; Stromeyer, 1969). Following repeated presentations of a single chromatic grid (e.g., green horizontal), an achromatic horizontal grid appears pinkish. Indeed, there are reports that such aftereffect induction with a single chromatic grid sometimes results in illusory colors on the orthogonal grid orientation even when this orthogonal grid has not been presented during induction.[1] Such illusory color, contingently elicited by a noninduced grid that is orthogonal to the induction grid, has been termed the *indirect* ME (Dodwell & Humphrey, 1990).

In one of their experiments on the indirect ME, Humphrey et al. (1989) alternated a chromatic grid with a homogeneous field of the complementary color (e.g., a green horizontal grid alternating with a magenta field). After induction, a pink aftereffect was observed on the induced orientation (an achromatic horizontal grid appeared pink), and a green aftereffect was observed on the noninduced orthogonal orientation (an achromatic vertical grid appeared green). Humphrey et al. hypothesized that the indirect ME results from a shift in contour coding activity, combined with the complemental color of the homogeneous field. According to this analysis, repeated presentation of the chromatic orientation stimulus results in a decrease in sensitivity of coding mechanisms for this orientation. When the orientation stimulus is terminated, there is a compensatory increase in activity of coding mechanisms for the orthogonal orientation (vertical), and this orthogonal orientation activity is paired with the color of the homogeneous field (magenta). Thus, the indirect ME, in common with the direct ME, results from the pairing of orthogonal patterns with complementary colors.

Humphrey et al. (1989) also hypothesized that the indirect ME could result from a shift in contour coding activity combined with a color afterimage. When presentation of the chromatic grid alternates with an achromatic field, the orthogonal orientation activity would be paired with the complementary color afterimage of the just-terminated chromatic grid. Consider the example in which a green horizontal grid is alternated with a homogeneous achromatic field. During intervals when the achromatic field is presented, the coding for the orthogonal orientation (vertical) is effectively paired with the complementary color afterimage (pink), and the resulting aftereffect on vertical would be green.

A considerable body of data supports the analysis of the indirect ME as a result of a shift in activity of orientation coding mechanisms (see Dodwell & Humphrey, 1990; Humphrey et al., 1989). However, as Humphrey et al. noted, the account is not sufficient to encompass

This research was supported by grants to L. G. Allan and S. Siegel from the Natural Sciences and Engineering Research Council of Canada and the United States National Institutes of Mental Health. Correspondence concerning this article should be addressed to either Lorraine G. Allan or Shepard Siegel, Department of Psychology, McMaster University, Hamilton, Ontario L8S 4K1, Canada.

all the data concerning the indirect ME: "If it were, we should expect to find such an aftereffect . . . in the condition in which a colored pattern was alternated with a black, colorless field" (pp. 107-108). As Humphrey et al. indicate, the evidence on this point is contradictory. Some investigators have reported that when a colored pattern is alternated with a black field, aftereffects are contingently elicited by both the pattern used in induction and the noninduced orthogonal pattern (e.g., Stromeyer, 1969; Yasuda, 1978). In contrast, other investigators have reported that this induction procedure, although resulting in an aftereffect on the induced pattern, does not result in an aftereffect on the noninduced orthogonal pattern (Ambler & Foreit, 1978; Humphrey et al., 1989).

In most evaluations of the indirect ME, very few subjects are used (Humphrey et al., 1989, is an exception). Furthermore, in previous studies of the phenomenon, the aftereffect has been evaluated by asking the subject to name or rate the color(s) that they have seen. As Humphrey et al. note (p. 106), these procedures are not very sensitive measures of aftereffects. It is possible that these features of the previous research are relevant to the divergent findings.

We have previously described a sensitive and effective procedure for the measurement of contingent color aftereffects in general, and of orientation-contingent color aftereffects in particular (Allan, Siegel, Collins, & MacQueen, 1989; Allan, Siegel, Toppan, & Lockhead, 1991; Siegel, Allan, Roberts, & Eissenberg, 1990). This procedure, a variant of the method of constant stimuli, was used in all the experiments that will be described in this report. In the first experiment, we alternated a chromatic grid with a homogeneous black field during induction, and we subsequently evaluated the illusory color contingently elicited by both the grid used during induction and the orthogonal grid.

EXPERIMENT 1

Method

Subjects. The subjects were 29 male and female students with no previous experience in contingent aftereffect tasks. They were enrolled in introductory psychology at McMaster University and received course credit for their participation. The subjects participated in the experiment individually, with the experimenter present in the room throughout the session.

Aftereffect induction. The stimuli consisted of either horizontal or vertical grids (5.9 cm square, subtending approximately 2.7°) presented on a 25.5 × 19.5 cm computer monitor. The entire monitor screen subtended approximately 11.6° × 8.9°. The grids were composed of 20 bars (10 black bars alternating with 10 chromatic bars); the spatial frequency of the gratings was 3.7 cpd.

The subjects were assigned to one of four induction groups, which differed in the pairing of color with orientation: black and green horizontal bars (GH, $n = 14$); black and green vertical bars (GV, $n = 6$); black and magenta horizontal bars (MH, $n = 4$); and black and magenta vertical bars (MV, $n = 5$).[2] During a 15-min induction period, the chromatic grid was presented 300 times: 2-sec presentations of the chromatic grid alternated with 1-sec presentations of a black screen. Background music was presented during induction.

Aftereffect measurement. Illusory color was measured both before and after the induction phase of the experiment (preinduction and postinduction determination, respectively). There was a 2-min period in normal room illumination between aftereffect induction and the postinduction determination of illusory color, to minimize the influence of simple afterimages. For both assessments, the subjects received 50 presentations of a horizontal grid and 50 presentations of a vertical grid. On each presentation, the space between the black bars of the grid could be one of five colors: one of two shades of pale pink (P1 and P2, with P2 being more saturated than P1), one of two shades of pale green (G1 and G2, with G2 being more saturated than G1), or achromatic. Grid orientation (horizontal or vertical) and color (P1, P2, G1, G2, and achromatic) were randomly ordered, with the restriction that each orientation be presented in each color 10 times. On each of the 100 presentations of the grid, the subject had to make a binary response, "green" or "pink." The grid remained on the screen until the subject responded. The next grid was presented 1 sec after the response was entered on the computer keyboard.

Prior to the start of the experiment, the subjects were familiarized with the color-judgment task. Before preinduction aftereffect determination, the subjects received 16 practice trials. For each practice trial, the grid was one of the four unsaturated hues (G1, G2, P1, or P2) and was either horizontal or vertical. Each of the eight hue-orientation combinations was presented twice (in random order). In contrast to the preinduction and postinduction assessments, feedback was provided on these practice trials. Immediately after making a "green" or a "pink" response, the subjects were informed that their response was "correct" or an "error" via speech synthesis by the computer that controlled the experiment. These practice data were ignored.

Apparatus. Temporal parameters, stimulus presentation, and recording of responses were controlled by a Macintosh IIcx computer equipped with an 8-bit video display card. The stimuli were displayed on an Apple color monitor (Model M0401PA). The brightness and contrast controls of the monitor were set in accordance with the manufacturer's specifications. Brightness was set at the point where the black portion of a display just started to turn black. Contrast was set at the maximum value that did not produce blooming.

The color on the monitor is the combination of red (R), green (G), and blue (B). When each input is at its maximum value (R=G=B=65,535), the result is white. When each input is at its minimum value (R=G=B=0), the result is black. Changing the relative proportions of R, G, and B produces various hues at different saturations. Luminance was measured with a Tektronix digital photometer (Model J16, equipped with a Model J6503 luminance probe), with a procedure similar to that of Houck and Hoffman (1986). The photometer probe was aimed at the display while it was completely illuminated with the color that was being assessed. Chromaticity was assessed with a Minolta Chroma Meter II Incident. The RGB values, the luminance values (candles/square meter), and the chromaticity values (CIE x- and y-coordinates) for the green and magenta induction grids, and the various hues used to measure the aftereffect, are shown in Table 1.

Instructions to subjects. The experimenter read the same instructions to each subject. Briefly, before both pre- and postinduction assessments, the subjects were told that they were participating in a color-discrimination task: "You will be asked to discriminate between stimuli presented in various shades of pink and green. The stimuli consist of black horizontal bars or black vertical bars on a colored background. On each presentation, you are to tell me whether the space between the black bars looks pinkish or greenish. You are to maintain your head upright at all times." Before induction, they were told what they would see (e.g., "horizontal black bars on a bright green background will be repeatedly presented").

Table 1
RGB Values, Luminance Values (in Candles/Square Meter), and Chromaticity Values (CIE x- and y-Coordinates) for the Macintosh IIcx

Stimuli	R	G	B	Luminance	x	y
			Induction			
magenta	65535	0	65535	19	.274	.132
green	0	65535	0	40	.271	.609
			Assessment			
P2	65535	61166	61166	60	.279	.302
P1	65535	62965	62965	61	.277	.301
achromatic	65535	65535	65535	63	.272	.302
G1	62965	65535	62965	61	.272	.308
G2	61166	65535	61166	60	.271	.314

Results

The psychometric function relating the probability of the subject reporting that the grid appeared green, P(G), to the physical color of the assessment grid (ranging from P2 to G2) was determined. The preinduction and postinduction functions are displayed in Figure 1. For simplicity in presentation, the psychometric functions displayed in Figure 1 are collapsed across the dimension of induction orientation: the panel labeled Green Induction represents the combined assessment data for Groups GH and GV, and the panel labeled Magenta Induction represents the combined assessment data for Groups MH and MV.

The preinduction functions for the two assessment orientations were similar. A mixed design analysis of variance (ANOVA) was performed on the mean number of "green" responses over the five assessment colors. The between-subjects factor was induction color (green or magenta), and the within-subjects factor was assessment orientation (induced or noninduced). There were no significant effects (all Fs < 1.00), indicating that the number of "green" responses in preinduction to the two orientations did not differ.

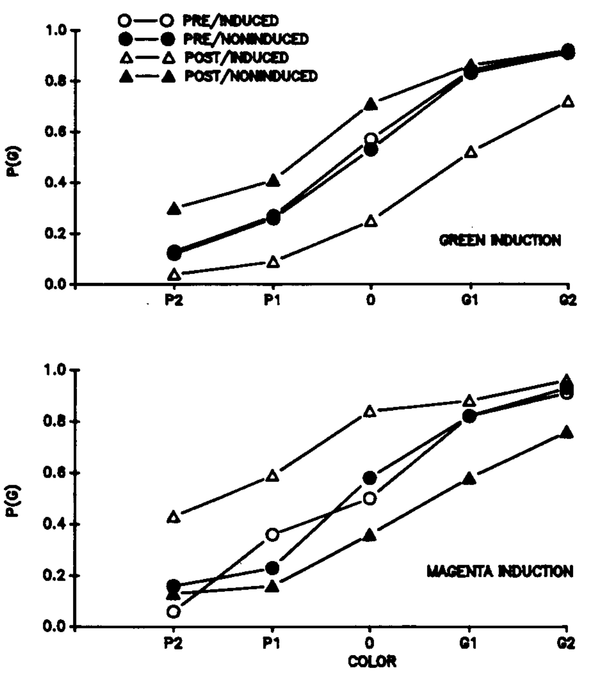

Figure 1. Preinduction and postinduction psychometric functions. The panel labeled Green Induction represents the combined assessment data for Groups GH and GV, and the panel labeled Magenta Induction represents the combined assessment data for Groups MH and MV (Experiment 1).

The functions moved apart after induction. Two repeated measures ANOVAs, one for green induction and the other for magenta induction, supported the conclusion that after induction illusory color was present on the induced orientation and also on the noninduced orthogonal orientation. These analyses were performed on the mean number of "green" responses over the five assessment colors. The two factors were assessment phase (preinduction or postinduction) and assessment orientation (induced or noninduced). In both analyses, assessment orientation interacted significantly with assessment phase [green induction, $F(1,19) = 57.96, p < .001$; magenta induction, $F(1,8) = 14.26, p < .006$].

These interactions can be seen in Figure 2, in which the mean number of "green" responses in preinduction and in postinduction is given for each assessment orientation—induced and noninduced. For green induction, the number of "green" responses to the induced orientation decreased significantly from preinduction to postinduction [$F(1,19) = 68.94, p < .001$], and the number to the noninduced orientation increased significantly [$F(1,19) = 11.10, p < .004$]; the induced orientation appeared pink, and the noninduced orientation appeared green. For magenta induction, the number of "green" responses to the induced orientation increased significantly from preinduction to postinduction [$F(1,8) = 14.58$, $p < .005$], and the number to the noninduced orientation decreased significantly [$F(1,8) = 7.20, p < .027$]; the induced orientation appeared green and the noninduced orientation appeared pink.

Discussion

In all combinations of grid orientation and color, a color aftereffect was contingently elicited by both the grid orientation presented in induction and the noninduced orthogonal grid. These findings are consistent with the analysis of the indirect ME as a manifestation of a shift in orientation coding activity combined with a complementary color afterimage (e.g., Dodwell & Humphrey, 1990; Humphrey et al., 1989). Moreover, these findings indicate that the use of the black field does not (as suggested by Humphrey et al.) so weaken the afterimage that no indirect ME develops.

These results are similar to those of Stromeyer (1969) and Yasuda (1978), but they are different from those reported by others (Ambler & Foreit, 1978; Humphrey et al., 1989). In the latter experiments, it was reported that aftereffect induction involving alternate presentation of a chromatic pattern and black field resulted in an aftereffect on the induced pattern, but not on the orthogonal pattern. It is possible that the indirect ME, induced with these procedures, is not reliably demonstrable with sim-

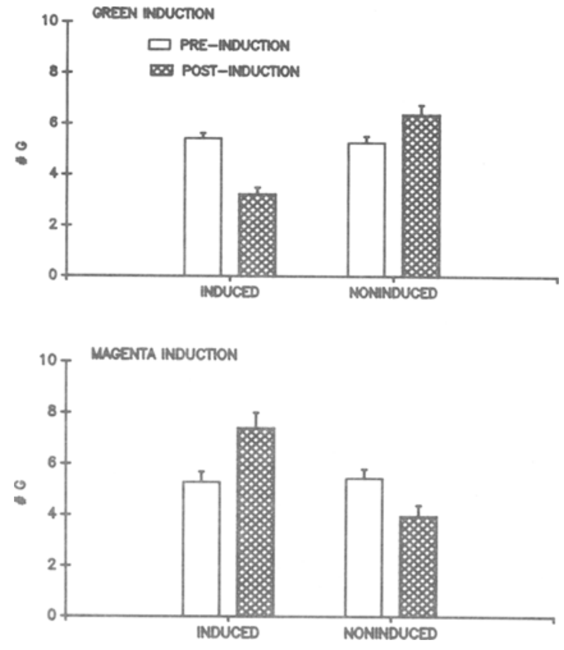

Figure 2. The mean number of "green" responses in preinduction and in postinduction for each assessment orientation, induced and noninduced (Experiment 1).

ple color-naming procedures. Experiment 2 was designed to evaluate further the characteristics of the aftereffect induced with the conditions used in this experiment.

EXPERIMENT 2

In the previous experiment, illusory color was assessed on both the induced grid orientation (e.g., horizontal) and the orthogonal grid orientation (e.g., vertical). In the present experiment, illusory color was assessed on both the induced grid orientation (e.g., horizontal) and a nonorthogonal grid orientation (e.g., 135° diagonal). Several investigators (Ambler & Foreit, 1978; Humphrey et al., 1989; Stromeyer, 1969) did not obtain aftereffects on such noninduced nonorthogonal patterns. It is possible, however, that the aftereffect was too weak to be detected by the color-naming or color-rating procedures. In Experiment 2, we used the method of constant stimuli to evaluate this possibility.

Method

Twenty subjects were assigned to two induction groups (*n*/group = 10). In Group GH, the chromatic grid consisted of black and green horizontal bars; in Group G135, the chromatic grid consisted of black and green diagonal (135°) bars. The horizontal grid was the same as that used in Group GH in the previous experiment. The diagonal grid consisted of 19 bars (9 black bars alternating with 10 chromatic bars). As in Experiment 1, during a 15-min induction period, the chromatic grid was presented 300 times: 2-sec presentations of the chromatic grid alternated with 1-sec presentations of a black screen.

In assessment (practice, preinduction, and postinduction), illusory color on both horizontal and diagonal (135°) grids was evaluated. Where unspecified, the procedures of this experiment were the same as those in Experiment 1.

Results and Discussion

In Figure 3,[3] the mean number of "green" responses in preinduction and in postinduction is given for each assessment orientation, horizontal and diagonal. A mixed design ANOVA, with induction group (GH or G135) as a between-subjects factor and assessment orientation (horizontal or diagonal) as a within-subjects factor, revealed no significant effects in preinduction (all $p > .05$).

For both induction groups, the number of "green" responses for the induced orientation decreased from preinduction to postinduction. There was relatively little change for the noninduced nonorthogonal orientation. Two mixed design ANOVAs, one for the induced orientation and the other for the noninduced orientation, were performed on the mean number of "green" responses over the five assessment colors. The between-subjects factor was group (GH or G135) and the within-subjects factor was assessment phase (preinduction or postinduction). For the induced orientation, only the main effect of assessment phase was significant [$F(1,18) = 152.84$, $p < .001$], indicating that for both induction groups the number of "green" responses to the induced orientation decreased after induction. For the noninduced orientation, there were no significant effects (all $p > .05$), indicating that for both induction groups there was no change, from preinduction to postinduction, in the number of "green" responses.

These results are in agreement with those reported by Ambler and Foreit (1978), Humphrey et al. (1989), and

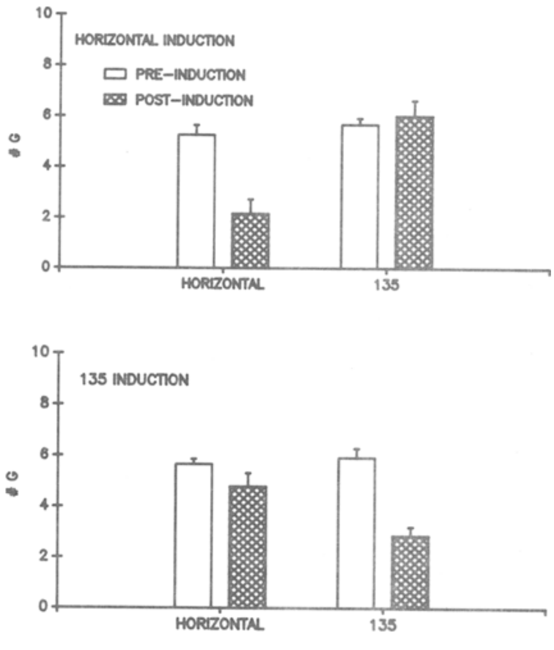

Figure 3. The mean number of "green" responses in preinduction and in postinduction for each assessment orientation—horizontal and diagonal—for Groups GH and G135 (Experiment 2).

Stromeyer (1969). After one-grid induction, an aftereffect is observed on the induced orientation but not on a nonorthogonal noninduced orientation.

EXPERIMENT 3

During the induction phase of Experiments 2 and 3, a chromatic grid was alternated with a black field. The finding that nonorthogonal patterns do not elicit illusory colors confirms previous findings (Ambler & Foreit, 1978; Humphrey et al., 1989; Stromeyer, 1969). The finding that orthogonal patterns do elicit illusory colors, although it confirms some previous reports (Stromeyer, 1969; Yasuda, 1978), contrasts with findings of others (Ambler & Foreit, 1978; Humphrey et al., 1989).

One experiment reported by Humphrey et al. (1989) was specifically designed to evaluate the effect of the color of the field, alternated with presentations of a chromatic grid, on the aftereffect contingently elicited by the induction and orthogonal grids. Subjects in one group received induction with a black field (e.g., a green grid alternated with a black field). For a second group, the color of the field was the same as the grid color (e.g., a green grid alternated with a green field). For a third group, the color of the field was complementary to the grid color (e.g., a green grid alternated with a magenta field). For a fourth group, the color of the field was not complementary to the grid color (e.g., a green grid alternated with a blue field). An aftereffect was observed on the induced orientation in all groups (in this example, the achromatic horizontal grid appeared pinkish). However, only when the field was complementary to the grid color was an aftereffect observed on the noninduced orthogonal orientation (in this example, only subjects induced with the green horizontal grid alternating with the magenta field perceived a vertical achromatic grid as greenish).

Humphrey et al. (1989) suggested that their results were generally consistent with the view that the indirect ME resulted in a perpendicular shift in orientation coding mechanisms, combined with a complementary color. In the complementary-field group, this complementary color was provided by the actual hue of the field. As discussed previously, the complementary color necessary for the indirect ME may be provided by the afterimage of the chromatic grid used in induction. This might suggest that the black-field condition should promote the ME, and indeed this has been reported by several investigators (Stromeyer, 1969; Yasuda, 1978; Experiment 1 of the present report). In contrast, Humphrey et al. (1989) did not find that the indirect ME developed when the chromatic grid was alternated with a black field. They suggested that a black field might weaken the strength of the afterimage. They further suggested that a white field should promote such afterimages. They did not evaluate this possibility.

Experiment 3 was designed to assess further the effect of various field colors. Subjects received aftereffect induction consisting of presentations of a green horizontal grid alternating with a homogeneous field. For one group, the field was magenta—the condition that Humphrey et al. (1989) reported *does* result in aftereffects on both induced and orthogonal orientations. For a second group, the field was white—the condition that Humphrey et al. suggested *should* result in aftereffects contingent on both the induced and the orthogonal grid orientations. For the third group, the field was green—the condition that Humphrey et al. reported results in an aftereffect on the induced, but not on the orthogonal, orientation. Finally, for the fourth group, the field was black—the condition that has yielded divergent findings.

Method

During induction, a 2-sec presentation of a green horizontal grid was alternated with a 2-sec presentation of a homogeneous square with the same dimensions as the grid. The 48 subjects were assigned to four induction groups (n/group = 12), which differed in the color of the homogeneous square: black, white, green, and magenta. The grid and the homogeneous square were each presented 225 times during the 15-min induction phase. The presence of a color aftereffect was evaluated for the orientation presented during induction (horizontal) and for the orthogonal noninduced orientation (vertical). In other details, the procedure of this experiment was the same as that of Experiment 1.

Result

In Figure 4, the mean number of "green" responses in preinduction and in postinduction is given for the two assessment orientations for the four groups. A mixed-design ANOVA on the preinduction data, with induction group (black, white, green, or magenta) as a between-subjects factor and assessment orientation (horizontal or vertical) as a within-subjects factor, revealed no significant effects in preinduction (all $Fs < 1.00$).

For all groups, P(G) for the induced orientation (horizontal) was less in postinduction than in preinduction. For three groups (black, white, and magenta), P(G) for the noninduced orientation (vertical) was greater in postinduction than in preinduction. For Group Green, however, there was little change from preinduction to postinduction for the noninduced orientation.

Two randomized groups ANOVAs, one for the induced orientation and the other for the noninduced orientation, were performed on the difference in the number of "green" responses between postinduction and preinduction. Induction group (black, white, green, or magenta) was the between-subjects factor. The four groups did not differ significantly on the induced orientation [$F(3,44) < 1.00$]. For the noninduced orientation, the main effect was significant [$F(3,44) = 7.64, p < .001$]. Tukey pairwise comparisons revealed that the "green" group differed significantly from the three other groups (all $ps < .01$).

Discussion

Our results for the induced orientation are the same as those reported by Humphrey et al. (1989); the size of the aftereffect was independent of the color field that alternated with chromatic grid presentations. Also, our results for the "magenta" and "green" groups on the noninduced orientation were the same as those reported by Humphrey

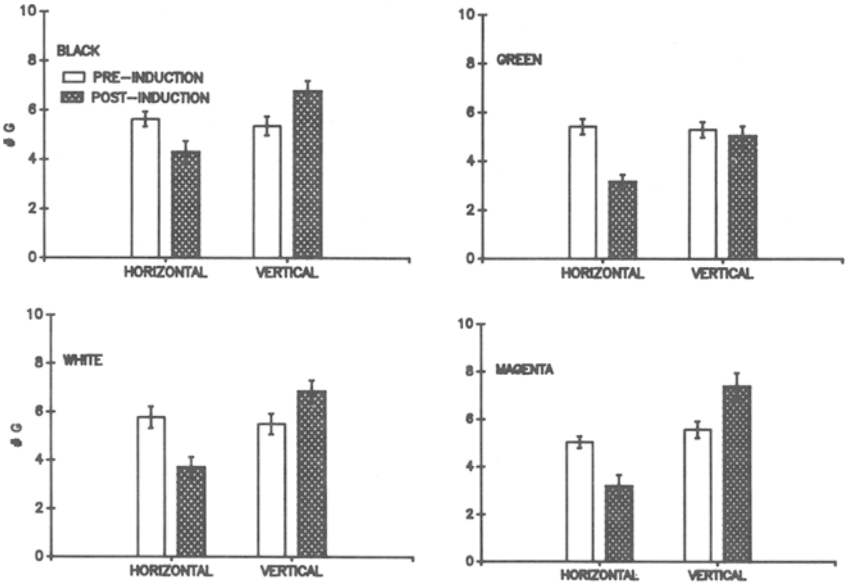

Figure 4. The mean number of "green" responses in preinduction and in postinduction for the two assessment orientations—horizontal and vertical—for Groups Black, Green, White, and Magenta (Experiment 3).

et al.: a significant aftereffect with a complementary-colored field and no aftereffect with a same-colored field.

We observed an aftereffect on the noninduced orientation when the homogeneous field was white. This outcome accords with the account of the indirect ME proposed by Humphrey et al. (1989). We also observed an aftereffect on the noninduced orientation when the homogeneous field was black. This confirms the results of Experiment 1 (and the reports of Stromeyer, 1969, and Yasuda, 1978). It seems clear that there are circumstances in which this induction condition yields aftereffects on both the induced and orthogonal orientations, contrary to the findings of Ambler and Foreit (1978) and Humphrey et al. (1989).

EXPERIMENT 4

In contrast to the direct ME, which is induced with two chromatic grids, the indirect ME is induced with a single chromatic stimulus. Our purpose in the remaining experiments was to evaluate similarities between the direct and indirect MEs. In the present experiment, we determined whether there was interocular transfer of the indirect ME.

Using the standard, two-grid induction procedure, McCollough (1965) noted that when only one eye was exposed during induction, there was no evidence of an aftereffect when the other (noninduced) eye was assessed. Others (e.g., Kaufman, May, & Kunen, 1981; Meyer, Coleman, Dwyer, & Lehman, 1982; Murch, 1972; White & Riggs, 1974) have confirmed that, with complete occlusion of the noninduced eye, there is little, if any, interocular transfer. Allan et al. (1991) used the method of constant stimuli to measure interocular transfer of the direct ME. They also found that the aftereffect did not transfer between eyes. In Experiment 4, we evaluated interocular transfer of the indirect ME.

Method

Twenty-four subjects were divided into two groups: interocular (n = 10) and monocular (n = 14). In the interocular group, the right eye was patched during induction and the left eye was patched during practice, preinduction, and postinduction assessments. In the monocular group, the right eye was patched in all phases. For both groups, the patch was removed during the 2-min period in normal room illumination before postinduction assessment.

The induction grid consisted of horizontal black and green bars. During the 15-min induction period, the chromatic grid was presented 300 times: 2-sec presentations of the chromatic grid alternated with 1-sec presentations of a black screen. The presence of a color aftereffect was evaluated for the orientation presented during induction (horizontal) and for the orthogonal noninduced orientation (vertical). In unspecified details, the procedures of this experiment were the same as those used in Experiment 1.

Results and Discussion

In Figure 5, the mean number of "green" responses in preinduction and in postinduction is given for the two assessment orientations for the two groups. A mixed design ANOVA with eye (interocular or monocular) as the between-subjects factor and assessment orientation (horizontal or vertical) as the within-subjects factor revealed no significant effects in preinduction (all $ps > .05$).

For the monocular group, the number of "green" responses for the induced orientation (horizontal) decreased from preinduction to postinduction, and the number for the noninduced orientation (vertical) increased. There was little change from preinduction to postinduction for the interocular group. A mixed design ANOVA was performed on the difference in the number of "green" responses between postinduction and preinduction. The

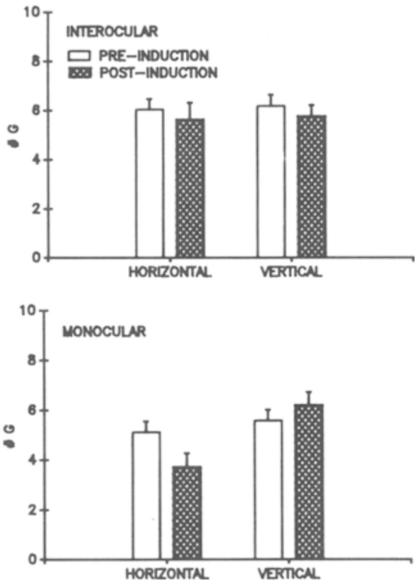

Figure 5. The mean number of "green" responses in preinduction and in postinduction for the two assessment orientations–horizontal and vertical–for Groups Interocular and Monocular (Experiment 4).

between-subjects factor was group (interocular or monocular), and the within-subjects factor was assessment orientation (horizontal or vertical). The interaction was significant [$F(1,22) = 4.66, p < .040$]. The preinduction-to-postinduction change for the horizontal orientation differed significantly from the change for the vertical orientation for the monocular group [$F(1,22) = 11.19, p < .003$], but not for the interocular group [$F(1,22) < 1.00$]. The aftereffect induced with one chromatic grid did not transfer interocularly.

The results of this experiment indicate that the aftereffects seen following one-grid induction, both on induced and on orthogonal orientations, are similar to those seen following the usual two-grid induction procedure. Both procedures result in contingent aftereffects that do not display substantial interocular transfer.

Our purpose in the next experiment was to evaluate another possible similarity between direct and indirect MEs: long-term retention.

EXPERIMENT 5

One dramatic characteristic of the direct ME is its longevity. Unlike simple color aftereffects, which persist for seconds, contingent color aftereffects last for minutes, days, and even longer (see, e.g., Jones & Holding, 1975). In previous studies of the indirect ME, the aftereffect had always been evaluated "immediately" after induction (allowing a few minutes in the light for the afterimage to dissipate). In Experiment 5, we evaluated the color aftereffect, on both induced and orthogonal orientations, at various intervals following one-grid induction.

Method

In this experiment, temporal parameters, stimulus presentation, and recording of responses were controlled by a Tandy 3000 computer equipped with a VGA display card. The stimuli were displayed on a Zenith flat-screen monitor (Model 1490). With this system, R=G=B=63 at maximum. All grids were 6.0 × 6.4 cm, presented on a black background at the center of the 27.5 × 20.3 cm monitor screen. The grid subtended about 2.7° by 2.9° of visual angle. The horizontal and vertical grids were composed of 16 bars (8 black bars alternating with 8 chromatic bars); the spatial frequency of the gratings was approximately 3 cpd. Chromaticity and luminance were assessed as described in Experiment 1. The RGB values, the luminance values (candles/square meter), and the chromaticity values (CIE x- and y-coordinates) for the green and magenta induction grids, and the various hues used to measure the aftereffect, are shown in Table 2.

Thirty-two subjects were divided into three groups. Group 0 h ($n = 10$) was treated as were the subjects in the prior experiments, in that postinduction assessment occurred "immediately" after induction (after the 2-min period in the light). For Group 1 h ($n = 14$), postinduction assessment occurred 1 h after the end of induction. For Group 24 h ($n = 8$), postinduction assessment occurred 24 h after the end of induction.

For all three groups, 2-sec presentations of a green horizontal grid alternated with 1-sec presentations of a black field for a total of 15 min. The presence of a color aftereffect was evaluated for the orientation presented during induction (horizontal) and for the orthogonal noninduced orientation (vertical).

Results and Discussion

In Figure 6, the mean number of "green" responses in preinduction and in postinduction is depicted for the two assessment orientations. A mixed design ANOVA with retention group (0, 1, or 24 h) as the between-subjects factor and assessment orientation (horizontal or vertical) as the within-subjects factor revealed no significant effects in preinduction (all Fs < 1.00).

For the 0- and 1-h groups, the number of "green" responses for the induced orientation (horizontal) decreased from preinduction to postinduction, and the number for the noninduced orientation (vertical) increased. There was little change from preinduction to postinduction for the 24-h group. A mixed design ANOVA was performed on the difference in the number of "green" responses between postinduction and preinduction. The

Table 2
RGB Values, Luminance Values (in Candles/Square Meter), and Chromaticity Values (CIE x- and y-Coordinates) for the Tandy 3000

Stimuli	R	G	B	Luminance	x	y
			Induction			
magenta	63	0	25	25	.552	.311
green	0	63	0	87	.309	.601
			Assessment			
P2	63	59	63	98	.297	.315
P1	63	61	63	103	.297	.324
achromatic	63	63	63	113	.298	.334
G1	61	63	61	106	.299	.342
G2	59	63	59	104	.299	.351

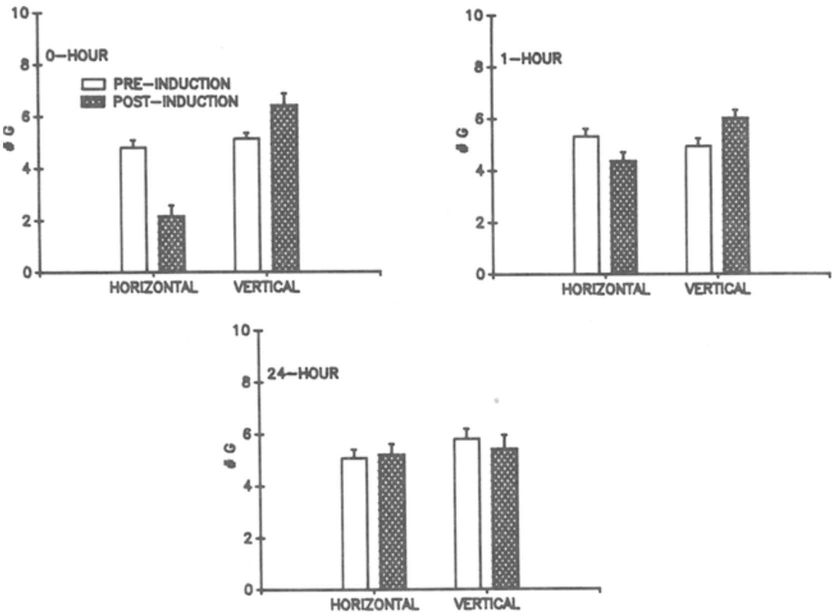

Figure 6. The mean number of "green" responses in preinduction and in postinduction for the two assessment orientations—horizontal and vertical—for Groups 0 h, 1 h, and 24 h (Experiment 5).

between-subjects factor was retention group (0, 1, or 24 h), and the within-subjects factor was assessment orientation (horizontal or vertical). Retention group interacted significantly with assessment orientation [$F(2,29) = 15.61$, $p < .001$]. The preinduction-to-postinduction change for the horizontal orientation differed significantly from the change for the vertical orientation for both the 0-h group [$F(1,29) = 53.98$, $p < .001$] and the 1-h group [$F(1,29) = 26.34$, $p < .001$], but not for the 24-h group [$F(1,29) < 1.00$].

The results of this experiment indicated that the one-grid induction procedure induced aftereffects, both on the grid used in induction and on the noninduced orthogonal grid, that lasted for at least an hour. Thus, this procedure, like the typical two-grid induction procedure, results in the perception of illusory colors that display substantial retention.

GENERAL DISCUSSION

Our data indicate that color aftereffects on noninduced orientations occur only when the color complementary to the grid color is present during induction: A green horizontal grid alternating with a magenta field induces an indirect ME, whereas a green horizontal grid alternating with a green field does not. The complementary color need not be physically present; it can be a color afterimage: A green horizontal grid alternating with an achromatic field, either white or black, induces an indirect ME. Our data also indicate that the indirect ME is not seen on an orientation that is not orthogonal to the induction orientation: Induction with a green horizontal grid results in an indirect ME on a vertical grid but not on a diagonal grid. These findings accord with the account of the indirect ME proposed by Humphrey et al. (1989).

In contrast with the present experiments, in almost all previous experiments done with only one induction pattern the assessment figures were composites of at least two patterns (Ambler & Foreit, 1978, Experiment 1; Humphrey et al., 1989; Stromeyer, 1969; Yasuda, 1978). It is conceivable, then, that the color observed on the noninduced pattern in these earlier studies was not an indirect ME, but rather the result of simultaneous contrast (see Stromeyer, 1984). Humphrey et al. (1989) considered this possibility, and they argued convincingly that "reports on noninduced patterns cannot be explained as a simple result of simultaneous contrast with adjacent induced patterns" (p. 104).

Since our assessment figures contained only one pattern, our results cannot be attributed to simultaneous contrast. One could entertain the possibility, however, that our results are due to successive contrast. It could be argued that the illusory color of a noninduced pattern is the result of successive contrast of the direct ME on the just-terminated assessment pattern. For example, after induction with a green horizontal grid, the illusory green seen on a vertical assessment grid could be the result of successive contrast of the pink direct ME on the just-terminated horizontal assessment grid.

During assessment in our experiments, the various grids were randomized with respect to orientation and color, and there was a 1-sec period between grid presentations. Postulated successive contrast would result if the illusory color on the just-terminated assessment stimulus persisted for the 1-sec period between assessment stimuli presentations and affected the perceived color of the next assessment stimulus. We know of no empirical evidence for successive contrast under these conditions. More importantly, the results of our experiments provide direct evidence against a successive contrast account of the indirect ME.

If successive contrast were responsible, color should be seen on a nonorthogonal noninduced pattern as well as on an orthogonal noninduced pattern. In Experiment 2, we showed this not to be the case. After induction with a chromatic grid, a direct ME was obtained on the induced orientation, but there was no illusory color on a noninduced orientation that differed by 45° from the inducing orientation (e.g., following induction with a green horizontal grid, a 135° grid did not elicit illusory color). A proponent of the successive contrast account might argue that the absence of color on this noninduced nonorthogonal orientation is the result of a direct ME on the noninduced orientation cancelling the successive contrast. It has been shown, however, that a direct ME does not transfer to an orientation that differs by 45° from the inducing orientation (Siegel & Allan, 1985). Thus, following induction with a green horizontal grid, there would not be a pink direct ME on a 135° grid to cancel the successive contrast.

Experiment 3 provides further evidence that successive contrast cannot account for the indirect ME. In one condition of that experiment, induction consisted of alternate presentations of a chromatic grid and a homogeneous field of the same color (e.g., green horizontal grids alternated with green homogeneous fields). Although there was a direct ME, there was no indirect ME (i.e., the horizontal grid appeared pinkish, but there was no illusory color on the vertical grid). A successive contrast account, however, would predict illusory color on noninduced patterns under these conditions. In summary, we agree with Humphrey et al. (1989) that illusory color on noninduced patterns cannot readily be explained as a simple result of chromatic contrast effects.

Despite its importance for understanding visual processing (e.g., Dodwell & Humphrey, 1990), there have been few reports of the indirect ME, and there are inconsistencies among the results of the few published studies. For example, it is unclear in the literature whether the indirect ME can be obtained when a black field is alternated with chromatic grid presentations. Our results demonstrate that the phenomenon is observed with a black field, and they provide support for Humphrey et al.'s (1989) theoretical interpretation, which predicts that the indirect ME should be seen with such an induction procedure. Humphrey et al. also predicted that the aftereffect should be apparent when a white field is alternated with chromatic grid presentations. We assessed this prediction and found support for it.

There have been no prior demonstrations that the more dramatic characteristics of the direct ME are features of the indirect ME. Our results show that the aftereffects seen following one-grid induction, on both induced and orthogonal orientations, are similar to those seen following the usual two-grid induction procedure. Both procedures result in contingent aftereffects that display substantial retention and that do not display interocular transfer, suggesting that they share the same underlying mechanism.

REFERENCES

Allan, L. G., Siegel, S., Collins, J. C., & MacQueen, G. M. (1989). Color aftereffect contingent on text. *Perception & Psychophysics*, **46**, 105-113.

Allan, L. G., Siegel, S., Toppan, P., & Lockhead, G. R. (1991). Assessment of the McCollough effect by a shift in psychometric function. *Bulletin of the Psychonomic Society*, **29**, 21-24.

Ambler, B. A., & Foreit, K. G. (1978). Induction of the McCollough effect II: Two different mechanisms. *Perception & Psychophysics*, **24**, 466-470.

Dodwell, P. C., & Humphrey, G. K. (1990). A functional theory of the McCollough effect. *Psychological Review*, **97**, 78-89.

Houck, M. R., & Hoffman, J. E. (1986). Conjunction of color and form without attention: Evidence from an orientation-contingent color aftereffect. *Journal of Experimental Psychology: Human Perception & Performance*, **12**, 186-199.

Humphrey, G. K., Dodwell, P. C., & Emerson, V. F. (1989). Pattern-contingent color aftereffects on noninduced patterns. *Perception & Psychophysics*, **45**, 97-109.

Jones, P. D., & Holding, D. H. (1975). Extremely long-term persistence of the McCollough effect. *Journal of Experimental Psychology: Human Perception & Performance*, **1**, 323-327.

Kaufman, J. H., May, J. G., & Kunen, S. (1981). Interocular transfer of orientation-contingent color aftereffects with external and internal adaptation. *Perception & Psychophysics*, **30**, 547-551.

McCollough, C. (1965). Color adaptation of edge detectors in the human visual system. *Science*, **149**, 1115-1116.

Meyer, G. E., Coleman, A., Dwyer, T., & Lehman, I. (1982). The McCollough effect in children. *Child Development*, **53**, 838-840.

Murch, G. M. (1972). Binocular relationships in a size and color orientation specific aftereffect. *Journal of Experimental Psychology*, **93**, 30-34.

Siegel, S., & Allan, L. G. (1985). Overshadowing and blocking of the orientation-contingent color aftereffect: Evidence for a conditioning mechanism. *Learning & Motivation*, **16**, 125-138.

Siegel, S., Allan, L. G., Roberts, L., & Eissenberg, T. (1990). Spatial contingency and the McCollough effect. *Perception & Psychophysics*, **48**, 307-312.

Stromeyer, C. F. (1969). Further studies of the McCollough effect. *Perception & Psychophysics*, **6**, 105-110.

Stromeyer, C. F. (1984). Orientation-specific color aftereffects and simultaneous color contrast. In L. Spillman & B. R. Wooten (Eds.), *Sensory experience, adaptation and perception* (pp. 509-527). Hillsdale, NJ: Erlbaum.

White, K. D., & Riggs, L. A. (1974). Angle-contingent color aftereffects. *Vision Research*, **14**, 1147-1154.

Yasuda, K. (1978). Color aftereffects contingent on MacKay complementary regular patterns. *Japanese Psychological Research*, **20**, 115-123.

NOTES

1. An orthogonal grid is one perpendicular to the induction grid. For example, the indirect ME is observed if, following induction with a green horizontal grid, an achromatic vertical grid appears greenish.

2. The larger number of subjects in Group GH resulted from the fact that data were initially collected from subjects in this condition to establish the phenomenon of the indirect ME. When it was clear that we had obtained the effect, we randomly assigned subjects to the various counterbalanced groups in the experiment. Eliminating these initial subjects in Group GH would not change the conclusions.

3. To conserve space, for the remaining experiments we will not present the psychometric functions. Rather, we will present the data so that they are visually compatible with the ANOVA.

(Manuscript received May 16, 1990;
revision accepted for publication May 6, 1991.)