The roles of pattern orthogonality and color contrast in the generation of pattern-contingent color aftereffects

G. KEITH HUMPHREY, PETER C. DODWELL, and VICTOR F. EMERSON
Queen's University, Kingston, Ontario, Canada

A previous report (Emerson, Humphrey, & Dodwell, 1985) presented evidence that several pattern-contingent color aftereffects could be established simultaneously in individual observers, using as induction patterns the three basic orthogonal pattern pairs of Hoffman's (1966) Lie transformation group theory of neuropsychology. Contingent aftereffects (CAEs) generated with these patterns show little interference between pattern pairs. The present experiments explored the induction and test conditions that are sufficient and/or necessary for generating single and multiple CAEs. The data indicated that, for CAE generation to occur, it is necessary that two orthogonal inducing patterns not be viewed in light of the same color. It is sufficient to induce with two distinct patterns in different colors, but more CAEs are reported if these two patterns are orthogonal than if they are nonorthogonal. The scheduling of the inducing conditions is relatively unimportant. In testing, the probability of obtaining a CAE report is greatly increased by presenting the subject with a test pattern designed to elicit two CAEs of different hues; orthogonality of test pattern quadrants has little influence. The results support the view that pattern "channels" bounded by orthogonal pairmates exist in the human visual system and that operations in one channel are relatively independent of operations in another.

Orientation-contingent color aftereffects (McCollough, 1965) demonstrate that the human visual system can store color information for prolonged periods if the chromatic input is paired with distinctive patterns. Although a great deal of research has been devoted to understanding the mechanisms underlying such effects (for reviews, see Harris, 1980; Over, 1977; Stromeyer, 1978), the processes responsible for storage of pattern-contingent chromatic information have yet to be identified.

Recently, we tested a novel approach to understanding the pattern specificity of color-contingent aftereffects (CAEs) (Emerson, Humphrey, & Dodwell, 1985). Multiple colored aftereffects were generated in individual observers in a single extended induction session. Each subject viewed three pairs of mutually orthogonal patterns taken from the "primitive model" of Hoffman's (1966) Lie transformation group theory of neuropsychology (LTG/NP). The members of each pair were presented in either red or green light. For example, a typical McCollough effect is induced by pairing vertical lines in green light (pink aftereffect) alternating with horizontal lines in

red light (green aftereffect). If this induction session is followed 5 min later by another, pairing a "star" pattern in red light with a "bullseye" in green light (Figure 1), the observer will report a pink tinge on the bullseye and a greenish hue on the star. A third induction session, using a pair of mutually orthogonal rectangular hyperbolas, one set shown in red and the other in green light, also generates CAEs of near-complementary hues. All three pairs of CAEs can exist simultaneously in one observer and show relatively little interference with each other. For instance, in the example above, the vertical lines in the achromatic star test pattern would appear green (as a result of the second induction session) whereas a vertical grating would be reported as pink. Thus, the CAE color reported for a vertical contour depends on the pattern of which that contour is an element. Because this result was observed repeatedly, a simple explanation invoking only the adaptation of local contour elements is not tenable. The coexistence of several CAEs in a single observer also implies that the LTG/NP pattern pairs may correspond to "channels" for global pattern processing (see also Dodwell, 1984; O'Shea & Dodwell, 1984).

The demonstration that multiple contingent aftereffects can be generated in a single observer (see also MacKay & MacKay, 1977) suggests that it should be possible, by varying the presentation conditions in a multiple-induction experiment, to specify more closely the general conditions under which simultaneous and independent storage of pattern-color contingencies is possible. The present experiments were designed to reveal the necessary and sufficient conditions for CAE generation and storage.

This research was supported by Grant A0044 of the Natural Sciences and Engineering Research Council of Canada (NSERC) to P. C. Dodwell and D. W. Muir. Preparation of the manuscript was facilitated by an NSERC grant (A8289) to G. K. Humphrey. We share authorship equally. Keith Humphrey is now at the Department of Family Studies, University of Guelph, Guelph, Ont. N1G 2W1. Victor Emerson is now at Dept. 2233 (CAR), Bell-Northern Research, P.O. Box 3511, Station C, Ottawa, Ont. K1Y 4H7. Reprint requests should be sent to P. C. Dodwell at: Department of Psychology, Queen's University, Kingston, Ont., Canada K7L 3N6.

Three questions were addressed: First, under what conditions of pattern-color pairing using a multiple induction technique does the visual system retain this information? Second, what role does pattern orthogonality play in the process? Third, is color contrast an important factor? The experiments were designed to assess the importance of orthogonality in the *induction* patterns in the first instance. In our previous research (Emerson et al., 1985), the induction figures fell naturally into three orthogonal pairs, as described above, so that when central fixation was maintained each pattern pair displayed local as well as global orthogonality. In the experiments reported here, we used two of the same orthogonal pairs (Figure 1) but combined the four patterns in different pairwise combinations, so that when central fixation was used contour orthogonality was sometimes present in the induction pair and sometimes not.

Most studies of contingent color aftereffects have used bipartite fields or quartered test patterns composed of adjacent orthogonal contours. Because the induction patterns in those experiments appeared in two different colors, one would also expect the CAEs to be of two contrasting colors. For example, in McCollough's (1965) original report, the induction patterns were horizontal and vertical gratings in blue and orange light, the test patterns being achromatic patterns composed of adjacent horizontal and vertical gratings. There is a tacit assumption here that the potential for color contrast in the test patterns improves the chance of reporting a CAE. However, the roles of orthogonality of adjacent contours and of color contrast in producing CAEs are confounded in such an arrangement. In the multiple induction procedure, however, the two variables (color contrast and orthogonality in the test patterns) can be examined separately. Thus, the present experiments were designed to use a variety of combinations of test pattern orthogonality, CAE color contrast, and induction schedules to specify some generally sufficient (and perhaps necessary) conditions for generating CAEs.

In Experiment 1, subjects viewed, in two separate sessions, two pairs of patterns, shown in lights of two different colors (red and green). In the first session, two inducing patterns were viewed; in the second session, a different pair was used. The inducing-pattern pairmates within each session either were or were not orthogonal to each other. The colors of the inducing patterns within a session were either the same or different. Across the two sessions, all subjects were shown two patterns in red light and two in green light. Test patterns were chosen so that (depending on inducing conditions) some would display color contrast in the aftereffect whereas others would not. Some test patterns contained mutually orthogonal pattern segments, whereas others contained nonorthogonal segments. The use of a number of such patterns allowed us to investigate which conditions, both in the inducing pattern pairs and in the test patterns, were associated with frequent CAE reports.

EXPERIMENT 1: DOUBLE INDUCTION OF CAES

Method

Subjects

Forty female undergraduates, naive with respect to the experiment, served as subjects. All had normal or corrected-to-normal vision. They were assigned randomly to five experimental conditions, with eight subjects in each. The subjects were paid \$3 for participating in the experiment. Three additional subjects reported seeing colors on the pretest and were not included.

Apparatus and Stimuli

The inducing patterns, shown in Figure 1, consisted of two pairs of orthogonal patterns: (1) vertical and horizontal square-wave gratings and (2) concentric circles ("bullseye") and radial sectors ("star"). The patterns were photographed on high-contrast copy film. Each was mounted in a slide holder with either a Kodak Wratten 92 (red) or 74 (green) filter and projected from a Kodak Carousel projector. (For convenience, these colors will be referred to as complementary, although they are not strictly so.) A Gerbrands two-channel projection tachistoscope control unit (Series 300) drove two shutters regulating the output from the two projectors. The patterns were black except for the colored bars and were projected on a plain white screen. Each pattern subtended 11.5° of visual angle on the screen at the viewing distance of 120 cm.

A high-contrast matte photograph of each of the test patterns shown in Figure 2 was prepared. Each test pattern consisted of alternating quadrants from one pair of inducing patterns. Four of the test patterns were each a composite of the two inducing patterns comprising an orthogonal pair (Figure 2, top). The other eight test patterns consisted of alternating quadrants from nonorthogonal pairs of inducing patterns (Figure 2, bottom).

Figure 1. The two pairs of patterns used during induction in Experiments 1 and 2. The patterns within each pair are orthogonal. Each subject was induced with all four patterns in Experiment 1 and with two patterns in Experiment 2.

Figure 2. The 12 test patterns. Orthogonal test patterns were composed of alternating quadrants of orthogonal pairmates. Nonorthogonal patterns were composed of alternating quadrants of nonorthogonal patterns. All subjects in Experiments 1 and 2 were tested (and pretested) on all 12 test patterns.

Design

The five experimental conditions are shown in Table 1. The arrangement of conditions is complicated and is not a balanced combination of different factors. Each group is numbered and given a name which identifies the induction conditions. Subjects in Group 1.1 viewed an orthogonal pair of patterns in different colored (red and green) lights in the first session and the second orthogonal pair, also in two colors, in the second session. Thus, in Group 1.1, subjects were exposed to orthogonal patterns in complementary colors *within* each inducing session. The name for Group 1.1 is "W: P orthog., C diff.," for "within-session patterns are orthogonal and in different colors." This condition replicates that used by Emerson et al. (1985) to demonstrate simultaneous multiple CAEs within subjects.

In Group 1.2, subjects were exposed to orthogonal pattern pairs within sessions, but the two members of the pattern pair within a session were shown in the same color. The name for Group 1.2 is "W: P orthog., C same" (within-session patterns are orthogonal and in the same color). In Group 1.3, two nonorthogonal patterns were shown within a session, but in different colors, for example, vertical grating in red and bullseye in green. Notice, however, that in this group (see Table 1) an orthogonal pair of patterns appeared in different colors *between* sessions (e.g., red vertical grating in Session 1 and green horizontal grating in Session 2). The name for Group 1.3 is thus "B: P orthog., C diff." (between-session patterns are orthogonal and colors are different). In Group 1.4, nonorthogonal patterns were shown in the same color within sessions, but orthogonal patterns were shown in different colors between sessions; the name for this group is "B: P orthog., C diff. (W: C same)" (between-session patterns are orthogonal, colors are different, but within-session colors are the same). The (W: C same) serves to differentiate Group 1.4 from the otherwise similar Group 1.3, for which (W: C diff.) applies. In Group 1.5, in which nonorthogonal patterns were viewed in different colors in each session, but orthogonal patterns were viewed in the same color *between* sessions, the name is "B: P orthog., C same" (between-session orthogonal patterns are shown in the same color).

The arrangement of Table 1 and the group nomenclature were chosen to emphasize those group properties held to be most relevant to the generation of CAEs, namely pattern orthogonality and color differences for orthogonal patterns. Other naming schemes are possible—for example, Group 1.4 is correctly described as "W: P non-orthog., C same," but this obscures the induction conditions we want to emphasize.

Procedure

Each subject was tested individually in a three-stage procedure: pretest, induction sessions, posttest. First, each subject was shown the 12 achromatic test patterns of Figure 2. If, in this pretest, no colors were reported on any test patterns, the first 10-min induction session was given. During this session, two patterns were presented alternately for 9.5 sec with an intervening 5-msec blank period. The subject was asked to keep her head in a fixed position and to maintain fixation at the center of the presented pattern. Induction occurred in an otherwise dark room. This session was followed by a 5-min rest in normal room light. The second 10-min induction, in which a different pair of patterns was presented, followed the rest period. There was a second 5-min rest period, followed by the posttest, which was given in normal fluorescent room light.¹

During the posttest, the subject was given a pen and a booklet containing photocopies of the 12 test patterns, one pattern per page. She was shown the test patterns in succession and told to fixate the center of each pattern in turn. The test patterns subtended the same visual angle as had the inducing patterns. Subjects were instructed to report any colors seen on the test patterns by outlining, as accurately as possible, the appropriate "colored" area on the cor-

Table 1
Examples of the Induction Protocols for the Subjects in the Five Induction Conditions of Experiment 1

Group	Session	Induction Patterns		Group Name
1.1	1			W: P orthog., C diff.
	2			
1.2	1			W: P orthog., C same
	2			
1.3	1			B: P orthog., C diff. (W: C diff.)
	2			
1.4	1			B: P orthog., C diff. (W: C same)
	2			
1.5	1			B: P orthog., C same (W: C diff.)
	2			

NOTE—Each subject was induced with two patterns in red light and two in green light. Two patterns were presented in the first induction session and the remaining two in the second. The group names emphasize the conditions under which the patterns are orthogonal and their associated induction colors different. On the assumption that these two factors combined are a sufficient condition for CAEs, Groups 1.1, 1.3, and 1.4 should yield CAEs.

responding pattern in the booklet and also writing down the name of the color. The order of presentation of the test patterns was varied across subjects.

Results

Scoring

As can be seen in Figure 2, each test pattern was derived from two inducing patterns. If a subject outlined completely, on a single test pattern, *both* of the quadrants representing a single inducing pattern (e.g., the vertical grating), that response was scored as a COMPLETE CAE. Any response outlining a smaller area was labeled a PARTIAL CAE. There is evidence that complete CAEs are specific to the inducing patterns, whereas partial CAEs tend to be associated with local features (Emerson et al., 1985), so the analyses reported below are based *only* on the complete CAEs. In recording the data, the responses were classed according to the inducing pattern from which the indicated portion of the test pattern was derived. Thus, CAE frequencies were obtained for each of the four inducing patterns for each subject.

The subject was free to assign any color name to the area outlined on a test pattern. If the induction phase had been effective, negative aftereffects would occur, so the subject would assign a color name like "red," "pink," or "orange" to the portion of a test pattern that was drawn from the induction pattern that had appeared in green light. Likewise, acceptable color names for the CAE to a red-induced pattern were "green," "blue," and their variants, such as "bluish-green." The large majority of responses were "pink" and "green." CAE reports that named a color approximately complementary to the color in which the pattern had been presented during induction were considered to be appropriate; the converse report (e.g., pink CAE to a pattern that had appeared in red light) was inappropriate. Only five other color names (brown, yellow, violet, beige, and purple) were reported, but these responses were all given by one subject as partial CAE reports and so were ignored.

The frequencies of both appropriate and inappropriate CAE reports were recorded, and scores corrected by subtracting, for each subject, the number of inappropriate reports from the number of appropriate ones. If a subject was responding at random, the expected frequency of CAE reports thus corrected would be zero. In fact, the 40 subjects in the five induction groups gave a total of 427 appropriate reports (264 complete and 163 partial) and 63 inappropriate reports (13 complete and 50 partial), yielding an adjusted total of 251 complete reports, on which all analyses below were performed, and 113 partial reports.

Because each inducing pattern appeared in 6 of the 12 test patterns, a subject could give more than one response to each pattern. It might be argued that once a subject had assigned a certain color name (e.g., green) to, say, the vertical portion of one test pattern she would be more likely to repeat that color name rather than give another to the vertical portions of other test patterns. Such a

strategy would be a matter of serious concern, because it would lead to high frequencies of CAE reports (either appropriate or inappropriate) associated with a particular inducing pattern for a particular subject, so that the expected corrected CAE would not be zero. However, there is abundant evidence that this strategy was not used. First, across subjects there were many more appropriate than inappropriate CAE reports, indicating that the induction conditions affected the selection of color names; in other words, the color names were not selected randomly. Second, the frequency of CAE reports varied widely across groups, suggesting that subjects did not generally feel constrained to give a response when no CAE was apparent. Finally, very few subjects reported appropriate CAEs to a particular induction pattern every time it appeared in a test pattern, and none reported inappropriate CAEs this way.

To evaluate the effects of different testing conditions, the responses were grouped according to two factors in the test patterns. One, shown in Figure 2, was whether or not the two induction patterns composing a test pattern were orthogonal; there were four orthogonal and eight nonorthogonal test patterns. The second concerned whether, in a single test pattern, the two CAEs were of different hues or the same hue. In the cases in which one pink and one green CAE would be expected, color contrast was said to exist; when two green or two pink CAEs were expected there would be no such color contrast. It was predicted that contrasting CAEs would enhance each other's vividness, resulting in a higher incidence of CAE reports in the contrasting than in the noncontrasting test patterns.

The two test conditions of test-pattern orthogonality and color contrast, combined factorially across the various induction conditions, yield the four cells of a 2×2 table. However, within any one induction group, frequencies can be entered into only two or three cells. For example, in Groups 1.1, 1.3, and 1.4, orthogonal induction patterns were always viewed in different colored lights, so that a test pattern composed of orthogonal patterns would always be expected to produce contrasting CAEs. On the other hand, orthogonal test patterns would never yield contrasting CAEs for subjects in Groups 1.2 and 1.5. Scrutiny of Figure 2 should convince the reader that, for each of the induction groups, only four of the non-orthogonal test patterns could support color-contrasting CAEs.

Induction Conditions

The corrected number of complete CAEs reported by each group was divided by 32 (8 subjects $\times$ 4 inducing patterns) to obtain the mean number of CAEs reported per subject per inducing pattern. These group means are displayed in Figure 3, expressed as percentages of the six CAEs that could possibly have been reported by each subject on each inducing pattern (i.e., each inducing pattern is represented in six test patterns), averaged across the four inducing patterns. Only the scores of Groups 1.1,

Figure 3. The mean number of CAEs reported per subject per inducing pattern, expressed as a percentage of the six CAEs that could have been reported by each subject on each inducing pattern.

1.3, and 1.4 differed significantly from zero [$t(7) = 6.632, 5.693, 3.734$, respectively; all $ps < .01$, two-tailed], showing that the frequency of CAE reports differed from chance only in those groups that had viewed orthogonal patterns in complementary colors in the induction phase, regardless of whether this had occurred within or between sessions.

A one-factor completely randomized ANOVA was calculated on the scores of all groups except 1.2, all subjects in this group having a score of zero. The ANOVA indicated significant between-group variability [$F(3,28) = 5.309, p < .01$] and was followed by a Newman-Keuls test. This post hoc test demonstrated that Group 1.5 differed significantly from each of Groups 1.1, 1.3, and 1.4 at $p < .05$ or better, and that these latter groups did not differ among themselves.

To ensure that this pattern of results was not an artifact of the dependent measure used, similar analyses were performed on the number of subjects reporting complete CAEs and on the number of inducing patterns on which complete CAEs were reported. The pattern of results in both cases was identical to that reported above.

During the induction phase, only subjects in Groups 1.1, 1.3, and 1.4 viewed orthogonal patterns paired with complementary colors, and only in those groups was the mean frequency of CAE reports greater than that expected by chance. This observation, in combination with the failure of Groups 1.1, 1.3, and 1.4 to differ among themselves, makes it reasonable to conclude that a sufficient condition for the reliable generation of

CAEs is that orthogonal patterns be paired with complementary colors, regardless of the particular induction schedules used here.

Test Conditions

The effects of test pattern orthogonality and (potential) color contrast in contributing to CAE reports were assessed by tabulating their factorial combinations in 2×2 tables. The percentage of CAE reports (corrected, complete) is shown in Table 2A for each induction group. The maximum possible frequency was 64 (128 in those cells marked with an asterisk). Table 2B shows these percentages normalized with respect to the "color-contrast-no-orthogonality" cell, the only condition common to the five induction groups. The frequency of this cell was set at 1.000. These standardized frequencies were then averaged across the five induction conditions for each combination of color contrast $\times$ orthogonality pairing. The summary, in Table 2C, indicates the probability that a CAE will be reported relative to the probability of a CAE report when a "color-contrast, no orthogonality" test pattern is used. Thus, any test condition (color contrast $\times$ orthogonality condition) with a cell entry greater than 1.0 has a greater likelihood of producing CAE reports than do test conditions with cell scores less than 1.0. From Table 2C, it can be seen that, regardless of induction condition, the probability of a CAE report is about doubled when a test pattern producing color contrast in the CAE is used. However, the effect of orthogonality in the *test* pattern is minimal, in contrast to its importance in the inducing pattern, and there is no interaction of orthogonality with color contrast. Thus, following a suitable induction regime, the frequency of CAE reports is determined not by the spatial relations between parts of a test pattern, but rather by the stored relation between induction patterns and colors.

Discussion

These results show that CAEs are readily established when orthogonal patterns are paired with complementary colors and are most likely to be reported when the chosen test patterns enhance the color contrast in the adjacent halves of the CAE. The high frequency of CAE reports in Group 1.1 is comparable to that reported following induction with a single pair of orthogonal patterns (McCollough, 1965), suggesting little or no interference between the CAEs generated by the two pairs of orthogonal patterns. Thus, it is reasonable to conceive of each pair as constituting a "channel," operations within which are relatively independent of operations within other, similar channels, an idea that is derived from Hoffman's (1966) LTG/NP model of visual processing (Dodwell, 1983; Emerson et al., 1985).

The similarity of CAE frequencies in Groups 1.1, 1.3, and 1.4 indicates that induction on the two orthogonal patterns constituting one channel does not have to occur within a single induction session to have a strong effect.

Table 2
The Effects of Test Pattern Orthogonality and Color Contrast in Contributing to CAE Reports (Experiment 1)

Orthogonality in Test Patterns?	Group									
	1.1		1.2		1.3		1.4		1.5	
	Potential Color Contrast?									
	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO
(A) Relative Frequencies										
YES	67.2			—	54.7		40.6			6.3
NO	51.6	26.6	—*		43.8	20.3	39.1	17.2	12.5*	
(B) Corresponding Normalized Values										
YES	1.303			—	1.250		1.040			.500
NO	1.000	.515	—		1.000	.464	1.000	.440	1.000	
(C) Averaged Over Induction Conditions										
	Orthogonality in Test Patterns?		Potential Color Contrast?							
			YES	NO						
		YES	1.198	.500	.849					
		NO	1.000	.473	.737					
			1.099	.487						

NOTE—(A) The percentage of corrected, complete CAE reports for each induction condition. (B) These percentages corrected to relative frequencies normalized with respect to the "color-contrast, no-orthogonality" cell, which was set at 1.000. (C) The standardized frequencies, averaged across the five induction conditions, for each color contrast $\times$ orthogonality pairing. The values indicate the probability that a CAE will be reported relative to the probability of a CAE report when a "color-contrast, no-orthogonality" test pattern is used. *Out of 128 (remainder out of 64).

A sufficient condition for CAE generation is induction by any pair of orthogonal patterns in complementary colors, although it has not yet been fully established that the orthogonal pattern pairs of LTG/NP play a special role in defining independent channels.

Interestingly, contour orthogonality evidently permits the visual system to preserve the separation of pattern "channels" and so generate CAEs within a broad range of induction conditions. Color contrast enhances CAEs in testing, whereas contour orthogonality plays little role in the test phase. Stromeyer (1969) found that CAEs reported following a single induction session with one color and one contour orientation were abolished by presenting the orthogonal contours in the same color. The present results for Groups 1.2 and 1.5 are consistent with Stromeyer's (1969) finding, suggesting that "erasure" of the nascent CAE may occur in the second induction session. However, it also appears that viewing nonorthogonal patterns in complementary colors may not be sufficient to generate CAEs; rather, the cumulative pattern-color pairing within a "channel" is the best predictor of CAE presence at testing (compare, e.g., Groups 1.3 and 1.5).

To examine further the roles of orthogonality and color complementarity in the induction patterns, a second experiment was conducted, this time with only a single induction session per group. It was predicted that, if some general form of erasure occurs (as hypothesized for Groups 1.2 and 1.5), the frequency of CAE reports following a single induction session should be the same whether or not the induction patterns were orthogonal.

If, on the other hand, pattern orthogonality is critical to CAE induction, attempts at induction using nonorthogonal patterns in complementary colors should fail, yielding results similar to those of Group 1.5.

EXPERIMENT 2: SINGLE INDUCTION

Method

Subjects

A total of 56 female undergraduates served in the four conditions outlined below. As in Experiment 1, induction and testing were done individually and each subject served in only one group. None of the subjects reported seeing colors in the preinduction viewing of the test patterns.

Apparatus and Procedure

The apparatus was identical to that used in Experiment 1, and the procedure was the same, except that each subject was given only one induction session, viewing two patterns in either one or two colors of light. The four groups are shown in Table 3, where two of the four induction contingencies used in each group are illustrated. Each induction condition illustrated in Table 3 was presented to half the subjects in a group, the colors being reversed for the other half.

The groups were numbered and named (Table 3) to facilitate comparisons with the groups of Experiment 1. Thus, Group 2.1 (in Experiment 2) corresponds to the first induction session of Group 1.1 (in Experiment 1). The group names likewise point to the relevant conditions of similarity. However, it should be noted that the conditions for Groups 2.3 and 2.4 correspond to *between-session* conditions for Groups 1.3 and 1.4.

The same test patterns were used as in Experiment 1, but in scoring the data an additional CAE report category was required, namely

Table 3
Examples of the Induction Protocols for Subjects in
the Four Induction Conditions of Experiment 2

Group	Sub-Group	Induction Patterns		Group Name
2.1 (n = 16)	a			P orthog., C diff.
	b
2.2 (n = 8)	a			P orthog., C same
	b
2.3 (n = 16)	a			P non-orthog., C diff.
	b
	c
	d
2.4 (n = 16)	a			P non-orthog., C same
	b
	c
	d

NOTE—Each subject was given a single induction session. Within each induction group, pattern-color pairings were counterbalanced. Group numbers and names were chosen to relate to the corresponding groups in Experiment 1 (see text).

for reports on patterns that had not been viewed in the induction phase. Special consideration was given to how this category would relate to the test conditions. For example, a test pattern comprising one inducing pattern and one noninducing pattern could, in fact, give rise to perceived "color contrast," but this might be quite different from the genuine color contrast generated by a pair of induction patterns. The first condition was called "one-hue" color contrast, the second "two-hue." To keep these conditions apart, scores were tabulated separately for two-hue and one-hue color contrast, as well as for the "no-hue" condition, when neither of the inducing patterns was part of a test pattern.

Results

Induction Conditions

Each subject viewed only two of the four patterns shown in Figure 1. In computing the CAE frequencies, the complete CAE reports (there were 272 complete reports in

total) given by each subject were tallied separately for the induced and noninduced portions of the test patterns; a correction for inappropriate reports could be applied only to the induced patterns, on which the appropriate CAE color could be specified. Each of these totals was then summed across subjects in each induction group and divided both by the number of subjects per group (8 in Group 2.2, otherwise 16) and by the number of inducing patterns (two). The resulting mean number of complete CAE reports given by a subject to each pattern is shown in Figure 4 as a function of inducing conditions.

Considering only the CAEs reported on inducing patterns, it is clear from Figure 4 that this frequency is greatest in Group 2.1, the standard McCollough-type induction. The CAE frequency in Group 2.1 was significantly greater than that in Group 2.3, the only other group in which the number of CAEs reported was significantly above chance.

The relatively high frequency of CAEs reported by Groups 2.1 and 2.3 on noninducing patterns cannot meaningfully be considered independently of the testing conditions. This analysis and a comparison of conditions in Experiments 1 and 2 are discussed more fully below.

In summary, subjects who experience only one color of light during their single induction session report virtually no CAEs, regardless of whether the induction patterns are orthogonal (Group 2.2) or nonorthogonal (Group 2.4). Subjects whose induction involved lights of complementary colors report a large number of CAEs, with the larger number being obtained when the patterns presented in the two colors are orthogonal pairmates (Group 2.1) than when they are not (Group 2.3).

Test Conditions

As in Experiment 1, the frequency of CAE reports depended on the testing conditions. To quantify the roles of test-pattern orthogonality and CAE color contrast in CAE reporting, two 3×2 tables were set up for each induction group (Table 4). Each table, one for patterns seen during induction and one for those patterns in Figure 1 not seen in induction, contained cells representing the six factorial combinations of CAE color contrast (two-hue, one-hue, none) and test pattern orthogonality (orthogonal, nonorthogonal).

For each group, the number of complete CAEs reported in each of the six "induced" cells was corrected for (complete) inappropriate reports, of which there were three in total. Each corrected CAE frequency was expressed as a percentage of the number of possible CAE reports for that cell (Table 4A); some of these percentages are described more fully below. They were normalized relative to the frequencies in the "one-hue, nonorthogonal" cell for inducing patterns, the one cell common to the four groups. This cell's value was set at 1.000 for each group, thereby tending to eliminate the effects of differential responding across induction conditions. The normalized scores, averaged across groups where necessary, are

Figure 4. The mean number of complete CAE reports given by a subject to each pattern as a function of inducing conditions.

shown in Table 4B. The summary scores for each test condition are shown in Table 4C, collapsed across induction conditions.

As in Experiment 1, the probability of reporting a CAE is slightly higher when the pattern used for testing is composed of orthogonal rather than nonorthogonal test quadrants, although this difference is not great. Also, as in Experiment 1, the presence of color contrast in the test pattern greatly increases the likelihood of CAE reports, here by a factor of about 3.5. Furthermore, there is no striking difference between one-hue and two-hue color contrast. Finally, subjects are about twice as likely to report a CAE when tested on an induction pattern as when tested on a noninduction pattern; however, this estimate is suspect, because there were only two CAE reports in Group 2.4.

In general, the pattern of results indicates that the best conditions for eliciting a CAE report are: (1) use of at least one induction pattern in the test pattern and (2) arrangement of the test pattern so that the color of the CAE on one of its quadrants contrasts with either the specific hue or the lack of color on the other. Of the 272 CAEs reported in Experiment 2, 252 (92.6%) involved color contrast of one type or another.

Of the 20 reports given in conditions in which neither type of color contrast was expected, 15 occurred in Group 2.3 in the "nonorthogonal, no contrast" cell of the *noninduced* pattern block. Because this was an unex-

pectedly high rate of responding, the responses in this cell were reanalyzed to determine whether the colors reported were related to the induction conditions. It turned out that in *every* case (15 reports from eight subjects) the color reported on one pattern was similar to the color in which its orthogonal pairmate had appeared during induction (i.e., the complement of the complement). Thus, a subject induced with, say, red vertical stripes and green concentric circles would tend to report, on a test pattern composed of the two noninducing patterns, red on the horizontal stripes and green on the radial pattern. The frequent occurrence of these reports (15 cases out of 64 possible, or 23.4%) and the predictability of the color names (100% "correct," using this rule) constitute strong evidence that induction with two nonorthogonal patterns in light of complementary colors generates further color-pattern interactions within their respective "channels." The probability of 15 correct out of 15 is about .0005 if red/green color names are chosen at random with $p = .5$ (binomial test).

Single Versus Double Induction

To compare results between Experiments 1 and 2, the frequency of CAE reports in the "nonorthogonal, color contrast" cell (the only condition common to all groups) was graphed for each of the nine induction groups; for Group 2.3, this involved pooling the data in the one- and two-hue cells in the "nonorthogonal" row. These frequen-

Table 4
Frequency of CAE Reports (Experiment 2)

		Group											
		2.1			2.2			2.3			2.4		
Induction Pattern	Test Patterns	Color Contrast											
		2 Hue	1 Hue	None	2 Hue	1 Hue	None	2 Hue	1 Hue	None	2 Hue	1 Hue	None
(A) Percentage of CAE Reports													
Induced	Orthogonal	73.4	—	—	—	—	6.3	—	43.8	—	—	7.8	—
	Nonorthogonal	—	59.4*	—	—	4.7	—	40.6	26.6	—	—	3.1	1.6
Noninduced	Orthogonal	—	—	3.1	—	—	0.0	—	26.6	—	—	6.3	—
	Nonorthogonal	—	18.8*	—	—	0.0	—	—	4.7	23.4	—	0.0	0.0
(B) Normalized Scores													
Induced	Orthogonal	1.236	—	—	—	—	.667	—	1.647	—	—	2.500	—
	Nonorthogonal	—	1.000	—	—	1.000	—	1.526	1.000	—	—	1.000	.500
Noninduced	Orthogonal	—	—	.026	—	—	.000	—	1.000	—	—	2.000	—
	Nonorthogonal	—	.316	—	—	.000	—	—	.176	.882	—	.000	.000
(C) Summary													
		Induction Pattern	Test Patterns	Color Contrast									
				2 Hue	1 Hue	None							
Induced		Orthogonal	1.236	2.074	.333	1.213							
		Nonorthogonal	1.526	1.000	.500	1.009							
			1.381	1.537	.417	1.111							
Noninduced		Orthogonal	—	1.500	.130	.757							
		Nonorthogonal	—	.123	.441	.564							
			—	.812	.227	.519							

Note—(A) The corrected CAE frequency expressed as a percentage of the number of possible CAE reports for that cell. (B) The corrected CAE frequencies normalized relative to the "one-hue, nonorthogonal" cell for inducing patterns, which was set at 1.000. (C) The summary scores for each test condition collapsed across induction conditions. *Out of 128 (remainder out of 64).

cies, expressed as a percentage of the number of possible CAE reports, are shown in Figure 5, where single induction conditions from Experiment 2 that represent one-half of the double induction protocols from Experiment 1 are grouped with the relevant double induction group(s).

Groups 1.1 and 2.1. These are the groups receiving standard McCollough induction conditions, that is, orthogonal patterns seen in complementary colors. The relative frequency of complete CAE reports on test patterns composed of induction patterns is the same in these two groups, indicating that double induction does not create destructive interference between the two channels of orthogonal patterns. In fact, although the same proportion (.875) of subjects in Groups 1.1 and 2.1 reported CAEs, those in Group 1.1 reported them across significantly more inducing patterns than did those in Group 2.1 [$t(22) = 3.389$, $p < .005$, one-tailed]. This replicates the main result of Emerson et al. (1985). Finally, the large discrepancy in the relative frequency of CAE reports on the induced and noninduced patterns by Group 2.1 shows that the reports are specific to the inducing patterns.

Groups 1.3, 1.5, and 2.3. The two groups from Experiment 1 have identical *first* induction sessions ("W: P non-orthog., C diff."), which are also identical to the single induction session of Group 2.3. Notice that the number of CAE reports for Group 2.3 is about the same

as that for Group 1.3, but much greater than that for Group 1.5. The difference between these two groups (1.3 and 1.5) is explained by considering their second induction sessions. Across the two induction sessions of Group 1.3, orthogonal pairmates are shown in complementary colors, but for Group 1.5 the orthogonal pairmates are shown in the *same* color. Thus, we can argue that at the end of a first session of "W: P non-orthog., C diff." a good substrate for CAEs exists (Group 2.3). If in the second session orthogonal pairmates are shown in complementary colors, the effect is somewhat potentiated (1.3), but if they are shown in the same color (1.5), the substrate is erased.

Groups 1.2, 1.4, 2.2, and 2.4. In these groups, orthogonal or nonorthogonal patterns are shown in the same colors, but in one group (1.4) this is followed by a second session in which, across sessions, orthogonal patterns are presented in complementary colors. Casual inspection of Figure 5 is sufficient to see that only when orthogonal patterns are presented in complementary colors during induction are CAEs reported reliably (1.4), even though only one color was used in each induction session. From a different perspective, it could be argued that viewing two nonorthogonal patterns in light of one color has no discernible effect (2.4); however, the visual system must store these pattern-color combinations, for, if the

Figure 5. The frequencies of CAE reports in the "nonorthogonal, color-contrast" cell common to all nine induction groups in Experiments 1 and 2. The frequencies are expressed as a percentage of the number of possible CAE reports. The single induction conditions of Experiment 2 that represent one-half of the double induction protocols of Experiment 1 are grouped with the relevant induction groups.

respective orthogonal pairmates are presented in the complementary color in the second induction session, a large number of CAEs is reported (1.4).

In summary, CAEs are reported reliably when orthogonal patterns are paired with complementary colors of light during the adaptation phase, whether within (1.1, 2.1) or across (1.3, 1.4) the two induction sessions. When this arrangement does not exist, few (1.5) or no (1.2, 2.2, 2.4) CAEs are reported. It should be emphasized that induction occurs reliably to two nonorthogonal patterns in two colors of light (2.3). Our evidence suggests that under these conditions there are, in fact, two nascent CAEs, one within each channel, because the report of colors on each inducing pattern's orthogonal patternmate tends strongly to be reported as complementary.

GENERAL DISCUSSION

The primary aim of these experiments was first to establish some general conditions of pattern-color pairing that determine the generation of CAEs. A second goal was to examine further the properties of patterns derived from Hoffman's LTG/NP, which had been used in a previous set of experiments on CAEs (Emerson et al., 1985).

The present experiments have established the roles that test pattern orthogonality and pattern-color contingency play in the generation of CAEs, and also the importance of actual or potential color contrast in the testing conditions. To generate CAEs, it is sufficient to adapt or-

thogonal pattern pairs in complementary colors, although neither of these conditions is strictly necessary (see Fidell, 1970). On the other hand, the actual manner of scheduling induction sessions appears not to be critical.

The present experiments have replicated Stromeyer's (1969) finding that potential CAEs can be "erased" by presenting the second of an orthogonal pattern pair in the same color, and have shown, in addition, that if this erasure is not induced, there is a tendency for the achromatic test version of a noninduced pattern to display the CAE complementary to that generated by its orthogonal patternmate. This is fair and quite unexpected support for the notion that the three pattern pairs of the primitive model of LTG/NP constitute independent channels for the initial processing of pattern information (Dodwell, 1983). Although only two of the three LTG/NP pairs were used in the present experiments, the third pair (upright and 45°-rotated rectangular hyperbolas) should follow the same principles. These latter two patterns are locally and globally orthogonal to each other, but not globally orthogonal to the horizontal/vertical grids and bullseye/star used here. The latter two pairs embody exactly those same within- and between-pair orthogonality constraints with respect to each other and the hyperbolas that probably form the basis for channel separation. Evidence for independent generation of CAEs in this third channel is provided in Emerson et al. (1985).

Thus, the present experiments provide new insight into the conditions under which CAEs, whether generated in multiple-contingency paradigms or not, can be estab-

lished. They also provide further support for the LTG/NP in demonstrating a degree of independence between pattern channels as these are defined within the LTG/NP model.

It might be proposed that our results could be understood in terms of an alternate model, some form of spectral analysis being an obvious candidate. It has been proposed that certain forms of contingent color aftereffects can be understood in terms of the adaptation of components that perform a form of two-dimensional Fourier analysis on the visual input (e.g., Green, Corwin, & Zemon, 1976; May & Matteson, 1976). We do not believe that such an analysis leads to further insight into the effects we have demonstrated. Although different patterns do, in general, have different spectral components, there is nothing in such a model that predicts, without ancillary hypotheses, the results obtained here.

An issue not addressed so far concerns the sufficiency of local orthogonality between two patterns for generating CAEs. Although the present experiments demonstrated the importance of global orthogonality in establishing independent CAEs (Emerson et al., 1985; and this report), it remains to determine directly how effective purely local orthogonality might be as a generator of CAEs in the absence of global orthogonality.

REFERENCES

- DODWELL, P. C. (1983). The Lie transformation group model of visual perception. *Perception & Psychophysics*, **34**, 1-16.
- DODWELL, P. C. (1984). Local and global factors in figure synthesis. In P. C. Dodwell & T. M. Caelli (Eds.), *Figural synthesis*. Hillsdale, NJ: Erlbaum.
- EMERSON, V. F., HUMPHREY, G. K., & DODWELL, P. C. (1985). Colored aftereffects contingent on patterns generated by Lie transformation groups. *Perception & Psychophysics*, **37**, 155-162.
- FIDELL, L. K. S. (1970). Orientation specificity in chromatic adaptation of human "edge-detectors." *Perception & Psychophysics*, **8**, 235-237.
- GREEN, M., CORWIN, T., & ZEMON, V. (1976). A comparison of Fourier analysis and feature analysis in pattern-specific color aftereffects. *Science*, **192**, 147-148.
- HARRIS, C. S. (1980). Insight or out of sight?: Two examples of perceptual plasticity in the human adult. In C. S. Harris (Ed.), *Visual coding and adaptability*. Hillsdale, NJ: Erlbaum.
- HOFFMAN, W. C. (1966). The Lie algebra of visual perception. *Journal of Mathematical Psychology*, **3**, 65-98. (Errata, *Journal of Mathematical Psychology*, 1967, **4**, 348-349)
- MACKEY, V., & MACKEY, D. M. (1977). Multiple orientation-contingent chromatic aftereffects. *Quarterly Journal of Experimental Psychology*, **29**, 203-218.
- MAY, J. G., & MATTESON, H. H. (1976). Spatial frequency-contingent color aftereffects. *Science*, **192**, 145-147.
- MCCOLLOUGH, C. (1965). Color adaptation of edge-detectors in the human visual system. *Science*, **149**, 1115-1116.
- O'SHEA, R. P., & DODWELL, P. C. (1984, April-May). *Local and global influences on the McCollough effect*. Paper presented at the Association for Research in Vision and Ophthalmology, Sarasota, Florida.
- OVER, R. (1977). Contingent aftereffects in the perception of colour and contour. In R. H. Day & G. V. Stanley (Eds.), *Studies in perception*. Perth: University of Australia Press.
- STROMEYER, C. F. (1969). Further studies of the McCollough effect. *Perception & Psychophysics*, **6**, 105-110.
- STROMEYER, C. F. (1978). Form-color aftereffects in human vision. In R. Held, H. W. Leibowitz, & H.-L. Teuber (Eds.), *Perception: Handbook of sensory physiology (VIII)*. New York: Springer-Verlag.

NOTE

1. Although central fixation was used during induction and testing, such a procedure is not necessary for the production of CAEs using patterns like those used in the present report. O'Shea and Dodwell (1984) recently demonstrated CAEs with regulated eye movements. Furthermore, the use of the multiple induction procedure, rest periods in room light before testing, and scoring only for complete CAEs should preclude the influence of simple afterimages during induction and ensure that the reports are not simple afterimages.

(Manuscript received October 2, 1984;
revision accepted for publication October 7, 1985.)