CONDITIONING AND PERCEPTION: THE MCCOLLOUGH EFFECT AND THE INDIRECT MCCOLLOUGH EFFECT

By

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CONDITIONING AND PERCEPTION

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ABSTRACT

According to a conditioning analysis of the orientation-contingent colour aftereffect (McCollough effect, ME), orientation stimuli (grids) become associated with colour. Challenges to this interpretation include the suggestion that specific patterned stimuli are required to elicit the effect, that the effect is not influenced by manipulations of the grid-colour correlation, and that some colour aftereffects appear to be elicited by stimuli that are never paired with colour (i.e. the indirect ME). The present results indicate: (a) nonpatterned stimuli — the lightness of a frame surrounding a coloured area – can contingently elicit colour aftereffects; (b) this frame lightness contingent-colour aftereffect can be used to demonstrate that correlational manipulations affect the ME; and (c) that the indirect ME is elicited by form and frame stimuli that have been previously paired with colour. Thus the present results support a conditioning analysis of both the ME and the indirect ME.

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PREFACE

This thesis is divided into two distinct sections. Each section represents either published material (Siegel, Allan, & Eissenberg, 1992), or material submitted for publication (Eissenberg, Allan, Siegel, & Petrov, submitted). Because these articles have multiple authorship, my contribution to each is explained here.

Siegel, Allan, and Eissenberg (1992) report five experiments. Experiments 3-5 represent my contribution to the paper, and thus are the relevant experiments for this thesis. Experiments 3 and 4 describe a novel contingent colour aftereffect, the frame-lightness colour aftereffect, that I suggested should occur based upon the conditioning analysis of contingent colour aftereffects. Experiment 5 uses this novel aftereffect to demonstrate the previously unobserved effects of correlational manipulations of grid and colour upon aftereffect magnitude. As such, all three experiments are original contributions to this work.

Eissenberg, Allan, Siegel, and Petrov (submitted) report eight experiments. All eight experiments represent my contributions to the paper, and thus all are relevant for this thesis. These eight experiments support a novel associative account of a colour aftereffect known as the indirect McCollough effect.

INTRODUCTION

This thesis is divided into two distinct sections. Each section represents either published material (Siegel, Allan, & Eissenberg, 1992), or material submitted for publication (Eissenberg, Allan, Siegel, & Petrov, submitted). The following introduction is intended to set the context for the two sections that follow.

Whenever two events are related, such as when one event reliably predicts another, there is an opportunity for an organism to learn about that relationship. Researchers within the field of classical conditioning study the rules that govern such learning. Typically, learning researchers explore associations involving so-called "biologically significant events," but organisms also appear capable of associating two "neutral" events. The study of learned relationships between paired neutral, or sensory, events is not new (e.g. Brogden, 1939), and it continues to be of interest to learning researchers (e.g. Rescorla & Durlach, 1981). Presentations of paired sensory events result in phenomena that have long interested perceptual researchers. One type of phenomenon resulting from such pairings is the contingent colour aftereffect.

The prototypic contingent aftereffect is an orientation-contingent colour aftereffect known as the McCollough effect (ME), after the investigator who first reported the phenomenon (McCollough, 1965). The ME can be observed following an induction period where two sensory events, orientation and colour, are paired. For example, subjects might be presented with a grid made of green and black horizontal bars alternating with another grid made of magenta and black vertical bars. The ME is observed when subjects report that grids made up of white and black bars appear coloured, and that the colour depends upon the orientation of the bars that make up the grid. In the above example, the white horizontal bars would appear pinkish, and the white vertical bars would appear greenish. There has been much recent debate regarding the mechanism that underlies the ME (Allan & Siegel, 1993; Dodwell & Humphrey, 1990; 1993; Siegel & Allan, 1992). This debate has been stimulated by reports of a closely related phenomenon: the indirect ME (e.g., Allan & Siegel, 1991; Humphrey, Dodwell, & Emerson, 1989; Shute, 1979; Stromeyer, 1969).

The indirect ME can be observed following an induction period where, for example, a green horizontal grid is alternated with a magenta (gridless) square. Following such an induction period, subjects report that achromatic (white) horizontal grids (the induced grid in this example) appear pink, and achromatic vertical grids (the noninduced orthogonal grid) appear green. The aftereffect reported on the induced grid is the ME, the aftereffect reported on the noninduced orthogonal grid is the indirect ME. The indirect ME has been taken as evidence for an underlying, (nonassociative) orthogonally organized visual processing system (e.g. Dodwell, 1992; Humprey et al, 1989).

The experiments that follow were designed to determine the nature of the mechanism that underlies contingent colour aftereffects like the ME and the indirect ME. In order to make this report more cohesive, this introduction briefly reviews research concerning mechanisms underlying the ME, with particular attention to the questions addressed by the current research. Following this review, the indirect ME is described in more detail, and an associative analysis of the mechanism underlying this aftereffect is presented. The experiments follow, in the form of two papers (Siegel, et al, 1992; Eissenberg et al, submitted). Note that the relevant experiments in the first paper (Siegel et al, 1992) are Experiments 3-5.

An Associative Analysis of the ME

The ME has typically been interpreted in a non-associative manner (e.g., McCollough's [1965] suggestion that her findings resulted from chromatic adaptation of orientation-specific detectors), but some investigators have suggested that the phenomenon may be best understood as an instance of Pavlovian conditioning (see review by Siegel & Allan, 1992). According to this associative analysis of the ME, the grid acts as a conditioned stimulus (CS) that reliably predicts the colour unconditioned stimulus (UCS) during induction. Because of this predictive relationship between grid CS and colour UCS, the grid, when presented without colour, elicits a conditioned response (CR) -- the colour aftereffect (e.g. Murch, 1976). While there is empirical support for this conditioning analysis of the ME (e.g. Allan & Siegel, 1986; Siegel & Allan, 1992), the analysis has its detractors (e.g. Dodwell & Humphrey, 1990; Skowbo, 1984, 1986).

Conditioning Phenomena and the ME. There is a great deal of evidence supporting a conditioning account of the ME, drawn primarily from demonstrations that the ME can be used to observe many conditioning-like effects. Thus ME magnitude is weakened following repeated presentations of the grid CS following induction (extinction; e.g. Riggs, White & Eimas, 1974), but displays some recovery after a rest period following these extinction trials (spontaneous recovery; e.g. Skowbo, 1988). Also, if subjects are exposed to non-coloured grid stimuli prior to induction, ME magnitude is decreased, a phenomenon known as latent inhibition (Skowbo, 1988).

Even more evidence for the conditioning account of the ME can be found when the results of induction periods containing compound stimuli are considered. For example, in the conditioning literature, prior training with one CS (CS_A for example) is said to block learning about another CS (CS_B) when CS_A and CS_B are compounded and paired with a

UCS (Kamin, 1969). That is, following pre-training with CS_A, subjects fail to learn about CS_B when the two are compounded. Importantly, subjects do learn about CS_B during compound trials if there has been no pre-training with CS_A. While Kamin (1969) used a light and a noise as CS_A and CS_B, and a shock as the UCS, the blocking effect has been demonstrated using ME induction procedures (Siegel & Allan, 1985). Prior training with diagonal patterns (CS_A) attenuated the magnitude of the ME reported on vertical-horizontal patterns (CS_B) when the diagonals were superimposed upon the vertical-horizontal patterns and these compounds were paired with colour (Siegel & Allan, 1985). Blocking of the ME has been replicated and the similarity between the ME and conditioning has been extended to include the Pavlovian phenomena of unblocking and overprediction (e.g. Brand, Holding, & Jones, 1987; Sloane, Ost, Etheriedge, & Henderlite, 1989).

Patterns that Elicit the ME. One reason for continued skepticism concerning the contribution of conditioning to the ME was the widely-asserted belief that only a few, special patterns (like horizontal and vertical grids) could be effective ME induction stimuli. Some investigators suggested that such limitations on effective ME patterns compromise the conditioning account (e.g., Dodwell & Humphrey, 1990; Skowbo, 1984). However, results of recent experiments demonstrate that a variety of forms (e.g., crosses and squares) are effective elicitors of colour aftereffects (e.g. Siegel et al, 1992, Expts 1 & 2). Successful demonstrations of form-contingent colour aftereffects led to the suggestion that nonpatterned stimuli might also contingently elicit colour aftereffects. Specifically, the lightness of a background, or frame, surrounding a coloured square might elicit a colour aftereffect following an induction period where colour is made contingent upon frame lightness. According to this hypothesis, following induction consisting of alternating presentations of a green square surrounded by a white frame and a magenta square surrounded by a black frame, colourless, framed assessment squares should appear coloured. That is, squares presented in the white frame should appear pinkish, and squares presented in the black frame should appear greenish. This frame lightness contingent colour aftereffect is demonstrated in the first two experiments of this thesis. Siegel et al (1992, Experiment 3) demonstrated that following an induction period where complementarily coloured "pictures" were presented such that colour was contingent on frame lightness (e.g. a black-framed green picture alternated with a white-framed magenta picture) subjects reported that framed achromatic stimuli appeared coloured, and the colour depended upon the lightness of the surrounding frame (e.g. black-framed horizontal grids appeared pink, white-framed horizontal grids appeared green). This frame lightness contingent colour aftereffect occurred when induction pictures contained only horizontal grids, horizontal or vertical grids that were randomly presented with respect to colour, or no grid stimulus (i.e. a framed gridless square). The frame lightness contingent colour aftereffect can also be demonstrated when both induction and assessment stimuli are composed of framed, gridless squares (Siegel et al, Experiment 4). Moreover, the frame lightness contingent colour aftereffect, like the ME elicited by grid stimuli, is long-lived (i.e. detectable 24 hours after the induction period; Siegel et al, Experiment 4).

The ME and the CS-UCS Correlation. Another criticism of the associative interpretation of the ME is that ME magnitude, unlike Pavlovian CRs, is not sensitive to manipulations of the correlation between the putative CS (grid) and the putative UCS (colour; e.g. Skowbo, 1986). In the Pavlovian conditioning literature, decreases in CS-UCS correlation are typically effected by introducing UCS presentations in the absence of the CS. Such interpolated UCS-alone presentations weaken the magnitude of the resulting CR, possibly because when a UCS is presented in the absence of the CS, that UCS is associated with the experimental context. Context-UCS associations compete with CS-UCS associations, thus decreasing the magnitude of CS-elicited CRs (Rescorla & Wagner, 1972). Previous attempts to demonstrate the influence of CS-UCS correlation on ME magnitude have failed. These attempts included reduction of the temporal correlation, via presentations of interpolated chromatic gridless squares (e.g. Siegel & Allan, 1987; Skowbo & Forster, 1983), as well as reduction of the spatial correlation, by extending the chromatic stimulus beyond the grid stimulus (Siegel, Allan, Roberts, & Eissenberg, 1990). These correlational manipulations might have failed to affect ME magnitude because no distinctive experimental context was provided, thus no context-UCS associations could develop (Siegel & Allan, 1987).

Demonstration of a frame lightness contingent colour aftereffect allowed introduction of an experimental context. That is, the frame lightness element of a framed grid could act as a distinctive experimental context in which interpolated chromatic gridless squares could be presented. The formation of context-UCS (i.e. frame-colour) associations should then compete with grid-colour associations, thus weakening ME magnitude. Indeed, when subjects were induced with white-framed green horizontal grids alternating with black-framed magenta vertical grids, interpolated white- and black-framed (gridless) chromatic stimuli did weaken ME magnitude (Siegel et al, 1992, Expt 5). Thus, contrary to previous reports (e.g. Skowbo & Forster, 1983) correlational manipulations, accomplished with interpolated gridless chromatic stimuli, do affect ME magnitude.

Though a great deal of evidence supported the conditioning interpretation of the ME (Siegel & Allan, 1992), criticism that only limited types of forms elicit the effect, and the failure of correlational manipulations to reduce the magnitude of the effect, weakened the conditioning analysis. The frame lightness contingent colour aftereffect presented in the first half of this report can be used to address both of these criticisms. First, as predicted by a conditioning analysis, MEs can be elicited by a wide variety of stimuli, including those that differ only in terms of their lightness. Moreover, when frame lightness elements of a stimulus act as an experimental context, correlational manipulations do effect ME magnitude as predicted by the conditioning analysis. Thus, the frame lightness contingent colour aftereffect is used to address two important criticisms of the conditioning analysis of the ME. Similarly, the frame lightness contingent colour aftereffect is central to an associative interpretation of the indirect ME.

The Associative Basis of the Indirect ME

While there is much evidence in support of an associative account of the ME (Siegel & Allan, 1992), the indirect ME presents a challenge to associative accounts because the stimulus eliciting the aftereffect is apparently not present during induction. Recall that the indirect ME can occur following induction with a coloured grid alternating with a complementarily coloured homogeneous field: for example a green horizontal grid alternating with a magenta square (e.g. Allan & Siegel, 1991). The indirect ME is observed when subjects report that achromatic stimuli containing the noninduced orthogonal grid orientation, vertical in this example, appear coloured. This effect presents a challenge for a conditioning analysis because a putative CR (the colour aftereffect) is elicited by a stimulus that has never been paired with the putative UCS (colour) during induction. This challenge can be answered by a consideration of the variety of stimuli that are paired with colour during indirect ME induction (and that subsequently may elicit colour aftereffects), and an appreciation of data and theory concerning compound conditioning effects. Consider one indirect ME induction procedure – a green horizontal grid alternating with a magenta gridless square (e.g. Allan & Siegel, 1991). If these chromatic stimuli are presented in the middle of an otherwise black video monitor (or on a projection screen in a darkened room), they are both square figures surrounded by black frames. Thus, green-horizontal grid presentations involve pairing of green with a variety of elements: the horizontal grid, the black frame, and the square form of the picture. Similarly, magenta-square presentations involve pairing of magenta with a black frame and square form.

It is likely that these various elements (orientation, frame lightness, and form) differ in salience (other things being equal, CRs develop more rapidly to more salient stimuli). Following training where a compound stimulus with elements of unequal salience is paired with a UCS, organisms respond more to the stimulus element with the greater salience. This phenomenon is known as overshadowing (Kamin, 1969; Pavlov, 1927, p. 143). For example, Kamin constructed a compound CS of two elements differing in salience: a relatively more salient light and a relatively less salient noise. Following training where this compound CS was paired with shock, the light elicited the CR of greater magnitude, and the noise elicited the CR of lesser magnitude -- the light overshadowed the noise.

Overshadowing has also been demonstrated during ME induction when the induction stimuli paired with each complementary colour consist of compound grids. That is, if induction consists of presentation of coloured grids with both diagonal and horizontal-vertical components that differ in salience, the more salient grid component elicits a greater ME than the less salient one (Siegel & Allan, 1985).

Like Siegel and Allan's (1985) induction procedure, the indirect ME induction procedure pairs compound stimuli with complementary colours. The indirect ME can be understood by explicit acknowledgment of the various elements of the induction stimuli (in addition to grid orientation) that are paired with colour. The horizontal green grid is a compound constructed of a horizontal grid ($GRID_h$), a black frame (FR_b) and a square

(SQ). During indirect ME induction this green $GRID_h$+FR_b+SQ compound alternates with a magenta FR_b+SQ compound.

Overshadowing may be important for understanding both the ME and the indirect ME. Overshadowing would result if grid orientation is more salient than other elements paired with colour during indirect ME induction. Following presentations of a green $GRID_h$+FR_b+SQ stimulus, subjects report horizontal grids appear pink; neither frame nor form elicit an aftereffect. This green stimulus alternates with a stimulus that has no grid -- a magenta FR_b+SQ stimulus. In this case, since no element of greater salience is present, black frame and square form come to elicit a colour aftereffect.

When assessed for the ME with the achromatic $GRID_h$+FR_b+SQ, $GRID_h$ elicits the colour aftereffect -- horizontal bars appear pink. Subjects are assessed for an indirect ME with an achromatic compound that includes a novel stimulus - the vertical grid ($GRID_v$). When assessed for an indirect ME with the achromatic $GRID_v$+FR_b+SQ, FR_b and SQ elicit the colour aftereffect; thus, this assessment stimulus appears green.

According to the associative view, the "indirect" ME is not indirect at all. Like the ME, the indirect ME is elicited "directly" by stimuli that have been effectively paired with colour during induction (the FR and SQ elements of the stimulus alternated with the coloured grid). This associative view of the indirect ME is tested in the experiments reported in the second part of this thesis (Eissenberg et al., submitted). That is, Eissenberg et al (submitted) demonstrate that GRID does in fact overshadow FR and SQ elements when these elements are compounded and paired with colour (Experiment 2) and that FR+SQ compounds do elicit an aftereffect (following an induction period where they have not been compounded with GRID; Experiments 2 and 3). Even more evidence in support of the associative analysis of the indirect ME comes from the fact that, when FR is not a reliable predictor of colour during induction, the magnitude of the indirect ME is reduced during assessment (Experiment 4). Indeed, noninduced grid stimuli are unnecessary in order to observe the effects of an indirect ME induction period. Subjects demonstrate two complementary aftereffects when they are assessed using only those compounds that were paired with colour during induction (e.g. GRID+FR+SQ and FR+SQ; Experiment 5). Further experiments test predictions made using the associative interpretation of the indirect ME with regard to aftereffects elicited by nonorthogonal grid stimuli (Experiments 6-8).

Taken together, the 11 experiments that make up this thesis support a conditioning interpretation of contingent colour aftereffects. Although much support for a conditioning account of the ME already exists (Siegel & Allan, 1992), that account is strengthened by reports of colour aftereffects contingent upon non-patterned stimuli, like frame lightness. Further support comes from the demonstration that, contrary to previous reports, correlational manipulations of CS and UCS (grid and colour, respectively) effect ME magnitude in a manner predicted by the conditioning analysis, so long as an experimental context (e.g. frame lightness) is provided. In contrast to the ME, the indirect ME posed a challenge to an associative account of contingent colour aftereffects, because a stimulus that did not predict colour during induction (the noninduced orthogonal grid) seemed to elicit a colour aftereffect during assessment. This challenge was met by an associative analysis of the indirect ME that describes indirect ME induction stimuli as stimulus compounds made up of distinct elements: either a coloured GRID+FR+SQ or a colured FR+SQ. When a GRID element is present, subjects associate that GRID element with colour, but in the absence of a GRID, subjects associate FR+SQ elements with colour. Demonstration of a frame lightness contingent colour aftereffect played a major role in this elemental analysis of indirect ME induction stimuli, as well as in testing predictions regarding noninduced orthogonal grid effects, and noninduced, nonorthogonal grid effects.

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The Associative Basis of Contingent Color Aftereffects

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According to a conditioning analysis of the orientation-contingent color aftereffect (McCollough effect, ME), orientation stimulus (grids) become associated with color. Contrary to this interpretation are reports that simple forms cannot be used to elicit illusory color and that the ME is not degraded by decreasing the grid-color correlation. The present results indicate: (a) Form stimuli can contingently elicit color aftereffects; (b) even a nonpatterned stimulus—the lightness of a frame surrounding a colored area—can contingently elicit color aftereffects; (c) this frame lightness-contingent aftereffect, like the ME, persists for at least 24 hr; and (d) the frame lightness-contingent aftereffect can be used to demonstrate that correlational manipulations affect the ME, as they affect other types of conditional responses.

Although the study of associations between two "neutral" events has a long history (e.g., Brogden, 1939), recently there has been renewed interest in this area (e.g., Rescorla & Durlach, 1981). In such studies, both events are sensory, and learning-researchers have developed special techniques to study the association between neutral events (Mackintosh, 1974, pp. 19–21; Rescorla, 1981; Rescorla & Durlach, 1981). The consequence of the pairing of sensory events is of interest not only to learning researchers, but also to perceptual researchers. Paired sensory events are central to a well-known perceptual phenomenon, the orientation-contingent color aftereffect.

The orientation-contingent color aftereffect has come to be called the *McCollough effect* (ME), after the investigator who first described the phenomenon (McCollough, 1965). The ME results from pairing grid orientation with color. For example, during an induction period the subject is presented with a grid constructed of black and green horizontal bars alternating with a grid of black and magenta vertical bars. Following such induction, complementary color aftereffects contingent on bar orientation are noted; black and white assessment grids appear colored. In this example, the white space between black horizontal bars appears pinkish, and the white space between black vertical bars appears greenish.

A number of investigators have suggested that the ME is a type of Pavlovian conditioning (e.g., Allan & Siegel, 1986; Brand, Holding, & Jones, 1987; Siegel & Allan, 1985). Generally, these investigators have adopted the conditioning analysis of the ME presented by Murch (1976):

> The lined grid in inspection functions as a conditioned stimulus (CS) while color functions as the unconditioned stimulus (UCS). As a result of the pairing of the CS (lined grid) with the UCS (color) a conditioned response (CR) develops so that the adaptive response of the visual system to the color is evoked by the lined grid. (p. 615)

This conditioning interpretation of the ME is supported by demonstrations that manipulations of the putative CS (grid) and UCS (color) have conditioninglike effects; thus, the ME, like Pavlovian conditioning, is subject to substantial retention, generalization, extinction, spontaneous recovery, "latent inhibition" by CS preexposure, overshadowing, blocking, and unblocking (see Allan & Siegel, 1986; Brand et al., 1987). There are, however, some findings that do not appear consistent with the conditioning interpretation of the ME (Skowbo, 1984, 1986). The experiments we report were designed to address two such findings: (a) Only a limited class of patterned stimuli, when paired with color, subsequently contingently elicit aftereffects, and (b) decreasing the correlation between grid and color does not degrade the ME.

Limited Class of Stimuli That Contingently Elicit Color Aftereffects

Several investigations have suggested that, on the basis of the conditioning interpretation of the ME, elicitation of illusory color should follow induction with virtually any patterned stimulus. For example, Foreit and Ambler (1978) reasoned that MEs should be demonstrable with form stimuli as well as orientation stimuli. They attempted to induce a contingent aftereffect by repeated presentations of a square constructed from magenta line segments and a cross constructed from green line segments. They reported, however, that their stimuli did not contingently elicit color aftereffects. Recent summaries of the ME literature have concluded that the aftereffect is not a Pavlovian conditioning phenomenon because, if it were, chromatic patterns of the sort used by Foreit and Ambler (1978) should be effective (see Skowbo, 1984); in contrast to this expectation, "MEs appear to be limited to a small class of rather special patterns" (Dodwell & Humphrey, 1990, p. 79).

Experiments 1–4 were designed to further examine stimuli that, when paired with color, can contingently elicit color aftereffects. In Experiment 1, stimuli very similar to those

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evaluated by Foreit and Ambler (1978) were used. In Experiment 2, different forms (triangles) were evaluated. In Experiments 3 and 4, we report a new contingent color aftereffect: illusory color contingent on the lightness (black or white) of a border (or *frame*) that, during induction, surrounds a chromatic area.

Correlation Between Grid and Color

As first discussed by Skowbo and Forster (1983), if the ME represents an instance of Pavlovian conditioning, correlational manipulations should affect the perceptual illusion much as they affect other CRs. Generally, decreasing the correlation[1] between a CS and UCS decreases the strength of conditioning. Such a decrease in correlation typically is effected by UCS presentations interpolated between paired CS–UCS presentations (see Rescorla & Wagner, 1972). On the basis of a conditioning analysis of the ME, then, presentation of the putative UCS (homogeneous chromatic stimuli) between presentations of the putative CS (chromatic grids) should degrade the perceptual illusion. Skowbo and Forster (1983) reported that this manipulation did not influence the magnitude of the ME and suggested that their results were contrary to an associative account of the phenomenon.

Skowbo and Forster's (1983) results were subsequently replicated by Siegel and Allan (1987). Siegel and Allan (1987) suggested that the ME, although immune to degradation by decreasing the temporal correlation between grid and color (by presenting homogeneous chromatic stimuli between presentations of chromatic grids), may be degraded by decreasing the spatial correlation between these stimuli (by extending the color beyond the confines of the grid). They were wrong. The spatial correlation manipulation, like the temporal correlation manipulation, did not decrease the illusion (Siegel, Allan, Roberts, & Eissenberg, 1990). Experiment 5 used the new contingent color aftereffect described in Experiments 3 and 4 to provide further evidence concerning the contribution of grid-color correlation to the ME.

Experiments 1A and 1B

The purpose of Experiment 1 was to further evaluate the claim that chromatic stimuli of the sort used by Foreit and Ambler (1978) are ineffective in eliciting contingent color aftereffects. The induction stimuli were forms constructed of line segments. One form was a square and the other was a cross constructed by rearranging the four line segments that formed the square. A different cross stimulus was used in Experiments 1A and 1B.

Although the induction stimuli were similar to those used by Foreit and Ambler (1978), the assessment procedure was different. Foreit and Ambler (1978) evaluated the aftereffect by asking subjects to match the illusory color to Munsell chips. We used a variant of the method of constant stimuli, which we have demonstrated to be an effective procedure for the measurement of contingent color aftereffects (Allan, Siegel, Collins, & MacQueen, 1989; Allan, Siegel, Toppan, & Lockhead, 1991; Siegel et al., 1990).

Method

Subjects

Adults from the McMaster University community with no previous experience in contingent aftereffect tasks were each paid \$5.00 for their participation in the experiment. Twelve subjects participated in Experiment 1A, and 9 participated in Experiment 1B. They participated individually, with the experimenter present in the room throughout the session.

Aftereffect Induction

The induction stimuli were colored (magenta or green) geometric forms (squares or crosses) presented on a black background in the center of a 27.5 cm × 20.3 cm (width × height) monitor screen. Each form consisted of four line segments. The dimensions of each segment were 7.5 cm × 0.5 cm (length × width), subtending approximately 6.1° × 0.4° visual angle.

The stimuli used in Experiments 1A and 1B are shown in Figure 1. In both experiments, one of the induction forms was a square (Figure 1A). The two experiments differed in the shape of the cross used as the second induction form. In Experiment 1A, the line segments were rearranged to form a simple Greek cross (see Figure 1B) of the sort used by Foreit and Ambler (1978).

Although the square and the cross used in Experiment 1A (and by Foreit and Ambler, 1978) occupy the same proportion of the screen, they vary in size; the horizontal and vertical extent of the cross was twice that of the square. Because MacKay and MacKay (1975) have shown that a color aftereffect can be contingent on size, a different cross was used in Experiment 1B. The four line segments were arranged to form a tick-tack-toe cross (see Figure 1C). The cross was constructed from the square by moving each side 3 cm toward the middle. In Experiment 1B, both the proportion of the screen occupied by the segments and the extent of the two forms were the same.

In Experiment 1A, the square was magenta and the cross was green for 5 subjects; for the remaining 7 subjects, the square was green and the cross was magenta. In Experiment 1B, the square was magenta and the cross was green for all 9 subjects.

The induction period lasted about 20 min. The two colored forms alternated every 3 s for a total of 200 presentations of each form. Background music was presented during induction for Experiment 1A.

Aftereffect Measurement

Illusory color was measured both before and after the induction phase of the experiment (preinduction and postinduction assessment, respectively). There was a 2-min period, in normal room illumination, between aftereffect induction and postinduction assessment of illusory color to minimize the influence of simple afterimages.

For both assessments, there were 50 presentations of the square and 50 presentations of the cross. On each presentation, the form 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), o

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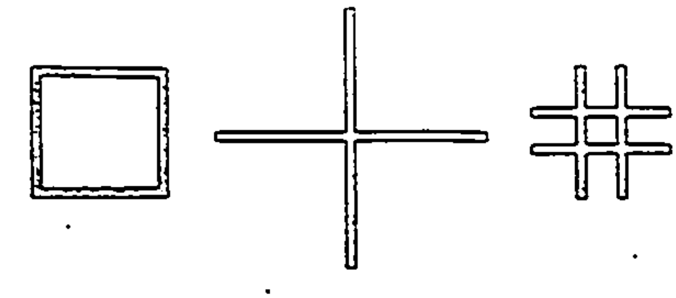
[1] In the learning literature, CS–UCS correlation is often referred to as CS–UCS *contingency*. In these experiments we use the term *correlation* to refer to the statistical relationship between the CS and UCS, so as not to confuse this relationship with the contingent color aftereffect.



A B C

Figure 1. Stimuli used in Experiment 1. (Experiment 1A used the square [panel A] and Greek cross [panel B]. Experiment 1B used the square [panel A] and tick-tack-toe cross [panel C].)

achromatic (0). Form (square or cross) and color (P1, P2, G1, G2, and 0) were randomly ordered, with the restriction that each form was presented in each color 10 times. On each of the 100 presentations, the subject had to make a binary response, "green" or "pink." The form remained on the screen until the subject responded. In Experiment 1A, after the subject responded the screen was black for 1 s and then the next assessment stimulus was presented. For Experiment 1B, there was no black period between presentations of the assessment stimuli.

In Experiment 1A, subjects were familiarized with the color judgment task prior to the start of the experiment. Before preinduction aftereffect assessment, subjects received 16 practice trials. For each practice trial, either a square or a cross was presented, and the form was one of the four unsaturated colors (G1, G2, P1, or P2). Each of the eight form–color 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 "pink" response, the correct color of the grid (the word *green* or *pink*) appeared on the computer monitor. These practice data were ignored. There were no practice trials in Experiment 1B.

Apparatus

Temporal parameters, stimulus presentation, and recording of responses were controlled by a Tandy 3000 computer, equipped with a video graphics adaptor (VGA) display card. The stimuli were displayed on a Zenith flat screen monitor (Model 1490) located about 70 cm from the subject. 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 = 63), 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. The RGB and illuminance values for all the chromatic stimuli used in Experiments 1A and 1B have been reported elsewhere (Allan et al., 1991).

Results

The psychometric function relating the probability of the subject reporting that the grid appeared green, P(G), to the physical characteristics of the assessment stimulus (ranging from P2 to G2) was determined. Figure 2A displays the preinduction and postinduction functions for each configuration for Experiment 1A. For simplicity in presentation, the functions were collapsed across form–color pairing; the magenta functions represent the assessment data for the form induced in magenta, and the green functions represent the assessment data for the form induced in green. Figure 2B displays the pre- and postinduction psychometric functions obtained in Experiment 1B.

As can be seen in Figure 2, the preinduction functions, obtained prior to exposure to chromatic induction stimuli, were similar for both configurations of the four line segments. The preinduction functions span the full range from 0 to 1.00, indicating that subjects were sensitive to the physical differences used. These functions moved apart after induction. Relative to preinduction, the form that was magenta in induction was more likely to elicit a "green" response in postinduction, and the form that was green in induction was less likely to elicit a green response.

For purposes of statistical analysis, the difference between the mean number of green responses to the two forms, over the five assessment colors, was determined for both preinduction and postinduction measurements for each subject. In preinduction, this measure of illusory color should approach zero. A contingent aftereffect would result in a positive illu-

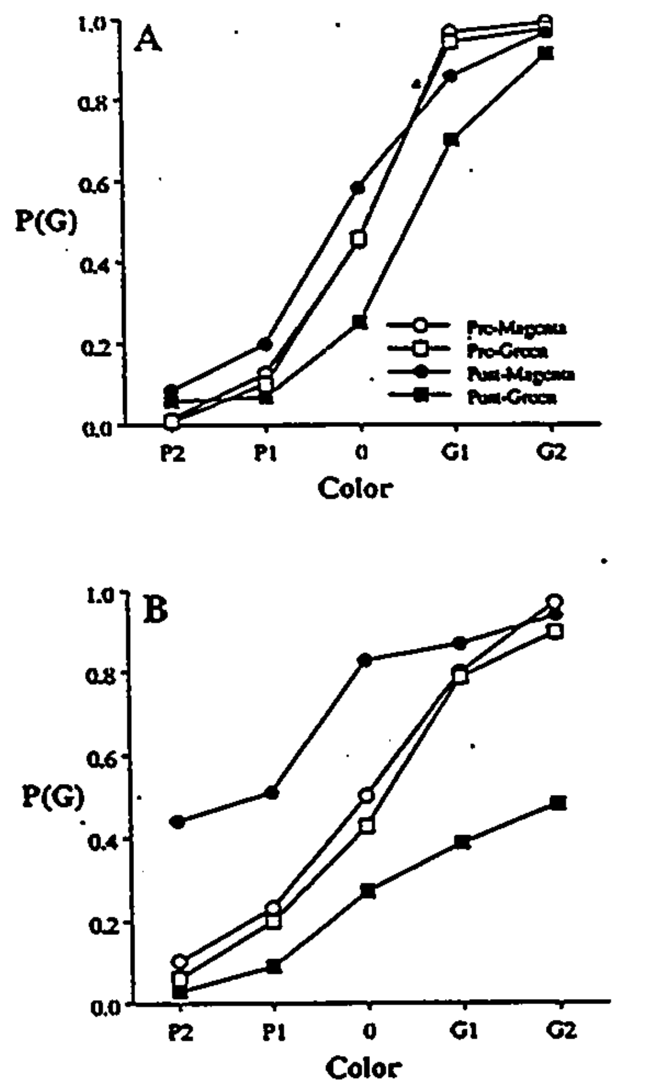


Figure 2. Pre- and postinduction psychometric functions obtained in Experiment 1A (Panel A) and Experiment 1B (panel B). (P = pink G = green.)

sory color measurement on the postinduction assessment; that is, more "green" responses to the magenta induction form than to the green induction form. For each subject, a *contingent aftereffect score* was computed—the difference between postinduction and preinduction measures of illusory color. The presence of an aftereffect is indicated by a positive contingent aftereffect score. The magnitude of the aftereffect is indicated by the size of this score.

To illustrate the computation of the aftereffect score, consider a subject induced with a magenta square and green cross. Before induction, it would be expected that the subject would judge about half of the 10 presentations of the square and of the cross over each of the five assessment colors as being green. For example, the square and cross might elicit means of 6 and 5 "green" responses, respectively. The illusory color score is computed by subtracting the mean number of "green" responses made to the green induction stimulus (the cross) from the mean number of "green" responses made to the magenta induction stimulus (the square). In this example, the preinduction score is 1. If induction is effective in inducing an aftereffect, during postinduction assessment this subject would judge the square as being more green (e.g., the square assessment stimuli might elicit a mean of eight "green" responses) and the cross as being less green (e.g., the cross assessment stimuli might elicit a mean of 3 "green" responses). The postinduction illusory color score is 5. The aftereffect score (the change in illusory color score from pre- to postinduction) for this subject is 4.

Of the 12 subjects in Experiment 1A, 11 displayed a contingent aftereffect (i.e., they had positive contingent aftereffect scores, $p < .003$, one-tailed binomial test). Of the 9 subjects in Experiment 1B, 8 displayed a contingent aftereffect ($p < .02$).

Discussion

In Experiment 1A, we demonstrated a contingent color aftereffect with forms similar to those used by Foreit and Ambler (1978). In Experiment 1B, we further demonstrated such a form-contingent aftereffect using forms that were the same with respect to horizontal and vertical extent. Foreit and Ambler (1978) concluded, "the McCollough effect is sensitive to line orientation but not to form (line configurations)" (p. 301). The results of Experiments 1A and 1B are in marked contrast to their conclusion. It could be that the color-matching procedure used by Foreit and Ambler was not sensitive enough to demonstrate the aftereffect.

The Foreit and Ambler (1978) findings have been interpreted, by Foreit and Ambler and by others (Skowbo, 1984), as evidence contrary to a conditioning interpretation of the ME. The present report that such stimuli can contingently elicit aftereffects thus provides evidence supporting a conditioning analysis of the ME.

The purpose of the next experiment was to further evaluate the effectiveness of different forms as contingent elicitors of illusory colors. Rather than forms based on those described by Foreit and Ambler (1978), two novel forms were arbitrarily selected—an upright and an inverted triangle.

Experiment 2

Each of the chromatic stimuli used in Experiment 2 were constructed from three line segments, positioned so as to form an isosceles triangle. During aftereffect induction, these triangles were alternately upright (base on bottom) and inverted (base on top). The line segments that formed the triangle were green when the triangle pointed in one direction and magenta when it pointed in the other direction.

Method

Subjects, Apparatus, and Stimuli

The subjects were 9 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. Four subjects received induction with a green upright triangle and a magenta inverted triangle. The remaining 5 subjects received induction with a magenta upright triangle and a green inverted triangle.

Temporal parameters, stimulus presentation, and recording of responses were controlled by a Macintosh IIcx computer equipped with an 8-bit video display card. This system enabled 65,536 gradations of saturation of each hue (ranging from 0 to 65,535), in contrast to the 64 gradations in the previous experiments. The triangles were displayed in the middle of a 23.5 cm × 17.5 cm Apple color monitor (Model M0401PA), located about 70 cm from the subject. The line segments that formed the sides of the triangle were 8 cm long × 0.8 cm thick. The line segment that formed the base of the triangle was 12 cm long × 0.5 cm thick. The entire triangle subtended approximately 9.8° × 4.9° of visual angle.

For the green induction triangle, R = B = 0 and G = 65,535; for the magenta induction triangle, R = B = 65,535 and G = 0. The illuminance values for the green and magenta triangles were 45 and 20 lux, respectively. The RGB values for the assessment triangles are shown in Table 1. The illuminance values for these various pale assessment stimuli ranged from 52 to 58 lux.

Procedure

Aftereffect induction. The induction period lasted 20 min. The two colored triangles alternated every 2 s for a total of 300 presenta-

Table 1
Red, Green, and Blue Values for Assessment Stimuli

Color	Assessment stimulus: P2	P1	0	G1	G2
	Experiments 2 & 3				
Red	65,535	65,535	65,535	62,965	61,166
Green	61,166	62,965	65,535	65,535	65,535
Blue	61,166	62,965	65,535	62,965	61,166
	Experiment 4				
Red	65,535	65,535	65,535	65,021	64,507
Green	64,507	65,021	65,535	65,535	65,535
Blue	64,507	65,021	65,535	65,021	64,507

Note. P2 and P1 are two shades of pale pink, P2 being more saturated than P1. G1 and G2 are two shades of pale green, G2 being more saturated than G1. 0 is achromatic. The red, green, and blue values are those displayed in the color picker dialog box of the Macintosh IIcx computer.

tions each. Depending on group assignment, the triangle constructed of green segments was upright and the triangle constructed of magenta segments was inverted, or vice versa.

Aftereffect measurement. The triangle direction-contingent aftereffect was evaluated with the method of constant stimuli described in Experiment 1. Both before and after induction, subjects received 50 presentations of an upright triangle and 50 presentations of an inverted triangle. For each assessment presentation, the line segments used to form the triangle were P2, P1, 0, G1, or G2, and the subject had to judge the triangle as either pink or green. Each triangle remained on the screen until the subject responded. After a response the screen was black for 1 s, and then the next assessment stimulus was presented.

As was the case in Experiment 1A, subjects were familiarized with the color judgment task prior to the start of the experiment. They were presented with 16 practice trials; each of the eight combinations of triangle direction (upright or inverted) and triangle colors (P1, P2, G1, and G2) was presented twice. In this experiment, subjects were informed that their response was "correct" or was an "error" via the speech synthesis capability of the computer. These practice data were ignored.

Results

Figure 3 displays the mean pre- and postinduction psychometric functions obtained in this experiment. For simplicity in presentation, the functions are collapsed across the two, counterbalanced groups; the magenta functions represent the assessment data for the triangle orientation (upright or inverted) that was magenta during induction, and the green functions represent the assessment data for the triangle orientation that was green during induction.

As is apparent in Figure 3, the preinduction functions were similar. These functions moved apart after induction. Relative to preinduction, the triangle direction that was magenta in induction was more likely to elicit a "green" response in postinduction, and the triangle direction that was green in induction was less likely to elicit a "green" response. A contingent aftereffect score was computed for each subject as described in Experiment 1. Eight of the 9 subjects in this experiment displayed a triangle direction-contingent color aftereffect ($p < .02$).

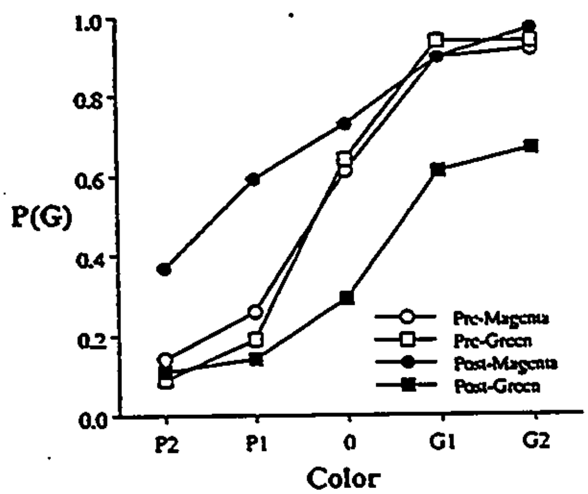


Figure 3. Pre- and postinduction psychometric functions obtained in Experiment 2. (P = pink; G = green.)

Discussion

The results of Experiment 2 are similar to those of Experiments 1A and 1B. Arbitrarily selected forms can be used to contingently elicit color aftereffects. The results of Experiments 1 and 2 should be added to other demonstrations of color aftereffects contingent on dimensions other than orientation; for example, spatial frequency (Breitmeyer & Cooper, 1972; Leppmann, 1973; Lovegrove & Over, 1972), movement direction (Hepler, 1968; Mayhew & Anstis, 1972; Stromeyer & Mansfield, 1970), and dot size (MacKay & MacKay, 1975). Although the existence of such ME "cousins" (Meyer, Jackson, & Yang, 1979) might be interpreted as evidence for a conditioning interpretation of contingent color aftereffects (Allan & Siegel, 1986), ME cousins have also been interpreted in ways that do not acknowledge any contribution of learning (see Harris, 1980).

The original report that color aftereffects cannot be contingently elicited by forms constructed of the same components was seen as clear evidence contrary to a conditioning interpretation of the phenomenon (Foreit & Ambler, 1978). The present results indicating that such forms can contingently elicit color aftereffects would thus appear to provide evidence for a conditioning interpretation. It is possible, however, that the creative skeptic might construct some nonassociative account of the contingent color aftereffect that, although lacking in parsimony, might nevertheless incorporate the results of Experiments 1 and 2 in a nonassociative manner (see Harris, 1980).

Experiment 3

The various form stimuli used in Experiments 1 and 2, and the other stimuli that have been reported to support the illusion, are patterns. In Experiment 3 we report a new contingent color aftereffect. During induction of this new aftereffect, complementary colors are paired with a nonpatterned feature of the induction stimulus—the lightness of a frame surrounding the colored area.

Method

Design

During aftereffect induction, approximately half the subjects received alternating presentations of a magenta "picture" (a square stimulus in the middle of the computer monitor) surrounded by a black "frame" and a green picture surrounded by a white frame (BlkFr-Mg/WtFr-Gn). For the remaining subjects, the relationship between frame lightness and picture color was reversed (WtFr-Mg/BlkFr-Gn). Aftereffect measurement was based on preinduction and postinduction judgments of the color of assessment pictures surrounded by black and by white frames. All assessment pictures, regardless of color (P2, P1, 0, G1, or G2) or frame lightness (black or white), were superimposed with a horizontal grid. Assessment pictures contained horizontal grids so that the area of color to be judged would be similar to that in Experiment 2, as well as in our prior experiments with this computer system (e.g., Allan & Siegel, 1991; Siegel et al., 1990). This enabled use of the assessment palette (i.e., the values of P2, P1, 0, G1, and G2) that previously had been demonstrated to be appropriate for generating psychometric functions. If subjects had to judge the color of the entire picture, rather than the space between the black horizontal bars, these saturation values would be too great (see Dunlap, Morriss, Fritchie, Linnett, & Curran, 1990; and Experiment 4 of this article).

During induction, frame lightness—not grid orientation—was associated with color. Nevertheless, because the assessment pictures contained horizontal grids, it was considered potentially important to have the colored induction pictures contain grids so as to maximize similarity between induction and assessment stimuli. Various groups differed with respect to the grids superimposed on the induction pictures. For some subjects the picture used in induction contained a grid that was always the same orientation as that used during assessment; all pictures consisted of alternating chromatic and black horizontal bars (yielding two groups, Groups H:BlkFr-Mg/WtFr-Gn and H:WtFr-Mg/BlkFr-Gn). For other subjects the grid orientation was randomly determined for each induction stimulus presentation; the grid was horizontal or vertical (Groups R:BlkFr-Mg/WtFr-Gn and R:WtFr-Mg/BlkFr-Gn) equally often. For the remaining subjects, no grid was presented in conjunction with the picture during induction; the picture was a homogeneous square (Groups N:BlkFr-Mg/WtFr-Gn and N:WtFr-Mg/BlkFr-Gn).

In summary, subjects were randomly assigned to groups in accordance with a 3 × 2 factorial design: three levels of grid orientation during induction (H, R, or N) and two levels of frame lightness–picture color relationship during induction (BlkFr-Mg/WtFr-Gn and WtFr-Mg/BlkFr-Gn). For all subjects, the aftereffects elicited by both black and white frames were assessed on a horizontal-grid picture.

Subjects

The subjects were from the same population as that used in Experiment 1. Eleven subjects were assigned to each of Groups H:BlkFr-Mg/WtFr-Gn and N:BlkFr-Mg/WtFr-Gn. Ten subjects were assigned to each of Groups R:BlkFr-Mg/WtFr-Gn, N:WtFr-Mg/BlkFr-Gn, and R:WtFr-Mg/BlkFr-Gn. Eight subjects were assigned to Group H:WtFr-Mg/BlkFr-Gn.

Apparatus and Stimuli

Temporal parameters, stimulus presentation, and recording of responses were controlled with the Macintosh IIcx computer system used in Experiment 2. The pictures were 5.8 cm² (subtending about 4.8° visual angle). The picture was centered on the 23.3 cm × 17.5 cm monitor screen, with the rest of the screen constituting the frame. The picture was surrounded by a thin black outline (1 pixel wide). With this outline, the separation between the picture and the white frame was clear during aftereffect assessment, when the subject had to name the color of very pale or achromatic pictures. If the picture contained a grid, the grid was composed of 20 bars (10 black bars alternating with 10 colored bars).

Procedure

Aftereffect induction. All subjects received alternate presentations of white-framed and black-framed pictures. Each stimulus was presented 376 times, and the duration of each presentation was 2 s; thus the induction phase of the experiment required about 25 min. The picture in the black frame was either magenta (for subjects assigned to BlkFr-Mg/WtFr-Gn groups) or green (for subjects assigned to WtFr-Mg/BlkFr-Gn groups). The alternative color was used for the picture in the white frame.

Aftereffect measurement. The frame lightness-contingent aftereffect was evaluated with the method of constant stimuli described earlier. Both before and after aftereffect induction, subjects received 50 presentations of a black-framed picture and 50 presentations of a white-framed picture. For all six groups, assessment pictures always had the same horizontal bar pattern as that used during induction for H groups. For each assessment presentation, the space between the black bars was P2, P1, 0, G1, or G2, and the subject had to judge the picture as either pink or green. The RGB and illuminance values for these assessment hues were the same as those used in Experiment 2. Each stimulus remained on the screen until the subject responded, and 1 s later the next assessment stimulus was presented. During this 1-s period, the entire monitor screen was the same lightness (white or black) as the frame of the last assessment figure.

As was the case in Experiments 1A and 2, subjects were familiarized with the color judgment task prior to the start of the experiment. They were presented with 16 practice trials; each of the eight combinations of frame lightness (black or white) and picture colors (P1, P2, G1, and G2) was presented twice. As in Experiment 2, subjects were informed that their response was correct or was an error via the speech synthesis capability of the computer. These practice data were ignored.

Results

Preinduction Assessment

Figure 4 displays the mean preinduction psychometric functions obtained from each of the six groups when assessed with the black frame (Figure 4A) and the white frame (Figure 4B). As would be expected, these functions, obtained prior to differential treatment, are similar for the six groups. However, as is apparent in Figure 4, frame lightness affected the functions. Assessment stimuli were seen as being greener when evaluated with the white frame than when evaluated with the black frame.[2]

For purposes of statistical analysis, the difference between the mean number of "green" responses to the picture in the black frame and to the picture in the white frame (over the five assessment colors) was determined. A 3 × 2 × 2 mixed design analysis of variance (ANOVA) was performed on the preinduction values, with induction grid orientation (H, R, and N) and frame lightness–picture color relationship (BlkFr-Mg/WtFr-Gn and WtFr-Mg/BlkFr-Gn) as the between-subject factors and frame lightness in assessment (black and white) as the within-subject factor. Only the main effect of

[2] The reason why frame lightness affects judged picture color is unclear. One possibility is simultaneous brightness contrast. It would be expected that such contrast would cause the picture within the black frame to be seen as lighter than the picture within the white frame. During assessment, the spaces between the black horizontal bars of the picture are either white or very pale colors. The response options offered to the subject are "pink" and "green." *Pink* connotes a pale stimulus (as well as one of a certain color) more than does *green*. Thus, subjects may be biased toward identifying the subjectively lighter stimulus (in the black frame) as pinker than the subjectively darker stimulus (in the white frame).

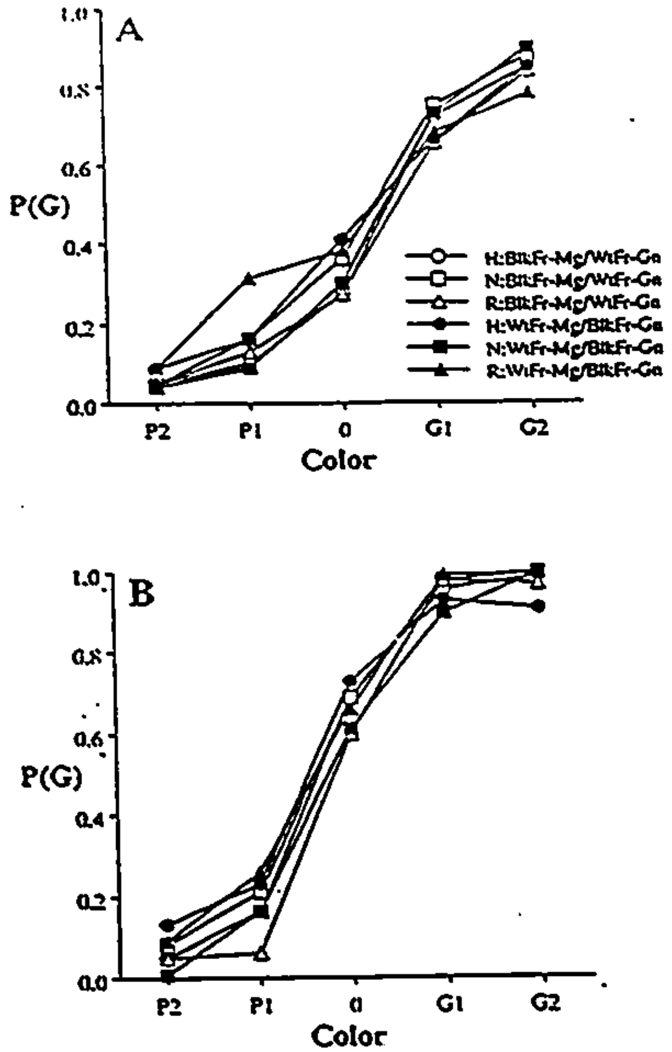


Figure 4. Preinduction psychometric functions obtained from each group in Experiment 3 when assessed with the black frame (panel A) and the white frame (panel B). (P = pink; G = green; H = horizontal grid; N = no grid; R = random horizontal and vertical grids; BlkFr = black frame; WtFr = white frame; Gn = green; Mg = magenta.)

frame lightness in assessment was significant, $F(1, 54) = 32.91$, $p < .001$, confirming the pattern seen in Figure 4. As discussed elsewhere (Allan et al., 1989), such information about bias in responding during preassessment is not usually available in contingent color aftereffect studies.

Frame Lightness-Contingent Aftereffect

Figure 5 depicts the mean pre- and postinduction psychometric functions obtained during assessment with black and white frames in the BlkFr-Mg/WtFr-Gn (Figure 5A and 5B) and WtFr-Mg/BlkFr-Gn (Figure 5C and 5D) groups. For simplicity in presentation, the functions presented in Figure 5 were collapsed across the dimension of induction-grid orientation (H, R, and N), as similar results were obtained in all three groups for both frame lightness–picture color relationships.

As can be seen in Figure 5, after BlkFr-Mg/WtFr-Gn induction, psychometric functions shifted in the direction of a frame lightness-contingent color aftereffect. After induction, pictures seen in the black frame appeared greener (Figure 5A), and pictures seen in the white frame appeared pinker (Figure 5B), than they did before induction. As can also be seen in Figure 5, there was a similar (although smaller) frame lightness-contingent color aftereffect following WtFr-Mg/BlkFr-Gn induction. For these subjects, pictures seen in the black frame appeared pinker (Figure 5C), and pictures seen in the white frame appeared greener (Figure 5D), than they did before induction.

As expected, the contingent aftereffects were greater in situations in which there is more psychometric space to demonstrate a shift between the pre- and postinduction functions. That is, bigger aftereffects were seen following BlkFr-Mg/WtFr-Gn induction than following WtFr-Mg/BlkFr-Gn induction (because of the bias in the preinduction functions; see Figure 4).

A contingent aftereffect score was computed for each subject as described earlier. Of the 32 subjects assigned to BlkFr-Mg/WtFr-Gn groups, 29 (90.6%) demonstrated a frame lightness-contingent color aftereffect ($p < .001$). Of the 28 subjects assigned to WtFr-Mg/BlkFr-Gn groups, 23 (82.1%) displayed the contingent color aftereffect ($p < .001$).

The mean aftereffect scores obtained in all six groups in this experiment are shown in Figure 6. A 3 × 2 ANOVA was performed on these aftereffect scores, with induction grid orientation (H, R, and N) and frame lightness–picture color relationship (BlkFr-Mg/WtFr-Gn and WtFr-Mg/BlkFr-Gn) as between-subject factors. Only the main effect of frame lightness–picture color relationship was significant, $F(1, 54) = 8.39$, $p < .006$. Subjects in the BlkFr-Mg/WtFr-Gn groups showed a significantly greater aftereffect than subjects in the WtFr-Mg/BlkFr-Gn groups. Grid orientation during induction, however, did not affect the size of the aftereffect.

Discussion

The feature that contingently elicited the illusory color in this experiment, frame lightness, does not have the characteristics of a pattern (like grid orientation) or a form (like the cross and square arrangements used in Experiment 1 or the triangle direction in Experiment 2). It would seem that, as expected on the basis of a conditioning analysis of contingent color aftereffects, a considerable variety of stimuli (other than orientation) are effective.

Experiment 4

Results of the previous experiment demonstrated a new contingent color aftereffect. Although this aftereffect was not contingent on the pattern of the stimulus associated with the color during induction, the aftereffect was assessed on a patterned stimulus. That is, all assessment stimuli consisted of horizontal-grid pictures. One purpose of Experiment 4 was to determine if the frame lightness-contingent aftereffect requires a grid pattern during assessment. In this experiment, during both aftereffect induction and assessment phases, the picture portion of the display consisted of a homogeneous square.

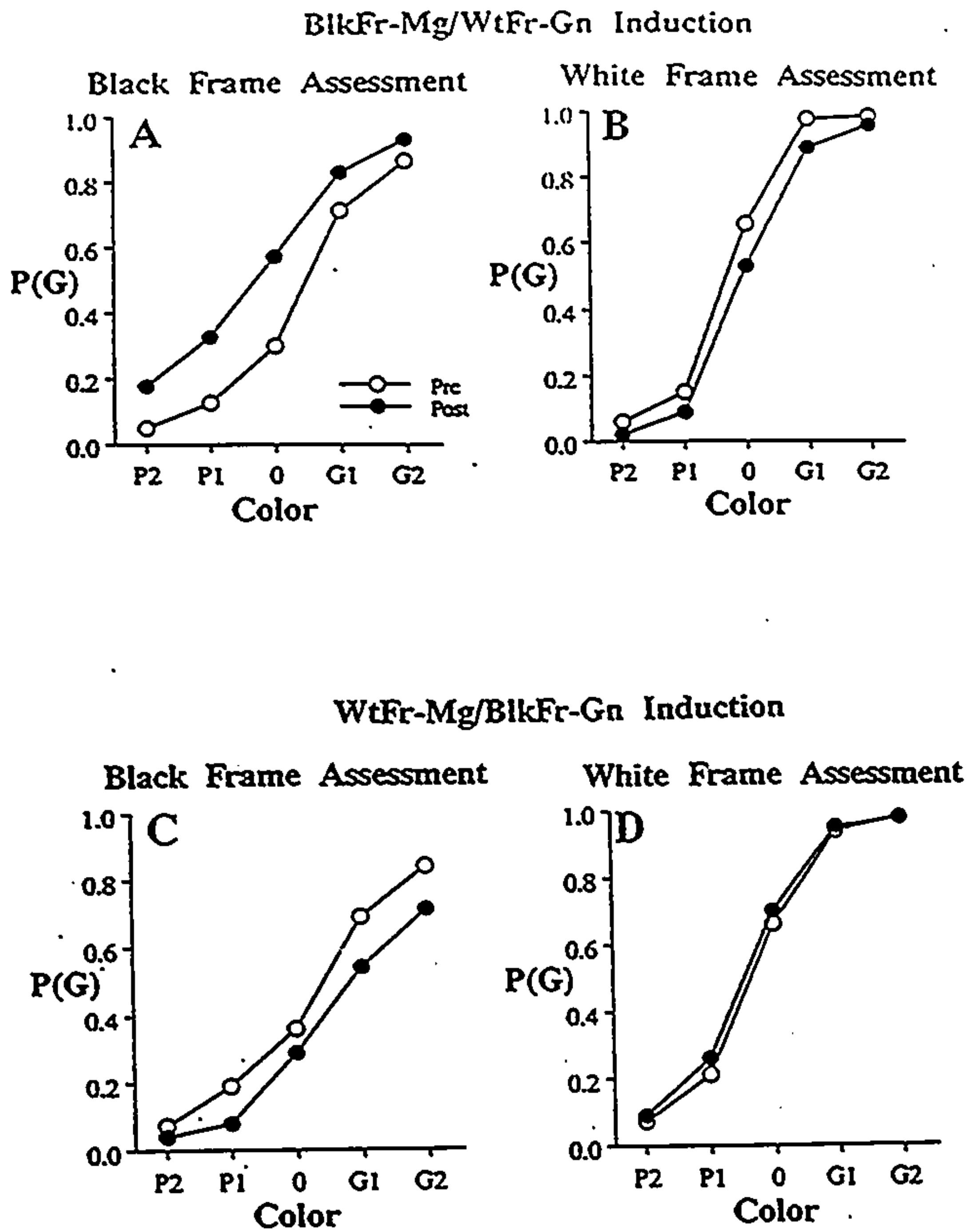


Figure 5. Pre- and postinduction psychometric functions obtained in Experiment 3 when subjects were assessed with black and white frames in BlkFr-Mg/WtFr-Gn (panels A and B) and WtFr-Mg/BlkFr-Gn (panels C and D) groups. (The functions are collapsed across the dimension of grid orientation. P = pink; G = green; BlkFr = black frame; WtFr = white frame; Mg = magenta; Gn = green.)

Another purpose of Experiment 4 was to evaluate retention of the lightness-contingent color aftereffect. One dramatic characteristic of the orientation-contingent aftereffect is its longevity. There are reports that the ME lasts for minutes, days, and even longer (e.g., Jones & Holding, 1975). This longevity has been interpreted as evidence for the conditioning interpretation of the ME (e.g., Allan & Siegel, 1986; Murch, 1976).

Method

Aftereffect induction was similar to that presented to BlkFr-Mg/WtFr-Gn subjects in Experiment 3. However, unlike Experiment 3, the pictures used both in induction and assessment contained no bars—they were simply homogeneous squares.

Thirty-five subjects (introductory psychology students who had never participated in contingent aftereffect research) were divided into three groups. Group 0-hr subjects ($n = 9$) were treated as th

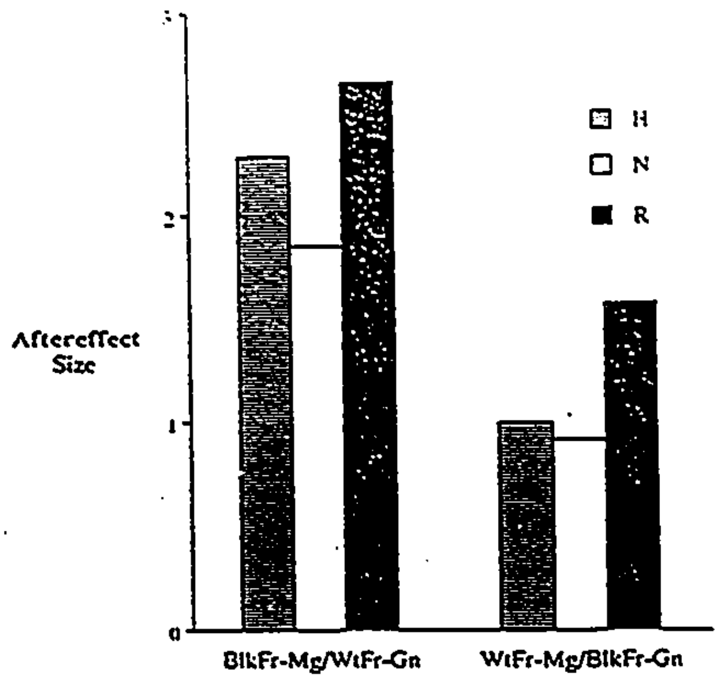


Figure 6. Mean aftereffect scores of all groups in Experiment 3. (H = horizontal grid; N = no grid; R = random horizontal and vertical grids; BlkFr = black frame; WtFr = white frame; Mg = magenta; Gn = green.)

subjects in the prior experiments, in that postinduction assessment occurred immediately after induction (after the 2-min period in the light). For Group 1-hr subjects ($n = 16$), postinduction assessment occurred 1 hr after the end of induction. For Group 24-hr subjects ($n = 10$), postinduction assessment occurred 24 hr after the end of induction.

During assessment, subjects had to judge the color of a larger area in the present experiment than in the previous experiment (i.e., they had to indicate whether the entire picture, rather than the spaces between the black bars in the picture, was pink or green). As discussed in Experiment 3, the color discrimination was easier for the relatively large assessment area of the present experiment (the entire, homogeneous picture), compared to the smaller area judged in the previous experiment (the spaces between horizontal black bars). The assessment colors used in the previous experiment would be too discriminable to permit observation of psychometric function shifts indicative of color aftereffects. Thus, in the present experiment the saturation of these assessment colors was decreased from the levels used in the previous experiment. The RGB values are shown in Table 1 (illuminance levels were similar to those reported in Experiment 2). In unspecified details, the procedure of this experiment was the same as that used in Experiment 3.

Results

The treatment of subjects in the 0-hr group in this experiment was similar to that of subjects in the BlkFr-Mg/WtFr-Gn groups of the previous experiment. Figure 7 summarizes the pre- and postinduction psychometric functions obtained in this group when assessed with the black (Figure 7A) and white (Figure 7B) frames.

The assessment palette used in the present experiment was different from the palette used in the prior experiment, thus complicating interexperiment comparisons. However, examination of Figure 7 indicates that frame lightness affected color judgment in this experiment as it did in the prior experiment. That is, there is an overall bias for black-framed pictures to be judged as pink more often than white-framed pictures. With the assessment palette used in the present experiment, frame lightness clearly affected color discriminability. The flatter slope of the psychometric functions seen with black-framed pictures (Figure 7A) than with white-framed pictures (Figure 7B) indicates that the colors were less discriminable in the black frame than in the white frame. With both black and white frames, however, the postinduction functions shifted in the direction of a frame lightness-contingent aftereffect. The black frame (which contained a magenta picture during induction) elicited a green aftereffect, and the white frame (which contained a green picture during induction) elicited a pink aftereffect.

Figure 8 displays the mean aftereffect scores for all three delay groups. As indicated in Figure 8, the magnitude of the

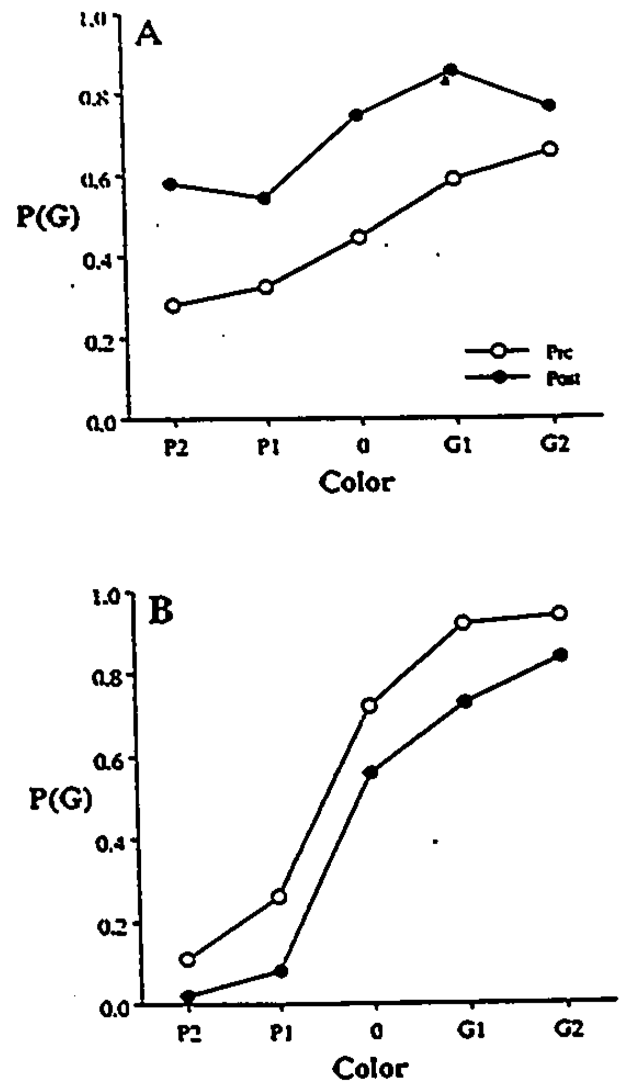


Figure 7. Pre- and postinduction psychometric functions obtained from subjects in the 0-hr group in Experiment 4 when assessed with the black (panel A) and white (panel B) frames. (P = pink; G = green.)

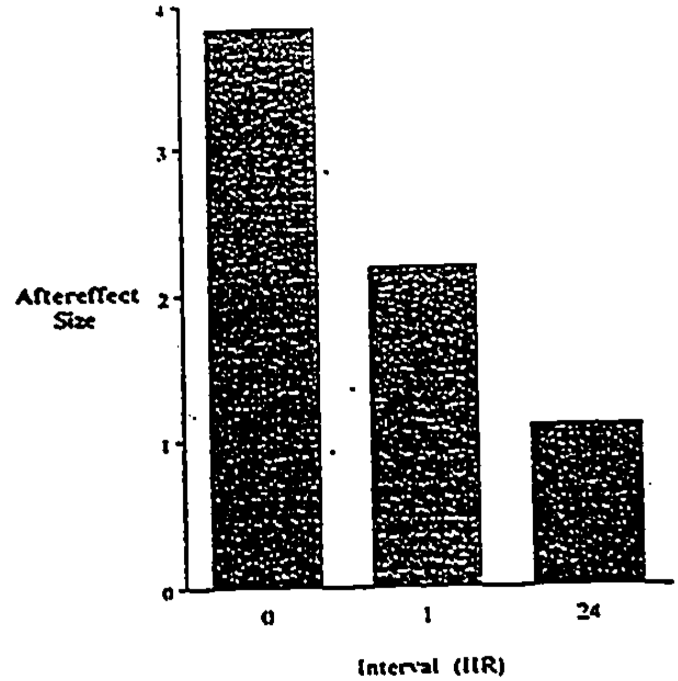


Figure 8. Mean aftereffect scores for groups in Experiment 4.

aftereffect decreased with increasing delays between induction and postinduction assessment. The data summarized in Figure 8 were analyzed with the method of contrasts using the maximum solution for an ordinal hypothesis (Abelson & Tukey, 1963). There was a significant decrease in the size of the aftereffect as the interval between induction and postinduction assessment increased, $F(1, 32) = 6.11, p < .02$.

Contingent color aftereffects were displayed by all 9 subjects in the 0-hr group (100%, $p < .002$), by 13 of the 16 subjects in the 1-hr group (81.2%, $p < .008$), and by 7 of the 10 subjects in the 24-hr group (70%, $p > .05$). Although the proportion of subjects in the 24-hr group that displayed the aftereffect did not differ significantly from chance, the aftereffect was nevertheless detectable at even this longest retention interval. A t test indicated that the mean aftereffect score of subjects in this group was significantly greater than zero, $t(9) = 2.02, p < .05$.

Discussion

Results of Experiment 4 are consistent with the results of Experiment 3 and further demonstrate that the lightness of a frame can contingently elicit a color aftereffect. In the prior experiment, this aftereffect was demonstrated on an assessment picture that contained horizontal bars. The present results indicate that such bars are not necessary to demonstrate the aftereffect. These results also indicate that this new aftereffect is still detectable at least 24 hr after induction. Thus, the frame lightness-contingent color aftereffect, in common with contingent aftereffects induced with patterned chromatic stimuli, displays substantial retention.

Experiment 5

The ME is seen when orientation stimuli, previously paired with color, elicit illusory color. The results of Experiments 1–4 illustrate that color aftereffects may also be seen with nonorientation stimuli. The fact that such arbitrary components of a chromatic display may subsequently contingently elicit color aftereffects supports a Pavlovian conditioning analysis of such aftereffects.

Based on a conditioning analysis, the ME, like other CRs, should be attenuated by decreasing the correlation between the conditioning stimuli. Thus, presentation of homogenous chromatic stimuli between chromatic grid presentations should decrease the magnitude of the aftereffect. In experiments specifically designed to evaluate this prediction, the additional chromatic stimuli did not affect the size of the ME (Siegel & Allan, 1987; Skowbo & Forster, 1983). The failure of correlational manipulations to affect the ME may argue against a conditioning explanation of the phenomenon (Skowbo, 1984; Skowbo & Forster, 1983), but there is another interpretation (Allan & Siegel, 1986; Siegel & Allan, 1987). In the present experiment, the frame lightness-contingent aftereffect was used to evaluate this alternative.

The alternative explanation for the failure of correlational manipulations to affect the ME is inspired by an influential theoretical analysis of CS–UCS correlation in Pavlovian conditioning—the Rescorla-Wagner model (Rescorla & Wagner, 1972). According to this model, associations between the experimental context and interpolated UCSs develop in parallel with CS–UCS associations. The reason interpolated UCSs decrease the strength of conditioning is that the context–UCS association competes with, and "blocks" (Kamin, 1969), the CS–UCS association (see Rescorla & Wagner, 1972). In the typical ME preparation, presentations of the putative UCS (homogeneous chromatic stimuli) between presentations of colored grids would not promote the development of context–color associations that would compete with the grid–color association. There is no distinctive context; both interpolated homogeneous chromatic stimuli, green and magenta, are simply presented in the middle of a black screen. As summarized by Siegel and Allan (1987), "the inability of experimental context cues to become associated with chromatic stimuli would render the contingency [correlation] manipulation ineffective" (p. 284).

Recently, Tiffany, Maude-Griffin, and Drobes (1991) similarly discussed the importance of a "superordinate experimental context" (p. 58) in experiments evaluating the effect of CS–UCS correlation in conditioning. The frame lightness-contingent aftereffect demonstrated in Experiments 3–4 suggests a technique for presenting such a "superordinate experimental context" during ME induction. Grid-color pairings can be presented in the context provided by the lightness of the frame surrounding the chromatic grid. Thus, both the context in which induction is conducted and the orientation stimulus specifically paired with color are effective as elicitors of illusory color.

In the present experiment, all subjects received green-horizontal and magenta-vertical grids appearing as pictures in frame. As is the case in a typical conditioning experiment, the UCS (i.e., color) was paired with both the nominal CS (i.e., grid orientation) and the context (i.e., frame lightness). In addition, subjects assigned to the low-correlation group received further presentations of the chromatic stimulus in this context; that is, they received extra homogeneous colored stimuli paired with the same contextual cues present during grid-color pairings.

Method

Subjects

Subjects from the same population as that used in Experiment 4 were divided into two groups that differed with respect to the correlation between grid orientation and color during aftereffect induction. For high-correlation (HC) subjects ($n = 14$), orientation stimuli were colored, and chromatic stimuli were not presented in the absence of orientation stimuli. For low-correlation (LC) subjects ($n = 12$), orientation stimuli were colored; in addition, nonorientation chromatic stimuli were presented.

Design

The induction session, which lasted for almost 22 min, was divided into 650 consecutive 2-s intervals. A framed picture was presented during each of these intervals. The first interval, and every 13th interval thereafter, were designated trials; thus, of the 650 intervals, 50 were trials. The 12 intervals between each trial were designated intertrial intervals. The stimuli presented during trials and intertrial intervals are depicted in Figure 9 (top and middle panels, respectively).

On each trial, subjects were presented with a chromatic framed grid. On alternate trials, subjects were presented with a grid of green and black horizontal bars surrounded by a white frame and a grid of magenta and black vertical bars surrounded by a black fame. The 12 intervals between each trial (intertrial intervals) consisted of alternate presentations of black- and white-framed unpatterned pictures. Groups differed with respect to the color of the picture within the frames presented during the intertrial intervals. As indicated in the middle panel of Figure 9, for HC subjects the picture was gray. That is, HC subjects received six presentations of a black-framed gray square, alternating with six presentations of a white-framed gray square, between trials. For LC subjects, intertrial-interval pictures were colored, with the relationship between picture color and frame lightness the same as during trials. That is, LC subjects received six presentations of a black-framed magenta square, alternating with six presentations of a white-framed green square, between trials.

Procedure

Subjects received pre- and postinduction assessment of contingent aftereffects, as in the previous experiments. In this experiment, however, illusory color elicited both by frame lightness (black and white) and by orientation (horizontal and vertical) was assessed. The four assessment stimuli were a black-framed homogeneous square, a white-framed homogeneous square, a gray-framed horizontal grid, and a gray-framed vertical grid (see Figure 9, bottom). For each assessment stimulus, the picture could be one of five colors (P2, P1, 0, G1, or G2). If the picture contained an orientation stimulus, the assessment colors were the same as those used in Experiment 3 (in which the assessment picture contained horizontal bars). If the picture was a homogeneous square, the assessment colors were the same as those used in Experiment 4 (in which there were no bars on the assessment stimulus). The four assessment stimuli and five assessment colors resulted in 20 combinations. Each combination was presented on seven occasions, for a total of 140 color determinations in both pre- and postinduction assessment (in contrast to the 100 determinations in the prior experiments).

Apparatus and Stimuli

All stimuli were presented with the Macintosh IIcx computer system. The dimensions of the picture and frame components of the stimuli used in this experiment were the same as those used in Experiments 3 and 4. Similarly, the characteristics of the colors used for the trial pictures, and intertrial-interval pictures for LC subjects, were as described in the previous experiments. The horizontal and vertical grids used in this experiment were the same as those used in Experiment 3.

One hue in the present experiment, gray, was not used in the prior experiments. The same gray (R = G = B = 30,000, and illuminance = 13 lux) was used for the intertrial-interval picture for HC subjects and the frame surrounding the grid pictures during assessment.

Results

Both frame lightness- and orientation-contingent aftereffects were evaluated.

Frame Lightness-Contingent Aftereffect

Pre- and postinduction assessment of frame lightness-contingent illusory color yielded psychometric functions that were similar to those obtained in Experiments 3 and 4. In preinduction, pictures surrounded by black frames appeared pinker than pictures surrounded by white frames. After induction, the functions moved apart in the direction of contingent aftereffects.

Frame lightness-contingent color aftereffects were displayed by 11 of the 12 LC subjects (91.7%, $p < .003$), but only 7 of the 14 HC subjects (50%, $p > .05$). The mean contingent aftereffect scores for the LC and HC groups were, respectively, 2.5 and 0.6. The frame lightness-contingent aftereffect was significantly greater in the LC group than in the HC group, $t(24) = 2.85$, $p < .009$.

Orientation-Contingent Aftereffect

Figure 10 presents the pre- and postinduction psychometric functions for each grid orientation for HC (Figure 9A) and LC (Figure 9B) subjects. As is apparent in Figure 9, the preinduction functions were similar, and they moved apart after induction in the direction of a contingent color aftereffect. That is, after induction the horizontal grid (which was green during induction) was perceived as being less green; similarly, the vertical grid (which was magenta during induction) was perceived as being more green.

All subjects displayed an orientation-contingent color aftereffect; however, the magnitude of the aftereffect differed in

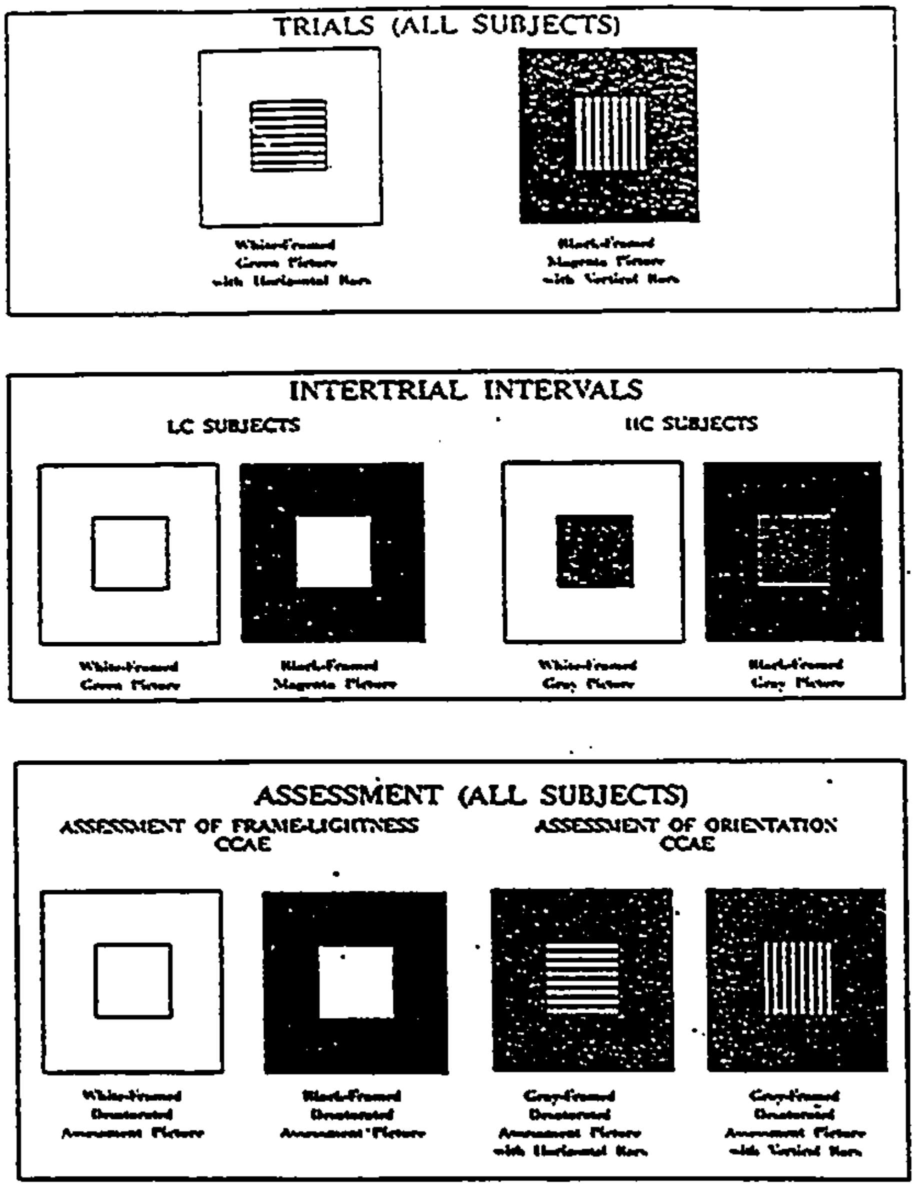


Figure 9. Stimuli used in Experiment 5. (During induction, all subjects received trials with the same stimuli [top panel]: a green horizontal grid surrounded by a white frame, alternating with a magenta vertical grid surrounded by a black frame. Groups differed with respect to the stimuli presented during intertrial intervals. Subjects in the low-correlation [LC] group were exposed to presentations of framed homogeneous colors, and subjects in the high-correlation [HC] group were exposed to framed gray pictures [middle panel]. During aftereffect assessment, all subjects judged the color of each of four picture–frame combinations [bottom panel], enabling evaluation of the aftereffects contingently elicited by grid orientation and by frame lightness. CCAE = contingent-color aftereffect.)

the two groups. The mean contingent aftereffect scores for the LC and HC groups were, respectively, 1.8 and 3.6. The orientation-contingent color aftereffect was significantly smaller in the LC group than in the HC group, $t(24) = 3.67$, $p < .002$.

Discussion

The results of this experiment indicate that correlational manipulations affect the strength of the ME. Both groups had the same grid-color pairings; they differed only with respect to whether chromatic stimuli were presented in the absence of the grid. Subjects in the LC group, who were exposed to intertrial chromatic stimuli, displayed smaller orientation-contingent color aftereffects than subjects in the HC group.

Decreasing the CS–UCS correlation in Pavlovian conditioning is hypothesized to retard learning because the intertrial UCSs become associated with background cues, and these background–UCS associations compete with the simultaneously forming CS–UCS associations (Rescorla & Wagner, 1972). This analysis of the decremental effects of decreasing CS–UCS correlation has been supported by the results of experiments in which the association between background

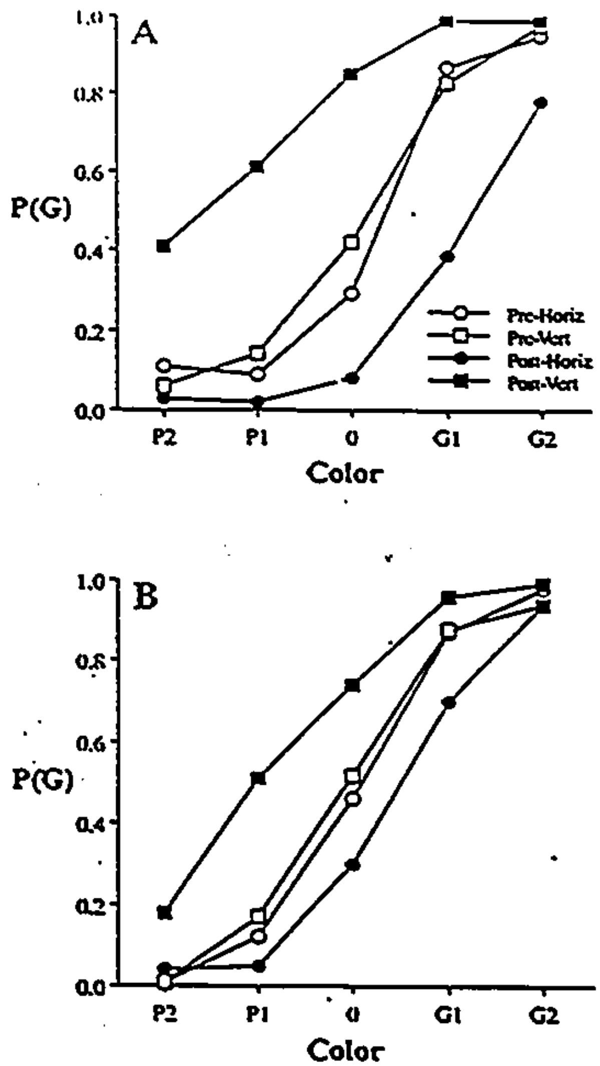


Figure 10. Pre- and postinduction psychometric functions for each grid orientation for high-correlation (Figure 9A) and low-correlation (Figure 9B) subjects in Experiment 5. (P = pink; G = green; Horiz = horizontal; Vert = vertical.)

cues and the UCS was monitored, as well as the CS–UCS association. Increases in the former were associated with decreases in the latter (e.g., Kremer, 1974; Odling-Smee, 1975). Similar results were obtained in the present experiment. A second cue, analogous to the contextual cues of the Pavlovian conditioning experiment, was provided by the frame. Just as the background, as well as the nominal CS, is paired with the UCS for LC subjects in Pavlovian conditioning, so the frame, as well as the grid, was paired with the UCS for the LC subjects in this ME experiment. As in other Pavlovian conditioning preparations, there was an inverse relationship between the background–UCS association and the CS–UCS association. That is, HC subjects, who showed a relatively strong orientation-contingent color aftereffect, evidenced a relatively weak frame lightness-contingent color aftereffect. Subjects in the LC group displayed weaker orientation-contingent color aftereffects and stronger frame lightness-contingent color aftereffects.

General Discussion

The ME is seen after pairing of grids differing in orientation with different colors. One account of the ME emphasizes Pavlovian conditioning. As elaborated by Murch (1976), the color aftereffect represents a CR elicited by the color-paired cue (a grid of a certain orientation in McCollough's original demonstration). Generally, most theorists have not adopted Murch's analysis and subscribe to a nonassociative interpretation of the phenomenon. Most such nonassociative interpretations are elaborations of McCollough's (1965) suggestion that the ME provides psychophysical evidence for neural units that are both color and orientation specific. The relevant effect of ME induction is to adapt these units; thus, for example, after induction with a green-horizontal grid, an achromatic horizontal grid appears pinkish because the fatigued green-horizontal detectors do not contribute to visual processing (see reviews by Dodwell & Humphrey, 1990; Harris, 1980).

The results of the present experiments support Murch's (1976) conditioning interpretation of the ME. Such support is provided by demonstrations that the ME is one of a more general class of contingent color aftereffects (i.e., stimuli other than line orientation are effective) and by the demonstration that the ME is attenuated by decreasing the correlation between grid orientation and color, despite consistent grid-color pairings (i.e., homogeneous chromatic stimuli presented between chromatic grid presentations degrade the ME).

Range of Stimuli That Can Contingently Elicit Color Aftereffects

Form Stimuli

Nonassociative interpretations of the ME have emphasized the limited class of stimuli that, following pairing with color, can contingently elicit illusory color. Thus, Foreit and Ambler (1978) concluded that line configurations, in contrast with line orientation, are not effective. In Experiment 1A, the cross and square were constructed with the configuration of line segments used by Foreit and Ambler. In Experiment 1B, the line segments of the cross were rearranged so that its horizontal and vertical dimensions were the same as those of the square. In both experiments, a color aftereffect contingent on line configuration was induced.

The results of Experiment 2 demonstrated yet another form-contingent color aftereffect. Line segments configured in the shape of a triangle were presented in one color (green or magenta) when the triangle was pointing up and the other color when the triangle was pointing down. Color aftereffects were subsequently seen, contingent on the direction of the triangle.

Lightness of Frame Surrounding Color

Demonstrations of a frame lightness-contingent color aftereffect (Experiments 3 and 4) further extend the range of stimuli that, following pairing with color, can contingently elicit aftereffects. In the induction phase of these experiments, green and magenta colors were paired with different lightnesses of a frame (black or white) surrounding the color. Frame lightness subsequently contingently elicited a color aftereffect, and this aftereffect (in common with the orientation-contingent color aftereffect) demonstrated substantial retention.

Conclusions Concerning the Range of Stimuli That Can Contingently Elicit Color Aftereffects

Various color aftereffects contingent on dimensions other than orientation have been demonstrated previously. Generally, the stimuli that have been used have been "simple, repetitive, redundant, and highly predictable patterns" (Dodwell & Humphrey, 1990, p. 83). The fact that the simple geometric forms constructed from the same components (Experiments 1 and 2) and even stimuli possessing neither form nor orientation (Experiments 3 and 4) are effective suggests that contingent color aftereffects are very general phenomena indeed.

Correlational Manipulations and the ME

On the basis of nonassociative interpretations of the ME, mere exposure to the grid and color should induce the aftereffect (e.g., for McCollough, 1965, such exposure would adapt the orientation-specific color detectors). In contrast, Murch's (1976) conditioning interpretation of the ME suggests that the phenomenon depends not only on grid-color pairings but also on color presentations that occur in the absence of the grid (see Skowbo, 1984). That is, the ME, like other CRs, should be decreased by presentations of the chromatic UCS at times other than when the CS is presented.

Although some reports suggest that such manipulations do not affect the ME (Siegel & Allan, 1987; Skowbo & Forster, 1983), it is likely that these earlier experiments were not appropriately designed to evaluate the associative consequences of decreasing the correlation between the orientation CS and chromatic UCS. That is, correlational manipulations work because the extra UCSs become associated with contextual, background cues (Rescorla & Wagner, 1972). When such a context for the ME was provided by frame lightness, decreasing the correlation between grid and color decreased the magnitude of the orientation-contingent color aftereffect (Experiment 5).

In a conditioning experiment, contextual cues become more strongly associated with the UCS in LC subjects than they do in HC subjects because there are more pairings of the UCS with the context in the former case than in the latter case (see Rescorla & Wagner, 1972). A parallel result was obtained in Experiment 5. Subjects in the LC group, who displayed an attenuated orientation-contingent aftereffect, displayed an enhanced frame lightness-contingent aftereffect.

Conclusions Concerning the Associative Basis of the ME and Other Contingent Color Aftereffects

Our results would be very difficult to reconcile with a nonassociative interpretation of contingent aftereffects. Such an analysis would not readily explain why forms constructed of the same components, or indeed nonpatterned stimuli, can contingently elicit color aftereffects. In addition, as emphasized both by critics (e.g., Skowbo, 1984) and by advocates (e.g., Allan & Siegel, 1986) of an associative analysis of the ME, the associative analysis suggests that the ME should be affected by manipulations of the grid-color correlation (while keeping grid-color pairing constant). Such a correlational effect does prevail with the ME.

Recently, Dodwell and Humphrey (1990) presented a new interpretation of the ME. According to their view, during ME induction there is adjustment of the adaptation level (Helson, 1964), or *neutral point*, by error-correcting devices (ECDs; Andrews, 1964). Normally, the correlation between color and orientation is zero. This correlation is violated during ME induction, and the ECD biases the system to reestablish the zero correlation by moving the neutral point. For example, if green–horizontal is presented in induction, then the neutral point for green in the presence of horizontals is shifted by the ECD toward the overrepresented end of the color continuum (green). In postinduction assessment, when an achromatic horizontal grid is presented, white light, which was neutral before induction, is now on the red side of the neutral point, and the assessment figure will appear pinkish.

Dodwell and Humphrey's (1990) model of the ME is associative, to the extent that subjects learn a new relationship between grid and color during induction.[3] Thus, anything that will decrease this acquisition, such as the LC manipulation in Experiment 5, might be expected to decrease the ME. However, the model would require elaboration to explain why decreasing the grid-color correlation decreases the ME when effective context cues are provided (Experiment 5), but not when there are no such context cues (Siegel & Allan, 1987; Skowbo & Forster, 1983). In contrast, context cues are pivotal to influential models of Pavlovian conditioning (Rescorla & Wagner, 1972).

According to Dodwell and Humphrey (1990), the ECDs responsible for maintaining color–pattern neutrality do so with respect to a well-specified class of processors, the global vectorfields specified in the Lie transformation group theory of visual perception. This might suggest that Dodwell and Humphrey would not expect the form-contingent and frame lightness-contingent color aftereffects reported here. However, they also stated, "We do not claim that all MEs . . . fall neatly into the separate vectorfield channels hypothesis" (Dodwell & Humphrey, 1990, p. 87). Indeed, Dodwell and colleagues have demonstrated contingent color aftereffects that are not readily interpretable by their model (Dodwell & O'Shea, 1987, see note added in proof, p. 579).

Although our findings that forms and frame lightness are effective stimuli are consistent with the conditioning interpretation, this interpretation does not require that all stimuli be equivalent in their ability to act as CSs. With contingent

[3] The issue of whether Pavlovian conditioning establishes new associations as a result of contiguous CS–UCS presentations or rather involves "learning relations between stimulus events" (Estes, 1969, p. 165) is a matter of spirited debate among learning theorists (Mackintosh, 1977; Papini & Bitterman, 1990).

aftereffects, as with other CRs, some stimuli are probably better than others in becoming associated with color. Such selective associability is characteristic of many conditioning preparations (e.g., flavor stimuli, but not extroceptive stimuli, are readily associated with gastrointestinal distress; see Domjan, 1983). Several investigators have suggested that contingent color aftereffects are yet another manifestation of this phenomenon (Allan & Siegel, 1986; Harris, 1980; Siegel & Allan, 1987; Westbrook & Harrison, 1984). Indeed, there is some evidence that contingent color aftereffects display selective associability. Recently, Allan et al. (1989) reported that words can contingently elicit color aftereffects (following exposure to one word composed of green letters and another word composed of magenta letters, achromatic versions of these words elicit illusory chromatic aftereffects). However, when exposed to these same chromatic letter strings in a different order, such that they do not form words, no contingent color aftereffects are induced. If associative processes contribute to this text-contingent color aftereffect, the results suggest that people selectively associate words, but not nonwords (even though they are constructed from the same components as the words), with color.

In summary, the results of the present experiments strongly implicate learning in contingent color aftereffects. An especially clear learning account of the phenomenon is Murch's (1976) Pavlovian conditioning interpretation. Some prior evidence asserted to be contrary to this interpretation is likely the result of insensitive aftereffect assessment procedures (Foreit & Ambler, 1978), or inappropriate and unreflective application of CS-UCS correlation manipulations (Siegel & Allan, 1987; Skowbo & Forster, 1983).

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An Associative Interpretation of the Indirect McCollough Effect

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Running Head: Associative interpretation of the indirect ME

Abstract

Following an induction procedure in which a colored grid is alternated with a complementarily-colored square, subjects report color aftereffects on both the grid orientation present during induction and the orthogonal noninduced grid. The aftereffect reported on the induced grid orientation is called the McCollough effect (ME). The aftereffect reported on the noninduced grid orientation is called the "indirect" ME. There is evidence that the ME represents an instance of Pavlovian conditioning. The present results support a conditioning interpretation of the indirect ME. According to this interpretation, the indirect ME results from an association between a compound stimulus (made up of lightness and form elements) and color. These results are not consistent with interpretations of the indirect ME that attribute the phenomenon to special orthogonal coding mechanisms within the visual system.

An Associative Interpretation of the Indirect McCollough Effect

Both perception and learning researchers have studied the effects of paired presentations of sensory events (see Hall, 1991). Generally, the procedure has been used by perception researchers to understand the organization of the visual system (e.g., Dodwell & Humphrey, 1990; McCollough, 1965), and by learning researchers to understand associative processes (e.g., Brogden, 1939; Rescorla & Durlach, 1981). One phenomenon resulting from such sensory pairings has attracted the interest of both perception and learning researchers -- the orientation-contingent color aftereffect, first reported by McCollough in 1965 and usually known as the McCollough effect (ME). The ME traditionally has been interpreted in a nonassociative manner (e.g., McCollough's suggestion that her findings resulted from chromatic adaptation of orientation-specific detectors), but some investigators have suggested that the phenomenon may be understood as an instance of Pavlovian conditioning (see reviews by Harris, 1980; Siegel & Allan, 1992). The experiments reported here are a further demonstration of the utility of incorporating conditioning principles in understanding contingent color aftereffects.

The ME and the Indirect ME

McCollough (1965) demonstrated that exposure to colored vertical and horizontal lines results in a complementary color aftereffect contingent upon line orientation. For example, after an induction period consisting of presentations of a grid made of green and black horizontal lines alternating with another grid made of magenta and black vertical lines, subjects report color aftereffects contingent upon grid line orientation. That is, subjects report that achromatic horizontal grids appear pink, and achromatic vertical grids appear green.

Interestingly, several investigators have demonstrated that induction with only one chromatic grid results in contingent aftereffects on both that grid orientation and the orthogonal, noninduced grid orientation (e.g., Allan & Siegel, 1991; Ambler & Foreit, 1978; Humphrey, Dodwell, & Emerson, 1989; Shute, 1979; Stromeyer, 1969, 1984). For example, following presentation of a green horizontal grid alternating with a homogeneous magenta square with no grid (a "gridless" stimulus), achromatic horizontal grids appear pink, but also achromatic vertical grids appear green, even though vertical grids were not presented in induction (Allan & Siegel, 1991). This color aftereffect observed on the noninduced orthogonal orientation has been termed the "indirect ME."

As with the ME, most interpretations of the indirect ME do not emphasize learning principles (e.g., Ambler & Foreit, 1978; Humphrey et al., 1989). The experiments reported here evaluate a Pavlovian conditioning interpretation of the indirect ME. This associative analysis of the indirect ME is presented after a description of the associative interpretation of the ME.

<u>The Associative Basis of the ME</u>

The similarity in the pairing operations involved in ME induction and Pavlovian conditioning was recognized soon after the ME was reported, and several investigators suggested that learning principles may be relevant to understanding the perceptual phenomenon (see review by Siegel & Allan, 1992). For example, Murch (1976) argued that:

> "The lined grid in inspection functions as a conditioned stimulus (CS) while color functions as the unconditioned stimulus (UCS). As a result of the pairing of the CS (lined grid) with the UCS (color) a conditioned response (CR) develops so that the adaptive response of the visual system to the color is evoked by the lined grid." (p. 615)

The associative interpretation of the ME is controversial, with some investigators having found the case compelling (e.g., Allan & Siegel, 1986, 1993; Brand, Holding, & Jones, 1987; Murch, 1976; Siegel & Allan, 1992; Westbrook & Harrison, 1984), and others less so (e.g., Dodwell & Humphrey, 1990, 1993; McCarter & Silver, 1977; Skowbo, 1984, 1986).

Conditioning Phenomena and the ME. There is a great deal of evidence supporting a conditioning account of the ME. This support comes primarily from research demonstrating that the ME can be used to observe many conditioning-like effects. Thus ME magnitude is weakened following repeated presentations of the grid CS alone after induction (extinction; e.g., Riggs, White & Eimas, 1974), and displays some recovery after a rest period following these extinction trials (spontaneous recovery; e.g., Skowbo, 1988). Also, if subjects are exposed to non-colored grid stimuli prior to induction, ME magnitude is decreased (latent inhibition; e.g., Skowbo, 1988). Compound conditioning effects have also been documented: blocking (Brand et al., 1987; Siegel & Allan, 1985; Sloane, Ost, Etheriedge, & Henderlite, 1989; Westbrook & Harrison; 1985), unblocking (Brand et al., 1987), overshadowing (Brand et al., 1987; Siegel & Allan, 1985), and overprediction (Sloane et al., 1989).

Patterns that Elicit the ME. One reason for continued skepticism concerning the contribution of conditioning to the ME is the widely-asserted belief that only a few, special patterns can be effective ME induction stimuli. Some investigators suggested that such limitations on effective ME patterns compromise the conditioning account (e.g., Broerse & Grimbeck, in press; Dodwell & Humphrey, 1990; Humphrey, Herbert, Symons, & Kara, in press; Skowbo, 1984). However, results of recent experiments demonstrate that a wide range of stimuli can, following pairing with color, contingently elicit color aftereffects (Siegel et al., 1992; Siegel, Allan, & Eissenberg, in press). Thus, a variety of forms (e.g., crosses and squares) are effective. Similarly, the lightness of a frame surrounding a colored square can contingently elicit a color aftereffect. For example, following induction consisting of alternating presentations of a green square surrounded by a white frame and a magenta square surrounded by a black frame, colorless, framed assessment squares appear colored; that is, squares presented in the white frame appear pinkish, and squares presented in the black frame appear greenish. The fact that form and frame-lightness stimuli, in addition to orientation stimuli, are effective in ME induction is of special relevance to understanding the conditioning interpretation of the indirect ME.

The Associative Basis of the Indirect ME

While there is much evidence in support of an associative account of the ME, the indirect ME presents a challenge to associative accounts because the stimulus eliciting the aftereffect is apparently not present during induction. This challenge can be answered by a consideration of the variety of stimuli that are paired with color during indirect ME induction (and that subsequently may elicit color aftereffects), and an appreciation of data and theory concerning compound conditioning effects. Consider one indirect ME induction procedure -- a green horizontal grid alternating with a magenta gridless square (e.g., Allan & Siegel, 1991). If these chromatic stimuli are presented in the middle of an otherwise black video monitor (or on a projection screen in a darkened room), they are both square figures surrounded by black frames. Thus, green-horizontal grid presentations involve pairing of green with a variety of elements: a horizontal grid, a black frame, and a square form. Similarly, magenta-square presentations involve pairing of magenta with a black frame and a square form.

It is likely that these various elements (orientation, frame lightness, and form) differ in salience (other things being equal, CRs develop more rapidly to more salient stimuli). Following training where a compound stimulus with elements of unequal salience is paired with a UCS, organisms respond more to the stimulus element with the greater salience. This phenomenon is known as overshadowing (Kamin, 1969; Pavlov, 1927, p. 143). For example, Kamin constructed a compound CS of two elements differing in salience: a relatively more salient light and a relatively less salient noise. Following training where this compound CS was paired with shock, the light elicited the CR of greater magnitude, and the noise elicited the CR of lesser magnitude -- the light overshadowed the noise.

Siegel and Allan (1985) demonstrated overshadowing of the ME with compounds composed of two orientations: for example, one compound consisted of a 45° grid superimposed on a horizontal grid and the other of a 135° grid superimposed on a vertical grid. They showed that the more salient diagonal orientation overshadowed the less salient horizontal-vertical orientation. Like Siegel and Allan's (1985) induction procedure, the indirect ME induction procedure pairs compound stimuli with complementary colors. The horizontal green grid is a compound constructed of a horizontal grid ($GRID_h$), a black frame (FR_b) and a square (SQ). If grid orientation is more salient than frame lightness and square form, grid orientation would overshadow these less salient elements. During indirect ME induction, the green $GRID_h+FR_b+SQ$ compound alternates with a stimulus that has no grid -- a magenta FR_b+SQ stimulus. In this case, since no element of greater salience is present, black frame and square are not overshadowed. (For simplicity, it is assumed that the salience of FR_b and SQ is equivalent).

When assessed for the ME with the achromatic $GRID_h+FR_b+SQ$, $GRID_h$ elicits the color aftereffect -- horizontal bars appear pink. Subjects are assessed for an indirect ME with an achromatic compound that includes a novel stimulus - the vertical grid ($GRID_v$). When assessed for an indirect ME with the achromatic $GRID_v+FR_b+SQ$, FR_b and SQ elicit the color aftereffect; thus, this assessment stimulus appears green.

According to the associative view, the "indirect" ME is not indirect at all. Like the ME, the indirect ME is elicited "directly" by stimuli (the FR and SQ elements) that have been effectively paired with color during induction. For consistency with general usage, the term "indirect ME" will continue to refer to the effects seen after an indirect ME induction procedure, e.g., a grid stimulus alternating with a gridless stimulus.

Subjects and Apparatus

Subjects. The subjects in all 8 experiments reported here were male and female students with no previous experience in contingent aftereffect tasks. They were enrolled in introductory psychology at Mount Allison University (Experiment 2) or at McMaster University (all other Experiments), and received course credit for their participation. The subjects participated in the experiment individually, with the experimenter present in the room throughout the session.

Apparatus. In all experiments, temporal parameters, stimulus presentation, stimulus color, and recording of responses were controlled by a Macintosh IIcx computer equipped with an 8-bit video display card. Stimuli were displayed on an Apple color monitor (Model M0401PA). Color values for the specific colored stimuli used in this experiment are presented elsewhere (Allan & Siegel, 1991).

Experiment 1

The associative interpretation of the indirect ME is assessed in Experiments 2-8. Experiment 1 was designed to show that the indirect ME is demonstrable with the apparatus and procedures of these subsequent experiments. Following induction with a green grid (either horizontal or vertical) and a gridless magenta square, the extent to which both grid orientations contingently elicited color aftereffects was evaluated.

Method

Aftereffect Induction. In one induction condition, subjects ($\underline{n}$=5) observed a green horizontal grid alternating with a magenta square. In the other induction condition, subjects ($\underline{n}$=5) observed a green vertical grid alternating with a magenta square. Induction stimuli were both approximately 5.9 cm square, and subtended approximately 2.7° of visual angle. These stimuli were presented in the center of the monitor screen (27.5 cm x 20.3 cm, subtending approximately 11.6° x 8.9° of visual angle). The remainder of the monitor screen was black.

The grids were composed of 20 bars (10 black bars alternating with 10 green bars); the spatial frequency of each grid was 3.7 cpd. Each stimulus was presented for 2 sec, and each was presented 176 times. The induction period lasted approximately 13 min. Background music was presented during induction.

Aftereffect Measurement. Color aftereffects were measured before (preinduction) and after (postinduction) the induction phase of the experiment using a variant of the method of constant stimuli (Allan, Siegel, Toppan, & Lockhead, 1991). Room lights were turned on for 2 min between induction and postinduction assessment to minimize the influence of simple afterimages. During both assessments there were 50 presentations each of the horizontal and vertical grids. Assessment grids were identical to induction grids in all respects except for the color of the alternate (non-black) bars. On each presentation the assessment stimulus 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 (00). Figures and colors were randomly ordered in both assessment phases, with the restriction that each figure be presented in each color 10 times. For each of the 100 stimulus presentations, the subject had to make a binary response, "pink" or "green." The assessment stimulus remained on the screen until the subject responded. The next stimulus was presented 1 sec after the experimenter entered the subject's response on the computer keyboard.

Prior to the start of the experiment subjects were given practice with the color judgment task. For each practice trial, the grid was one of the four unsaturated colors (G1, G2, P1, or P2) and was either horizontal or vertical. Each of the eight color-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 "pink" response, subjects were informed that their response was "correct" or "error" via the speech synthesis capability of the computer used to control the experiment. These practice data were ignored.

Instructions to Subjects. Before the practice, preinduction, and postinduction phases, subjects were told that they were participating in a color discrimination task where they would be asked to determine whether figures were pink or green. They were instructed to be as accurate as possible, but to guess if they were unsure of the color. They were further instructed to keep their head upright throughout the experiment. Before the induction period, subjects were informed that their task was to focus on the alternating figures that were presented.

Results

The psychometric function relating the probability of the subject reporting that an assessment grid appeared green, P(G), to the physical characteristics of the assessment stimulus (ranging from P2 to G2) was determined. Figure 1 displays the mean pre- and postinduction assessment functions for the induced and noninduced grid orientations. For simplicity of presentation, the data are collapsed across the dimension of induction orientation (horizontal or vertical). As is apparent from Figure 1, subjects showed similar psychometric functions for the induced and noninduced orientations prior to the induction period. These functions moved apart after induction. Orientation stimuli which were green during induction were less likely to elicit a "green" response in postinduction. This decreased probability is illustrated by a downward shift in the postinduction psychometric function for the induced orientation. In contrast, noninduced orientation stimuli were more likely to elicit a "green" response following induction, illustrated by an upward shift in psychometric function.

Insert Figure 1 about here

For purposes of statistical analysis, the sum of the pre- and postinduction green responses across the five assessment colors was determined for each subject separately for both the induced and noninduced orientations. These data were analyzed for differences from pre- to postinduction using the Wilcoxon signed-rank test.[1] The number of green responses to the induced orientation was significantly decreased ($T = 0$, $N = 9$, $p < .05$) from pre- to postinduction, indicating that subjects reported the induced figure as less green, or more pink, after the induction period. In contrast, the number of green responses to the noninduced orientation was significantly increased ($T = 7.5$, $N = 10$, $p < .05$) from pre- to postinduction, indicating that subjects reported the noninduced orientation as more green after the induction period.

Discussion

This experiment provides a further demonstration of the indirect ME. Following an induction procedure where a green grid was alternated with a magenta gridless square, the induced grid orientation appeared pink (the ME), and the orthogonal noninduced grid orientation appeared green (the indirect ME). According to the associative interpretation of the indirect ME, the color aftereffect reported on the noninduced grid was elicited by components of the figure that were, in fact, paired with color. That is, induction consisted of presentations of a green GRID+FR_b+SQ compound alternating with a magenta FR_b+SQ compound. The direct ME is elicited by the more-salient GRID element, and the indirect ME is elicited by the less-salient FR and SQ components.

Experiment 2

An assumption of the associative view of the indirect ME is that the GRID element is more salient than either the FR or SQ elements of a GRID+FR+SQ compound. This assumption is critical because it can be used to explain why FR and SQ elicit an aftereffect even though they are paired with complementary colors during indirect ME induction. The purpose of Experiment 2 was to provide evidence in support of this critical assumption by demonstrating a conditioning phenomenon attributed to salience differences: overshadowing (Kamin, 1969; Pavlov, 1927). Overshadowing can be observed following conditioning trials where a UCS is paired with a compound stimulus made up of elements of unequal salience. Although subjects might demonstrate strong CRs to either element if trained with each element separately, when presented as a compound the CR elicited by the more-salient element is strengthened at the expense of the CR elicited by the less-salient element.

The salience assumption regarding elements of indirect ME induction compounds yield clear overshadowing predictions. First, when FR and SQ elements are paired with color in the absence of a GRID element, these less-salient elements should elicit a color aftereffect. Second, a more-salient GRID element should overshadow the FR and SQ elements if compounded with them during aftereffect induction. Thus an effective elicitor of a color aftereffect (FR+SQ compound) should become less effective when compounded with a more salient GRID element (GRID+FR+SQ); the GRID should overshadow FR and SQ elements.

The procedure for demonstrating overshadowing is shown in Figure 2. Independent groups of subjects were induced with either an indirect ME induction procedure (Group IME) or a ME induction procedure (Group ME). As in Experiment 1, the induced grid was counterbalanced with respect to orientation, so Figure 2 shows only one of the two induction procedures used in Experiment 2. As can be seen from Figure 2, the two groups differed only in that group IME observed a magenta FR_b+SQ, whereas group ME observed a magenta GRID+FR_b+SQ. All subjects were assessed using three stimulus compounds: $GRID_h$+FR_b+SQ, $GRID_v$+FR_b+SQ, and FR_b+SQ. The critical overshadowing comparison involves the aftereffect elicited by the FR_b+SQ assessment compound. The FR_b+SQ compound should elicit an aftereffect following indirect ME induction because these two elements are paired with color (magenta) during induction: for subjects in group IME, FR_b+SQ assessment compounds should appear green. If GRID overshadow FR_b and SQ, the FR_b+SQ aftereffect should be attenuated in group ME. That is, elements (FR_b+SQ) that effectively elicit an aftereffect would be less effective at eliciting an aftereffect following induction where they are compounded with another, more-salient element (GRID): for subjects in group ME, FR_b+SQ assessment compounds should appear relatively desaturated.

Insert Figure 2 about here

Method

Aftereffect induction. The induction compounds that subjects observed defined group membership. For group IME, subjects observed a green grid alternating with a magenta square (see Figure 2). As in Experiment 1, grid orientation was counterbalanced. Some subjects (n=5) observed a green horizontal grid, while others (n=5) observed a green vertical grid. For group ME, subjects observed a green grid alternating with a magenta square upon which an orthogonal grid was superimposed (see Figure 2). Again, grid orientation was counterbalanced such that some subjects (n=5) observed a green horizontal grid, and others (n=5) observed a green vertical grid. In other details, the induction phase was as described in Experiment 1.

Aftereffect measurement. In Experiment 1, the indirect ME was evaluated in the typical manner. Two types of assessment stimuli were presented: black-framed compounds containing an induction-orientation grid (to evaluate the ME) and black-framed compounds containing a noninduction-orientation grid (to evaluate the indirect ME). In Experiment 2, for all subjects, aftereffects were assessed using these two stimuli, as well as a third stimulus -- a black-framed square that did not contain a grid (see Figure 2). Black-framed assessment squares were identical in all respects to other assessment stimuli, except that they contained no grid. For both pre- and postinduction assessment phases there were 45 presentations of the three types of assessment compounds. Each compound was thus presented in each of the five assessment colors 9 times. During practice, each of the 12 color-orientation combinations (four colors and three assessment compounds) was presented twice (in random order).

Results

Figure 3A displays the mean psychometric functions (collapsed across induction grid orientation) for the three assessment compounds in the pre- and postinduction assessment phases for Group IME, and Figure 3B displays the functions for Group ME. For purposes of statistical analysis, as in Experiment 1, the sum of the pre- and postinduction green responses over the five assessment colors was determined for each of the three assessment compounds.

Group IME replicates the induction procedure of Experiment 1, and, as in Experiment 1, subjects demonstrated the ME (assessment compounds containing the induced grid appeared less green following induction, $T = 0$, $N = 10$, $p < .01$), and the indirect ME (assessment compounds containing the noninduced grid appeared more green, ($T = 4$, $N = 9$, $p < .05$). Subjects were also assessed using gridless compounds (made up FR_b+SQ). For group IME, these gridless assessment compounds appeared more green following induction ($T = 0$, $N = 10$, $p < .01$). In fact, as may be seen in Figure 3A, the aftereffect to the gridless compound was greater than the aftereffect to the noninduced grid. In order to compare the magnitude of these aftereffects, the difference between the pre- and postinduction number of green responses to the gridless square and to the noninduced grid was calculated, resulting in an "aftereffect score" for each subject to each compound. The magnitude of the score is proportional to the strength of the aftereffect and the sign of the score (negative or positive) reveals the reported color (pink or green, respectively). For example, if a subject said "green" 20 times to an FR_b+SQ compound in preinduction, and 30 times to the same compound in postinduction, that subject received an aftereffect score of +10 on that compound, indicating that the subject saw this stimulus as more green after the induction period. The mean aftereffect score for the gridless compound was 10.4, and the mean aftereffect score for the noninduced grid was 5.0 -- a statistically significant difference ($T = 3$, $N = 10$, $p < .05$).

Insert Figure 3 about here

Group ME represents an ME induction procedure where orthogonal grids are presented in complementary colors (e.g., McCollough, 1965). As expected, subjects demonstrated the ME. That is, assessment compounds containing a grid that was paired with green during induction appeared less green after induction (T = 0, N = 10, $p < .01$), and assessment compounds containing a grid that was paired with magenta during induction appeared more green after induction (T = 0, N = 10, $p < .01$). Subjects were also assessed using gridless compounds (made up of FR_b+SQ). For group ME, these gridless assessment compounds did not appear more green following induction (T=12, N = 9, $p > .05$).

The critical comparison in this experiment involves the magnitude of the aftereffect elicited by the gridless assessment compounds for the two groups. Group IME should display aftereffects of greater magnitude to the gridless compound, since no GRID element was present during induction to overshadow the less salient FR and SQ elements. The mean aftereffect score for the gridless compound was 10.5 for group IME and 2.1 for group ME. This difference was statistically significant (Mann-Whitney $U = 10$, $p < .01$).

Discussion

The results of Experiment 2 support the assumption that GRID overshadows FR and SQ. Color aftereffects elicited by FR+SQ compounds were assessed following induction where an FR+SQ compound was paired with color without a GRID (group IME) or compounded with a GRID (group ME). When paired with color, and in the absence of a GRID, FR+SQ compounds elicit a color aftereffect. When paired with color, and when compounded with a GRID, FR+SQ compounds do not elicit a significant color aftereffect. Thus GRID elements overshadow FR and SQ elements during aftereffect induction.

Interestingly, after indirect ME induction, the aftereffect elicited by the gridless assessment stimulus was greater than that elicited by the assessment stimulus containing the noninduced grid. That is, the introduction of a novel grid element within the square element attenuated the aftereffect elicited by that square element. Such a finding is congenial with the associative interpretation of the indirect ME. According to this interpretation, the so-called indirect ME is actually directly elicited by the FR and SQ elements that have been paired with a homogeneous colored field during induction. If a novel orientation stimulus is added to this compound during assessment, the assessment SQ element is very different than the induction SQ element. It is no longer a homogeneous square, but rather is a pattern constructed of adjacent black bars. Thus, following indirect ME induction the gridless square elicits a green aftereffect because both the FR and SQ components have been paired with color during induction. Compared to this gridless stimulus, the noninduced orientation stimulus elicits a relatively small green aftereffect because it contains only the FR element that was paired with color during induction; the SQ element of the induction compound is substantially altered in this noninduced assessment stimulus.

Experiments 3A and 3B

Inasmuch as Experiment 2 is the first demonstration of an aftereffect elicited by a gridless FR+SQ compound following indirect ME induction, the procedure is replicated, with more subjects, in Experiment 3A. In addition, another induction procedure that has been used to demonstrate the indirect ME is used to demonstrate the FR+SQ aftereffect in Experiment 3B.

Experiment 3A

The purpose of Experiment 3A was to replicate the findings obtained in the IME group in Experiment 2.

Method

Aftereffect induction and measurement. As in Experiment 2, there were two induction conditions, counterbalanced with respect to induction grid orientation. In one induction condition, subjects (n=15) observed a green horizontal grid alternating with a magenta square. In the other induction condition, subjects (n=15) observed a green vertical grid alternating with a magenta square. Aftereffects were assessed as reported in Experiment 2: Three types of assessment stimuli were presented; a black-framed, induction-orientation grid (to evaluate the ME), a black-framed, noninduction-orientation grid (to evaluate the indirect ME), and a black-framed square that did not contain a grid.

Results

Figure 4A displays the mean psychometric functions (collapsed across induction grid orientation) for the three assessment compounds in the pre- and postinduction assessment phases of Experiment 3A. The results are similar to those seen for the IME group in Experiment 2. Assessment compounds containing the induced grid appeared less green following induction, the ME, ($T = 1$, $N = 30$, $p < .01$), assessment compounds containing the noninduced grid appeared more green, the indirect ME, ($T = 18$, $N = 30$, $p < .01$), and the gridless assessment compound also appeared more green ($T = 4.5$, $N = 29$, $p <$ ..01). Again, the green aftereffect to the gridless compound was greater than the green aftereffect to the noninduced grid ($T = 86.5$, $N = 29$, $p < .01$).

Insert Figure 4 about here

Experiment 3B

Experiment 3B, like Experiment 3A, evaluated the role of the gridless square in eliciting the indirect ME. As in Experiment 3A, subjects were assessed with grids and gridless squares. To assess the generality of the results of Experiment 3A, a different indirect ME induction procedure was used in Experiment 3B.

In experiments reported thus far, the indirect ME was induced by alternating a green grid with a magenta square. Other induction procedures are also effective in producing the indirect ME. For example, the indirect ME is demonstrable following an induction procedure where a colored grid alternates with an achromatic (white or black) field (e.g., Allan & Siegel, 1991; Stromeyer, 1969; Yasuda, 1978). Several researchers have suggested that, with such an induction procedure, the complementarily colored afterimage that follows chromatic grid presentation substitutes for the an actual complementarily colored field (e.g., Humphrey et al., 1989; Shute, 1979). In Experiment 3B, a green grid alternated with a white square. According to the associative interpretation of the indirect ME, the afterimage produced by the just-terminated chromatic GRID+FR_b+SQ is paired with FR_b+SQ.

Method

Where unspecified, the methods of this experiment were the same as those in Experiment 3A. There were 32 subjects, and they were run in one of two counterbalanced conditions. In one induction condition, subjects (n=16) observed a green horizontal grid alternating with a white square. In the other induction condition subjects (n=16) observed a green vertical grid alternating with a white square.

Results

Figure 4B displays the mean psychometric functions (collapsed across induced grid orientation) for the three assessment compounds in the pre- and postinduction assessment phases of Experiment 3B. The results are similar to those seen in Experiment 3A, except no indirect ME was observed. Assessment compounds containing the induced grid appeared less green following induction, the ME, ($T = 0$, $N = 32$, $p < .01$), assessment compounds containing the noninduced grid did not appear more colored following induction ($T = 175$, $N = 29$, $p > .05$), and the gridless assessment compound did appear more green ($T = 15$, $N = 31$, $p < .01$). Again, the green aftereffect to the gridless compound was greater than the green aftereffect to the noninduced grid ($T = 51.5$, $N = 32$, $p < .01$).

Discussion

As expected on the basis of the associative interpretation of the indirect ME, there was a color aftereffect elicited by the FR+SQ stimulus which did not include the noninduced grid. This result mirrors that reported for group IME in Experiment 2. Indeed, the aftereffect elicited by this gridless assessment stimulus was greater than that elicited by the one containing the noninduced grid. Thus, the addition of the orthogonal orientation component to the black-framed square is not only unnecessary for the indirect ME, but actually attenuates the phenomenon (presumably because the novel GRID decreases the similarity between the induction and assessment SQ elements).

Experiment 4

According to the associative interpretation of the indirect ME, frame lightness is one elicitor of the indirect ME. One way to decrease the magnitude of a CR elicited by a CS is to decrease the correlation between the CS and the UCS (see Rescorla, 1988). Such a procedure affects the magnitude of the ME, as it does other CRs (Siegel et al., 1992). Thus, by reducing the correlation between frame lightness and color during induction, the indirect ME should be attenuated. This prediction was evaluated in Experiment 4 using an "irrelevant frames induction procedure."

The Irrelevant Frames Induction Procedure

This procedure is like the indirect ME induction procedure used in previous experiments (e.g., the green grid alternating with a magenta square), except that the induction stimuli are not always presented in black frames. Rather, they are equally often presented in black and white frames.

Experiment 4 used counterbalanced conditions of irrelevant frames induction. To illustrate the procedure, one such condition is presented in Figure 5. For the condition depicted in Figure 5, during induction subjects are presented with four stimuli: a green

$GRID_h+FR_b+SQ$, a magenta FR_b+SQ, a green $GRID_h+FR_w+SQ$, and a magenta FR_w+SQ. Since FR_b and FR_w are paired equally often with green and magenta during induction, there is no correlation between frame lightness and color. As in the previous experiments. all assessment stimuli are presented in black frames.

Insert Figure 5 about here

The irrelevant frames induction procedure causes only one element, FR, to be an unreliable predictor of color. As may be seen in Figure 5, the horizontal grid is always green, and the gridless square is always magenta. Since GRID overshadows the other elements, and since $GRID_h$ is green in induction, the $GRID_h+FR_b+SQ$ assessment compound should appear pink. Any aftereffects seen on the other two assessment compounds ($GRID_v+FR_b+SQ$ and FR_b+SQ) should be elicited by the square form (since FR was not consistently paired with color). The gridless square assessment compound should appear green (since the gridless square was magenta during induction). Based on the results of Experiments 2 and 3, the so-called indirect ME (i.e., the aftereffect elicited by the noninduced orientation compound, $GRID_v+FR_b+SQ$), should be greatly attenuated by the irrelevant frames induction procedure. As is the case with the other assessment compounds, FR was uncorrelated with color during induction; furthermore, this noninduced compound contains only a very degraded version of the square form that was paired with color during induction. In summary, on the basis of the associative interpretation of the indirect ME, the irrelevant frames induction procedure should profoundly attenuate the phenomenon.

Method

This experiment was run concurrently with Experiment 3A. As in Experiment 3A, subjects were run in one of two induction conditions, counterbalanced with respect to induction grid orientation. In one induction condition, subjects (n=15) observed a green horizontal grid alternating with a magenta square. In the other induction condition, subjects (n=15) observed a green vertical grid alternating with a magenta square. However, the induction procedure in Experiment 4 differed from that reported previously. Induction consisted of 176 presentations each of a green grid and a gridless magenta square, but half of these presentations were compounded with FR_b, and half with FR_w (see Figure 5).

Results

Figure 6 displays the mean psychometric functions (collapsed across induced grid orientation) for the three assessment compounds in the pre- and postinduction assessment phases. Assessment compounds containing the induced grid appeared less green following induction, the ME, ($T = 0$, $N = 30$, $p < .01$), assessment compounds containing the noninduced grid appeared more green, the indirect ME, ($T = 104$, $N = 29$, $p < .05$), and the gridless assessment compound also appeared more green ($T = 6$, $N = 30$, $p < .01$).

Insert Figure 6 about here

The irrelevant frames induction procedure should not affect the magnitude of the aftereffects elicited by induced grid and gridless square, but should reduce the magnitude of the aftereffect elicited by the noninduced grid. Experiment 3A was used as a basis of comparison in order to test these predictions. Experiment 3A and the present experiment were run concurrently. (Experiment 3A is a more appropriate basis for comparison than Experiment 3B, because while both Experiments 3A and 4 used a magenta gridless induction stimulus, Experiment 3B used an achromatic gridless stimulus). The magnitude of the aftereffects elicited by the three assessment compounds in Experiment 3A were compared to those reported in the present experiment using the Mann-Whitney $\underline{U}$ test. Neither the aftereffects elicited by the induced orientation compound, nor the aftereffects elicited by the gridless compound, differed between the two experiments ($\underline{p}$s $> .05$). In contrast, the aftereffects elicited by the noninduced orientation compound did significantly differ between experiments (Experiment 3A, mean aftereffect score = 4.8; Experiment 4, mean aftereffect score = 1.9; $\underline{U} = 296.5$, $\underline{p} < .05$). Thus the irrelevant frames procedure did reduce the magnitude of the aftereffect elicited by the assessment compound containing the noninduced grid orientation.

Discussion

The irrelevant frames induction procedure was designed to make frame lightness an unreliable predictor of color, while maintaining the induction grid orientation and the square form as reliable predictors of color. Frame lightness was made irrelevant by presenting induction compounds with two different frame lightness (FR_b and FR_w). The results of this procedure were as predicted: the magnitude of the color aftereffect elicited by compounds containing the induced grid orientation (i.e., the ME), and that elicited by the gridless square, were not significantly affected by the irrelevant frames manipulation. In contrast, the magnitude of the aftereffect elicited by compounds containing the orthogonal grid orientation (i.e., the usual indirect ME) was significantly reduced.

Although the irrelevant frames induction procedure attenuated the indirect ME, it did not eliminate the phenomenon. That is, a small but reliable aftereffect was elicited by the compound (mean aftereffect score = 1.9). This aftereffect likely results because the induction procedure, although rendering FR an unreliable predictor for color, does not affect the reliability of SQ as a predictor of color. There is some similarity between the square form on the noninduced assessment compound (constructed of adjacent black bars) and that of the homogeneous square used in induction -- that is, the square aftereffect generalizes to square-like noninduced assessment compound.

The results of Experiment 4 suggest that, with multiple predictors of color during induction (e.g., FR and SQ), alterations in frame lightness attenuate (but do not eliminate) the indirect ME. Humphrey et al. (1989) employed procedures that involved induction with black-framed stimuli and assessment with white-framed stimuli, and reported the color aftereffects on orthogonal assessment stimuli that define the indirect ME. Such a finding is not contradictory to our findings, however, the results of this experiment suggest that the so-called indirect ME reported by Humphrey et al. (1989) would be enhanced if induction and assessment stimuli were contained in frames of the same lightness.

Experiment 5

The indirect ME is assessed by evaluating the aftereffect seen on a stimulus that contains the noninduced grid orientation. Most theorists have assumed that this grid elicits the indirect ME (e.g., Allan & Siegel, 1991; Humphrey et al., 1989), but the results of the prior experiments in this report indicate that the grid is <u>not</u> the elicitor of the indirect ME -- in fact, the novel grid serves to decrease the magnitude of the phenomenon. Rather, the FR and SQ elements of the assessment compound are responsible for the phenomenon. If this view is correct, assessment compounds that include the noninduced grid are not necessary to reveal the results of the induction procedure. Rather, assessment need only contain the elements that reliably predict color.

The results of Experiments 2, 3, and 4 did reveal a color aftereffect on gridless assessment figures, but these experiments differed from the typical indirect ME experiment in that there were three, rather than two, assessment stimuli. That is, the indirect ME is typically demonstrated by assessment with the induced and noninduced grids. This was the procedure followed in Experiment 1, where the current induction and assessment procedures effectively produced the phenomenon. The present experiment is the same as that of Experiment 1, except that the two assessment stimuli consist of the induced grid and a gridless square.

Method

Aftereffect induction, including counterbalancing of induction grid orientation (n=5/counterbalanced condition), was identical to that of Experiment 1. Aftereffect assessment was the same as that reported in Experiment 1, except that the two types of compounds were the induced grid orientation and the gridless square.

Results and Discussion

Figure 7 displays the mean pre- and postinduction psychometric functions (collapsed across induction grid orientation) for the induced grid and the gridless square. As is apparent from Figure 7, the grid and gridless assessment compounds yielded similar preinduction psychometric functions. After induction, however, there was a marked shift in psychometric function, depending upon the type of assessment compound. The grid appeared more pink (downward shift), while the gridless square appeared more green (upward shift).

Insert Figure 7 about here

The preinduction and postinduction number of green responses were computed as described in Experiment 1. As expected, the grid compound showed a significant decrease in the number of green responses from pre- to postinduction ($T = 0$, $N = 10$, $p < .01$), indicating that subjects reported these induced grid compounds as less green, or more pink, following the induction period. Also, and again as expected, the square compound showed a significant increase in the number of green responses from pre- to postinduction ($T = 1$, $N = 10$, $p < .05$) indicating that subjects reported these square compounds as more green following the induction period.

The results demonstrate that, following indirect ME induction, there is no need to present an orthogonal grid to demonstrate the effects of the procedure. Rather, the phenomenon may be seen on a gridless assessment stimulus that contains the FR and SQ elements that were paired with color during induction.

Experiment 6

According to the associative interpretation of the indirect ME, FR and SQ elements (not the noninduced orthogonal grid) elicit the indirect ME. Based on this associative interpretation, and on the results presented thus far, the IME might be expected to occur regardless of the content of the assessment display that is surrounded by the appropriate FR and SQ elements. For example, following induction with green $GRID_h$+FR_b+SQ and magenta FR_b+SQ, a FR_b+SQ assessment stimulus should elicit an aftereffect if it is compounded with a nonorthogonal grid orientation (e.g., 135^o diagonal grid, $GRID_{135}$). There are reports, however, that subjects do not report color aftereffects when assessed with nonorthogonal stimulus compounds (e.g., Allan & Siegel, 1991; Humphrey et al., 1989). Although these findings appear contrary to the associative analysis of the indirect ME, there is another interpretation. The failure to observe aftereffects elicited by a nonorthogonal stimulus compound might result because the elements of such compounds simultaneously elicit complementary aftereffects (i.e., both pink and green aftereffects are elicited), the result being that the assessment compound appears colorless. Orientation elements of the nonorthogonal assessment compound elicit aftereffects of one color due to stimulus generalization from the induction orientation (see Ellis, 1977); in the example described above (induction with green $GRID_h$+FR_b+SQ and magenta FR_b+SQ), the diagonal grids elicit a pinkish aftereffect as a result of generalization from the horizontal induction orientation. These aftereffects are opposed by the green aftereffect elicited by the FR_b and SQ elements. Because of these simultaneously elicited pink and green aftereffects, the diagonal assessment compound fails to elicit a measurable color aftereffect.

Experiment 6 was designed to provide another demonstration that subjects report no color aftereffects on noninduced, nonorthogonal grid stimuli (diagonal grids) following indirect ME induction (e.g., Siegel & Allan, 1991). In Experiment 6, subjects were induced with a black-framed green grid alternating with a black-framed magenta square. However, subjects were then assessed for color aftereffects using four assessment compounds: Individual black-framed compounds contained either the induced grid (e.g., horizontal), the noninduced orthogonal grid (vertical, in this example), the gridless square, or a noninduced nonorthogonal grid (i.e.,, diagonal).

Method

Aftereffect induction, including counterbalancing of induction grid orientation, was identical to that of Experiment 1, except that subjects observed 200 presentations each of a green grid and a magenta gridless square. In one induction condition, subjects (n=6) observed a green horizontal grid alternating with a magenta square. In the other induction condition, subjects (n=6) observed a green verical grid alternating with a magenta square. Aftereffect assessment was the same as that reported in Experiment 2, except that four types of compounds were presented during each assessment phase: subjects were presented with black-framed compounds including the induced grid orientation, the noninduced orthogonal grid orientation, no grid, or a nonorthogonal grid orientation (a 135° diagonal grid). The 135° diagonal assessment grids were composed of 29 bars (15 black bars alternating with 14 non-black bars) of the same width as the horizontal and vertical bars. Diagonal grids were the same size and shape as the vertical and horizontal grids. Each of the four types of stimulus compound (horizontal, vertical, gridless, and diagonal) was presented in each assessment color 7 times, for a total of 140 stimulus presentations during each assessment phase. During practice, each of the 16 color-orientation combinations (four colors and four assessment compounds) was presented twice (in random order).

Results

For ease of visual display, results of experiments using four assessment figures are presented in a manner consistent with the accompanying analysis. The sum of the pre- and postinduction green responses across the five assessment colors was determined for each subject separately for each of the four assessment compounds. Figure 8 displays the mean pre- and postinduction number of green responses for each of the four assessment compounds collapsed across the five levels of assessment color. These data were analyzed for differences from pre- to postinduction using the Wilcoxon signed-rank test. The number of green responses to the induced orientation was significantly decreased ($T = 0$, $N = 12$, $p < .01$) from pre- to postinduction, indicating that subjects reported the induced figure as less green, or more pink, after the induction period. In contrast, the number of green responses to the noninduced orthogonal orientation was significantly increased ($T = 0$, $N = 11$, $p < .01$) from pre- to postinduction, indicating that subjects reported the noninduced orthogonal assessment compound as more green after the induction period. Similarly, the number of green responses to the square assessment compound was significantly increased ($T = 0$, $N = 12$, $p < .01$) from pre- to postinduction, indicating that subjects reported the square assessment compound as more green after the induction period. Finally, the number of green responses to the nonorthogonal (diagonal) grid was not significantly changed ($T = 16.5$, $N = 11$, $p > .05$) from pre- to postinduction, indicating that subjects' reported perception of these stimuli had not changed following the induction period.

Insert Figure 8 about here

Discussion

This experiment reproduces the results reported in prior experiments in the present report, as well as those previously reported by others (e.g., Allan & Siegel, 1991; Humphrey et al., 1989). That is, following an induction period where a colored grid alternates with a colored gridless square, subjects demonstrate the ME (aftereffects are reported on the induced grid) and the indirect ME (aftereffects are reported on the noninduced orthogonal grid), but subjects also report that the gridless square assessment compound appears colored. Moreover, Experiment 6 also reproduces results relating to noninduced nonorthogonal stimuli (e.g., Allan & Siegel, 1991; Humphrey et al., 1989). That is, following an indirect ME induction procedure, noninduced nonorthogonal (diagonal) stimuli elicit no measurable color aftereffect.

Experiment 7

Experiment 6 demonstrated that noninduced nonorthogonal grid compounds do not elicit measurable color aftereffects following an induction period where a green grid is alternated with a magenta square. According to the associative interpretation of color aftereffects presented here, noninduced nonorthogonal grid compounds simultaneously elicit complementary aftereffects (i.e., both pink and green aftereffects are elicited), the result being that the assessment compound appears colorless. Orientation elements of the nonorthogonal assessment compound elicit aftereffects of one color due to stimulus generalization from the induction orientation (see Ellis, 1977); in the example described above, (induction with green $GRID_h$+FR_b+SQ and magenta FR_b+SQ), the diagonal grids elicit a pinkish aftereffect as a result of generalization from the horizontal induction orientation. This aftereffect is opposed by the green aftereffect elicited by the FR_b and SQ elements. Because of these simultaneously elicited pink and green aftereffects, the diagonal assessment compound fails to elicit a measurable color aftereffect.

If either the grid or the frame element that elicit the opposing color aftereffects failed to elicit that aftereffect, the other element's aftereffect should be observable. That is, if FR_b no longer elicited the green aftereffect in the example above, then diagonal grids should appear pink, because there is no green aftereffect to cancel out the aftereffect elicited by the diagonal grid. In Experiment 4 an induction procedure was introduced that reduces the aftereffect elicited by frame lightness elements: the irrelevant frames induction procedure. The irrelevant frames induction procedure is again used here, in order to determine if, when frame lightness is made irrelevant during induction, nonorthogonal grids elicit color aftereffects during assessment.

Using the irrelevant frames induction procedure, frame lightness is not a reliable predictor of color during induction. Thus FR should fail to elicit an aftereffect during assessment (see Experiment 4). Although the FR element should not elicit color aftereffects, other elements remain reliable predictors of color. As may be seen in the example irrelevant frames induction procedure diagrammed in Figure 5, $GRID_h$+SQ is always green, and SQ is always magenta. The aftereffect elicited by the elements of the $GRID_h$+SQ compound is determined by the overshadowing phenomenon demonstrated in Experiment 2. That is, subjects will less strongly associate color with SQ when SQ is compounded with $GRID_h$ than when SQ is presented in the gridless figure. In the latter case, subjects will associate SQ with color. Thus the irrelevant frames induction procedure diagrammed in Figure 4 favors two associations: $GRID_h$ is associated with green, and SQ is associated with magenta.

Like Experiment 6, The present experiment is designed to reproduce results reported in previous experiments, as well as testing predictions regarding noninduced nonorthogonal grid effects. As in Experiment 6, subjects are assessed with four assessment compounds: $GRID_h$+FR_b+SQ, $GRID_v$+FR_b+SQ, FR_b+SQ, and $GRID_{135}$+FR_b+SQ. When presented with the $GRID_h$+FR_b+SQ assessment compound, $GRID_h$ should elicit a color aftereffect, since FR was made irrelevant during induction and $GRID_h$ overshadows SQ -- the $GRID_h$+FR_b+SQ assessment compound should appear pink. When presented with the FR_b+SQ assessment compound, SQ should elicit a color aftereffect since FR was made irrelevant -- the FR_b+SQ compound should appear green. When presented with the $GRID_v$+FR_b+SQ assessment compound, SQ is the only element that is a reliable predictor of color, since FR was made irrelevant and $GRID_v$ was never paired with color. However, the aftereffect elicited by the SQ element is attenuated by the novel GRID element, thus the magnitude of the aftereffect elicited by the SQ element of a $GRID_v$+FR_b+SQ assessment compound following an irrelevant frames induction procedure should be small. Finally, when presented with a $GRID_{135}$+FR_b+SQ assessment compound, both $GRID_{135}$ and SQ might be expected to elicit color aftereffects, while FR_b should not. While $GRID_{135}$ was never paired with color, this element is expected to elicit a color aftereffect (pink) due to stimulus generalization from the induced GRID ($GRID_h$). While the SQ element was paired with color during induction, the aftereffect elicited by the SQ element is attenuated by the novel GRID element as above. Thus to the extent that generalization from the induced GRID element is greater than the attenuated SQ aftereffect, $GRID_{135}$+FR_b+SQ assessment compounds should appear pink.

Method

Subjects were run in one of two induction conditions, counterbalanced with respect to induction grid orientation. In one induction condition, subjects (n=10) observed a green horizontal grid alternating with a magenta square. In the other induction condition, subjects (n=10) observed a green vertical grid alternating with a magenta square. As in Experiment 6, subjects observed 200 presentations each of a green grid and a gridless magenta square. However, in the current experiment, half of these presentations were compounded with FR_b, and half with FR_w (see Figure 5 for an example of this irrelevant frames induction procedure).

Results

Figure 9 displays the mean pre- and postinduction number of green responses for each of the four types of assessment figures. These data were analyzed for differences from pre- to postinduction using the Wilcoxon signed-rank test. The number of green responses to the induced orientation was significantly decreased ($T = 0$, $N = 20$, $p < .01$) from pre- to postinduction, indicating that subjects reported the induced figure as less green, or more pink, after the induction period. In contrast, the number of green responses to the noninduced orthogonal orientation was not significantly changed ($T = 59.5$, $N = 17$, $p > .05$) from pre- to postinduction. However, the number of green responses to the square assessment compound was significantly increased ($T = 0$, $N = 20$, $p < .01$) from pre- to postinduction, indicating that subjects reported the square assessment compound as more green after the induction period. Finally, the number of green responses to the diagonal grid was significantly decreased ($T = 0$, $N = 19$, $p < .01$) from pre- to postinduction, indicating that subjects reported the noninduced nonorthogonal assessment compound as less green, or more pink, after the induction period.

Insert Figure 9 about here

Both the induced orientation assessment compound and the diagonal grid appeared more pink after induction. The magnitude of the aftereffect elicited by assessment compounds containing the induced grid was significantly greater than that elicited by those containing the diagonal grid (mean induced grid aftereffect score = -13.5; mean diagonal grid aftereffect score = -6.5; $T = 0$, $N = 20$, $p < .01$).

Discussion

According to the associative analysis of the indirect ME, noninduced nonorthogonal grid stimuli should elicit color aftereffects following indirect ME induction. These aftereffects have not been observable (e.g., Allan & Siegel, 1991) because the aftereffect elicited by the noninduced nonorthogonal grid element is opposed by the complementarily colored aftereffect elicited by the frame that surrounds the grid element. The grid element elicits color due to stimulus generalization from the induced grid, and the frame element elicits color because it reliably predicted color during induction.

The results reported here support this associative analysis. When frame lightness is no longer a reliable predictor of color, as in an irrelevant frames induction procedure, the frame element of an assessment compound no longer elicits a color aftereffect (see Experiment 4). Because there is no frame-elicited aftereffect, assessment compounds containing noninduced nonorthogonal grids do elicit an observable color aftereffect. Following an irrelevant frames induction procedure, subjects report that noninduced nonorthogonal grid stimuli appear to be the same color as the induced grid, but the magnitude of this aftereffect is significantly less than that elicited by the induced grid.

Experiment 8

The results of Experiment 7 demonstrated that, when frame is made irrelevant with respect to color during induction, noninduced nonorthogonal grid stimuli elicit a color aftereffect. This nonorthogonal grid aftereffect is of the same color as, but of lesser magnitude than the aftereffect elicited by the induced grid. According to the associative analysis of the indirect ME, the aftereffect elicited by assessment compounds containing nonorthogonal grids is due to stimulus generalization from the induction orientation. The fact that, after an irrelevant frames induction procedure, compounds containing a nonorthogonal grid elicit an aftereffect the same color as, but of lesser magnitude than, the induced grid aftereffect supports this associative analysis. This support would be strengthened by a demonstration that the magnitude of the nonorthogonal grid aftereffect depends upon the degree of similarity to the induced grid orientation. As the orientation of the nonorthogonal grid approaches the orientation of the induced grid, the magnitude of the aftereffect elicited by the nonorthogonal grid should increase. Thus, if the induced grid is a horizontal grid (180° bars), and an irrelevant frames induction procedure is used, a 112° grid should elicit an aftereffect of lesser magnitude than a 135° grid, which in turn should elicit an aftereffect of lesser magnitude than a 157° grid. Experiment 8 was designed to test this prediction. All subjects were induced with an irrelevant frames induction procedure, but three independent groups of subjects differed with respect to the orientation of the nonorthogonal grid used during assessment.

Method

Apparatus. In the present experiment, subjects' head orientation was maintained throughout the experiment by the use of a head restraint equipped with chin rest, forehead rest, and orientation stabilizers (Applied Scientific Laboratories, Model 819-2150).

Aftereffect induction. During induction, all subjects observed a green horizontal grid alternating with a magenta square. As in Experiment 7, subjects observed an irrelevant frames induction procedure consisting of 200 presentations each of the green grid and the gridless magenta square, with half of these presentations compounded with FR_b, and half with FR_w (see Figure 5).

Aftereffect measurement. In general, aftereffect measurement was the same as in Experiment 7. Subjects were assessed using compounds that contained the induced grid, the noninduced orthogonal grid, no grid, and a noninduced nonorthogonal grid. Subjects were assigned to one of three groups (n=10 / group) that differed with respect to the orientation of the nonorthogonal grid bars during both pre- and postinduction assessment. One group (Group 135) was assessed with the nonorthogonal grid made up of 29, 135° grid bars (15 black bars alternating with 14 non-black bars) that was used in Experiments 6 and 7. This group was therefore induced and assessed identically to the subjects in Experiment 7, with the addition of the head restraint. Another group (Group 112) was assessed with the nonorthogonal grid made up of 26, 112° grid bars (13 black bars alternating with 13 non-black bars). The third group (Group 157) was assessed with the nonorthogonal grid made up of 26, 157° grid bars (13 black bars alternating with 13 non-black bars).

Results

Group 135 of the present experiment represents assessment and induction procedures identical to those used in Experiment 7 (except for the use of the head restraint in the present experiment). Accordingly, pre- and postinduction number of green responses for assessment compounds from Group 135 were analyzed (Wilcoxon signed-ranks test) to determine if the subjects demonstrated a similar pattern of results to those reported in Experiment 7. In fact, the pattern of results for Group 135 was identical to those reported in Experiment 7. That is, the number of green responses to the induced orientation was significantly decreased ($T = 0$, $N = 10$, $p < .01$) from pre- to postinduction, indicating that subjects in Group 135 reported the induced figure as less green, or more pink, after the induction period. In contrast, the number of green responses to the noninduced orthogonal orientation was not significantly changed ($T = 15.5$, $N = 10$,

$p > .05$) from pre- to postinduction, indicating that subjects' reported perception of these stimuli had not changed following the induction period. However, the number of green responses to the square assessment compound was significantly increased ($T = 0$, $N = 9$, $p < .01$) from pre- to postinduction, indicating that subjects reported the square assessment compound as more green after the induction period. Finally, the number of green responses to the diagonal grid was significantly decreased ($T = 0$, $N = 10$, $p < .01$) from pre- to postinduction, indicating that subjects reported the noninduced nonorthogonal assessment compound as less green, or more pink, after the induction period. As in Experiment 7, the magnitude of the aftereffect elicited by assessment compounds containing the induced grid was significantly greater than that elicited by those containing the diagonal grid (mean induced grid aftereffect score = -14.6; mean diagonal grid aftereffect score = -6.9; $T = 0$, $N = 10$, $p < .01$).

Group 157 displayed a pattern of results similar to Group 135. That is, the number of green responses to the induced orientation was significantly decreased ($T = 0$, $N = 10$, $p < .01$), the number of green responses to the noninduced orthogonal orientation was not significantly changed ($T = 11.5$, $N = 9$, $p > .05$), the number of green responses to the square assessment compound was significantly increased ($T = 0$, $N = 10$, $p < .01$), and the number of green responses to the diagonal grid (157^{o}) was significantly decreased ($T = 2.5$, $N = 9$, $p < .05$) from pre- to postinduction.

Group 112 displayed a similar pattern of results with respect to the induced grid, orthogonal grid, and gridless square compounds, but differed with respect to the nonorthogonal (112^{o}) grid compounds. That is, the number of green responses to the induced orientation was again significantly decreased ($T = 0$, $N = 10$, $p < .01$), the number of green responses to the noninduced orthogonal orientation was not significantly changed ($T = 22$, $N = 9$, $p > .05$), and the number of green responses to the square assessment compound was significantly increased ($T = 0$, $N = 8$, $p < .01$). However, the number of green responses to the diagonal grid was not significantly altered ($T = 11$, $N = 9$, $p > .05$) from pre- to postinduction, indicating that subjects had not altered their perceived color of these compounds from pre- to postinduction.

The present experiment was designed to test a prediction made using an associative interpretation of the indirect ME: As the orientation of the nonorthogonal grid approaches the orientation of the induced grid, the magnitude of the aftereffect elicited by the nonorthogonal grid should increase. In the present experiment the induced grid was a horizontal grid (180°). Therefore, a 112° grid should elicit an aftereffect of lesser magnitude than a 135° grid, which in turn should elicit an aftereffect of lesser magnitude than a 157° grid. In order to gain a relative measure of generalization from the induced grid compound to the diagonal grid compound, a ratio of diagonal aftereffect magnitude to induced grid aftereffect magnitude was determined. First, aftereffect scores were calculated for all subjects for both stimulus compounds. The ratio of the nonorthogonal aftereffect over the induced grid aftereffect was then calculated, resulting in an "aftereffect ratio" for each subject. This ratio reflects the proportion of the induced grid aftereffect that generalized to the nonorthogonal grid. For instance, if a subject in Group 135 demonstrated an induced grid aftereffect score of -12 (the negative sign indicates this compound was seen as pink, with an aftereffect magnitude of 12), and a nonorthogonal grid aftereffect score of -6, that subject received an aftereffect ratio of .50.

According to an associative interpretation, then, subjects in Group 112 should demonstrate aftereffect ratios smaller than those demonstrated by subjects in Group 135, who in turn should demonstrate aftereffect ratios smaller than those received by subjects in Group 157. The average aftereffect ratio is plotted by group in Figure 10. As is apparent from the figure, Group 112 showed the smallest mean aftereffect ratio and Group 157 showed the highest mean aftereffect ratio. These data were statistically analyzed using a nonparametric trend test (the Terpstra-Jonckheere test of ordered alternatives, Neave & Worthington, 1988). All tied scores in this analysis were counted as evidence against the ordered alternative hypothesis. This analysis revealed a significant trend ($W = 62$, $p < .01$), indicating that aftereffect ratios were ordered as predicted by an associative interpretation of color aftereffects.

Insert Figure 10 about here

Discussion

The present experiment provides further support for an associative account of color aftereffects that incorporates stimulus generalization. That is, this experiment demonstrated that, when frame is made irrelevant with respect to color during indirect ME induction, noninduced nonorthogonal grid compounds elicit aftereffects with a magnitude that is dependent upon the nonorthogonal grid's degree of similarity to the induced grid.

General Discussion

The results of these experiments support an associative interpretation of the indirect ME. Indirect ME induction stimuli are conceptualized as compound stimuli with elements of unequal salience. Following an induction period where a GRID+FR+SQ compound is paired with color, the GRID element elicits a color aftereffect. The GRID overshadows the other elements of the compound because it is the most salient element. When no grid is present during induction, for instance when a FR+SQ compound is paired with color, the less salient FR and SQ elements come to elicit color aftereffects. The indirect ME demonstrated in Experiment 1 can be interpreted as the result of an association between an FR+SQ compound stimulus and color. That is, color aftereffects reported on noninduced grid stimuli are elicited by frame-lightness and form elements, not orientation.

Experiment 1 replicated the indirect ME as reported, for example, by Allan and Siegel (1991) and by Humphrey et al. (1989). The results of Experiment 2 supported the primary assumption of the associative view of the indirect ME: FR+SQ compounds are effective elicitors of color aftereffects when presented without a GRID during induction, but fail to elicit aftereffects when compounded with a GRID during induction. That is, GRID overshadows FR and SQ. Experiment 3 provided another demonstration that gridless FR+SQ assessment compounds elicit color aftereffects, and also demonstrated that these aftereffects are greater in magnitude than aftereffects on compounds that contain the noninduced grid. Experiment 4 demonstrated that reducing the correlation between FR and color during induction decreases the magnitude of the aftereffect elicited by the noninduced grid. In Experiment 5, the indirect ME procedure demonstrated to be effective in Experiment 1 was modified. Rather than assessing the indirect ME on a stimulus that contains the orthogonally-oriented grid, the aftereffect was assessed on a stimulus that contained no grid. The results of Experiment 5 indicated that the noninduced grid is not necessary for observation of the effects of an indirect ME induction procedure. Taken together, these results suggest that the indirect ME can be conceptualized within an associative framework that already provides important insight into the mechanism underlying the ME.

Experiment 6 replicated earlier findings (e.g., Allan & Siegel, 1991) of no aftereffect on a noninduced nonorthogonal grid. According to the associative interpretation presented here, noninduced nonorthogonal stimuli elicit two complementary color aftereffects following a typical indirect ME induction procedure. The grid element elicits a color aftereffect due to stimulus generalization from the induced GRID, and the FR and SQ elements elicit a complementary aftereffect because they were associated with color during induction. Noninduced nonorthogonal stimuli appear noncolored because these two complementary color aftereffects oppose one another. The results of Experiments 7 and 8 support this interpretation of the failure of compounds containing nonorthogonal grids to elicit color aftereffects. When frame is made irrelevant with respect to color during induction, a nonorthogonal grid compound does elicit color (Experiment 7). In fact, the nonorthogonal compound appears the same color as the induced GRID compound, but the magnitude of this nonorthogonal aftereffect is less than that elicited by the induced GRID. Moreover, as the degree of orientation of the nonorthogonal grid approaches that of the induced GRID, the magnitude of the aftereffect elicited by the nonorthogonal grid increases (Experiment 8).

It is important to note that previous studies that have addressed stimulus generalization and color aftereffects have been primarily limited to the ME (e.g., Ellis, 1977; McCollough, 1965). These studies conclude that while generalization of the ME does occur (MEs of decreasing magnitudes are reported on orientations other than those with which subjects were induced), generalization does not occur when test stimuli are tilted 45° away from the inducing stimulus (e.g., 135° grids, when subjects were induced with vertical and horizontal grid). These findings do not demonstrate that generalization is not possible at a 45° rotation, rather that such generalization is not observed following induction with orthogonal grids (i.e., ME induction). It is likely that generalization is not observed at 45° rotation because the generalized horizontal aftereffect is complementary to the generalized vertical aftereffect.

Associative Interpretations of the Indirect ME and Orthogonal Coding Mechanisms in Vision

The indirect ME traditionally has been defined as the aftereffect seen on the noninduced orthogonal orientation. Our suggestion that this orthogonal orientation component of the assessment stimulus may be extraneous to the indirect ME contrasts with alternative interpretations of the phenomenon. Indeed, according to the prominent alternative interpretation, the indirect ME provides evidence for orthogonal orientation coding mechanisms in the visual system (Allan & Siegel, 1991; Dodwell & Humphrey, 1990; Humphrey et al., 1989). This interpretation of the indirect ME is based on Dodwell and colleagues' suggestion that contingent color aftereffects are most readily elicitable by global vectorfields specified in the Lie transformation group theory of neuropsychology ("LTG/NP," named for the Norwegian mathematician, Sophus Lie). Patterns described by Lie transformations are orthogonal -- if superimposed on each other their contours will be perpendicular at every point of intersection. Thus, pairs of grids differing in orientation by 90 degrees (e.g., horizontal and vertical grids) are Lie derivatives; so is the pair constructed of concentric circles and radial lines (like the spokes of a wheel).

According to LTG/NP, stimulation with one pattern leads to reduced sensitivity in that pattern's coding mechanism. Consequently, when the pattern is no longer present, contrasting (orthogonal) pattern coding mechanisms are, relative to the less sensitive coding mechanism, more strongly activated: "This new level of activity is associated with color that is present following the inducing pattern" (Humphrey et al., 1989, p. 107). For example, when subjects observe a green horizontal grid, the coding mechanism for that grid is activated, and associated with green. Repeated presentations of the horizontal grid reduce the sensitivity of the coding mechanism. Thus, due to the reduced sensitivity of the horizontal grid coding mechanism, the orthogonal coding mechanism (vertical) is the more activated mechanism when no grid is present. If a color, like magenta, is presented during this period of relative orthogonal mechanism activation, that coding mechanism is paired with the color. Consequently, using LTG/NP, vertical (noninduced) grids elicit color because the more activated vertical grid coding mechanism has been paired with magenta during induction.

There is considerable evidence for the utility of the LTG/NP in understanding a variety of visual phenomena (e.g., Gibson & Radner, 1937; MacKay, 1957a, 1957b), and it is possible to incorporate the orthogonally paired coding mechanisms suggested by the LTG/NP interpretation of the indirect ME into an associative account of the phenomenon. Siegel and Allan (1992) suggested that, just as particular orientation can be associated with color to yield the ME, an indirectly activated orthogonal coding mechanism can be associated with color to yield the indirect ME; although the CS of the CS-UCS pairing occurs due to indirect coding mechanism activation, the nature of the CS-UCS association is Pavlovian.

The results of the present experiments do not support interpretations of the indirect ME that emphasize the contribution of orthogonal contour coding mechanisms (e.g., Allan & Siegel, 1991; Humphrey et al., 1989). For example, according to Humphrey et al. (1989) "the maximum contrast in orientation coding occurs for orientations approximately perpendicular to the inducing pattern" (p 107). If this statement is correct, then orthogonally oriented stimuli should be the best elicitors of color. They are not. The data presented here demonstrate that gridless compounds (with the appropriate FR and SQ elements) elicit greater aftereffects than do orthogonally oriented (noninduced) grid compounds. Furthermore, the current LTG/NP model of the indirect ME cannot account for a noninduced grid effect that is reduced in magnitude following an induction procedure that reduces the correlation between frame lightness and color. In fact, when looked at from a conditioning perspective, indirect ME induction procedures provide no reason to postulate orthogonal grid coding mechanisms at all. Following indirect ME induction, when subjects are assessed with two stimuli, the aftereffect that typically defines the indirect ME is readily demonstrated when it is assessed with a stimulus that contains the noninduced grid (Experiment 1), but also when it is assessed with a gridless stimulus (Experiment 5). LTG/NP must be modified if it is to be used as an account for these characteristics of the indirect ME.

Conclusions

Although the data reported in these eight experiments support the associative analysis of the indirect ME, there are other data that are more consistent with the LGT/NP. For example, Humphrey et al. (1989) reported that alternation of two colored nonorthogonal patterns (e.g., a green horizontal grid in a circular frame and red concentric circles) induces an indirect ME (in this example, vertical grids appear pink and radial lines appear green). Such a finding is unexpected if, as hypothesized here, grids overshadow other elements of the induction stimuli. Humphrey et al. (1989) also induced subjects with black-framed concentric circle patterns alternating with a homogeneous complementarily colored field, and observed indirect MEs on white-framed radial line patterns (orthogonal), but not on vertical or horizontal grids (nonorthogonal). Such a finding is not readily interpretable by the aftereffect mutual-cancellation explanation of the failure of nonorthogonal orientation stimuli to elicit color aftereffects (Experiments 6-8 of the present report). It should be noted that the experiments reported by Humphrey et al. (1989) used composite assessment figures (all orientations are present on the assessment figure), and a color-naming assessment procedure. As mentioned by Humphrey et al. (1989), such composite assessment patterns are conducive to observation of simultaneous color contrast (see Stromeyer, 1984), and color-naming may be insensitive. Indeed, simple color-naming sometimes fails to reveal aftereffects that are obtained with the method-of-constant-stimuli procedure used in the present experiments (Siegel et al., 1992, Experiment 1). Further research can determine whether such methodological differences are relevant to understanding the various findings, or whether the associative interpretation of the indirect

ME will need some modification. The LTG/NP interpretation will also require some modification to address the findings of the present experiments -- especially the fact that, at least in some circumstances, the noninduced orthogonal grid is not only unnecessary for the indirect ME, but actually attenuates the effect.

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Footnote

1. All tests are two-tailed. Where the number of green responses did not change from pre- to postinduction, the resulting difference score was 0. Difference scores of 0 were excluded from this and subsequent Wilcoxon analyses, and the degrees of freedom are decreased accordingly.

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Figure Captions

Figure 1. Pre- and postinduction psychometric functions for Experiment 1.

Figure 2. An example of the induction and assessment stimuli for each group in Experiment 2.

Figure 3. Pre- and postinduction psychometric functions for Group IME (Panel A) and Group ME (Panel B) of Experiment 2.

Figure 4. Pre- and postinduction psychometric functions for Experiment 3A (Panel A) and 3B (Panel B).

Figure 5. An example of the induction and assessment stimuli for the irrelevant frames induction procedure in Experiment 4.

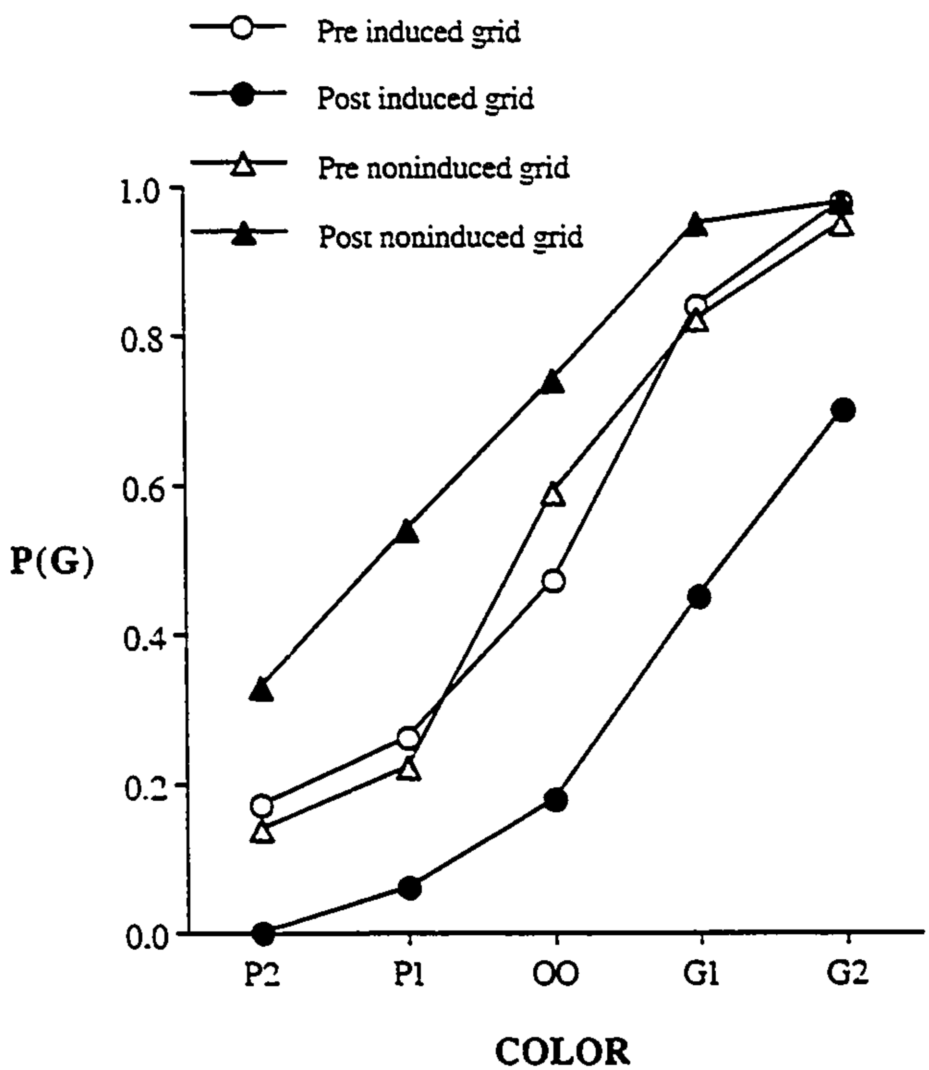
Figure 6. Pre- and postinduction psychometric functions for Experiment 4.

Figure 7. Pre- and postinduction psychometric functions for Experiment 5.

Figure 8. Pre- and postinduction number of green responses, by assessment compound, for Experiment 6.

Figure 9. Pre- and postinduction number of green responses, by assessment compound, for Experiment 7.

Figure 10. Mean aftereffect ratios (diagonal aftereffect score divided by induced grid aftereffect score) by group for Experiment 8.


Pre induced grid
Post induced grid
Pre noninduced grid
Post noninduced grid
1.0
0.8
0.6
0.4
0.2
0.0
P(G)
P2
P1
OO
G1
G2
COLOR

Induction Compounds for Experiment 2

Group IME Induction

Green
$GRID_h + FR_b + SQ$

Magenta
$FR_b + SQ$

Group ME Induction

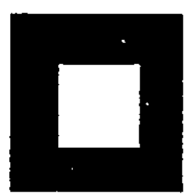
Green
$GRID_h + FR_b + SQ$

Magenta
$GRID_v + FR_b + SQ$

Assessment Compounds for Experiment 2 -- All Subjects

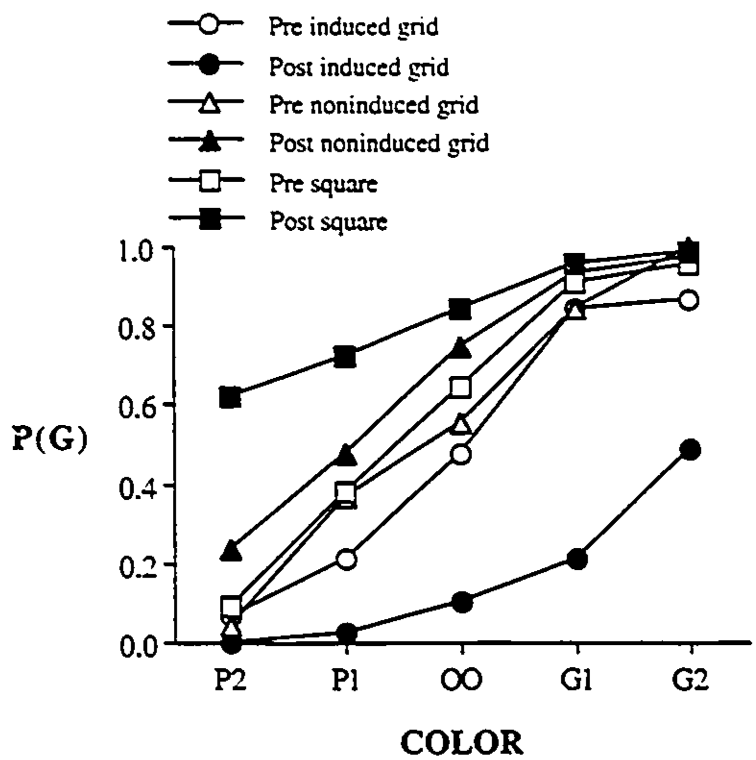
$GRID_h + FR_b + SQ$

$GRID_v + FR_b + SQ$

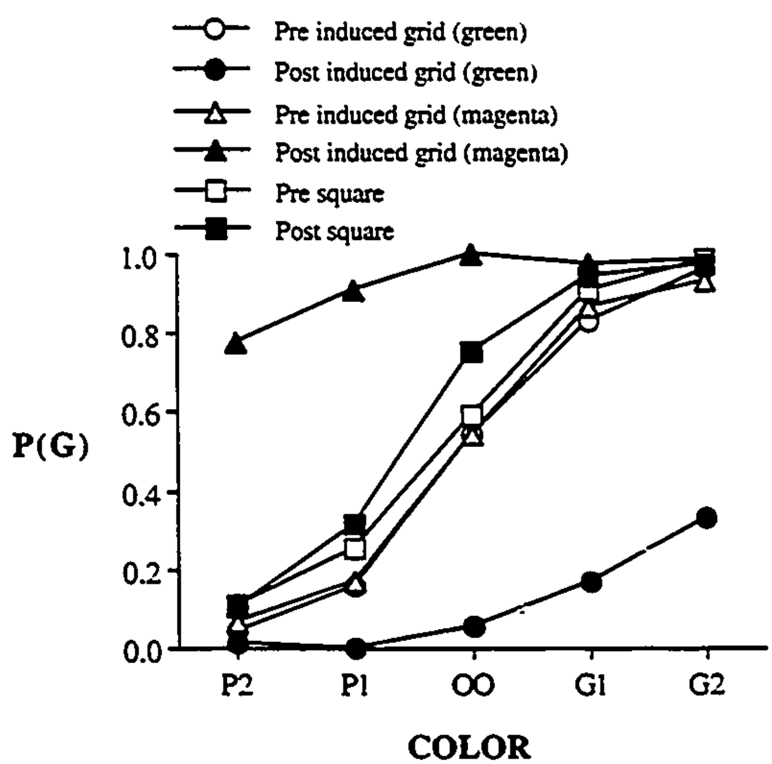


$FR_b + SQ$

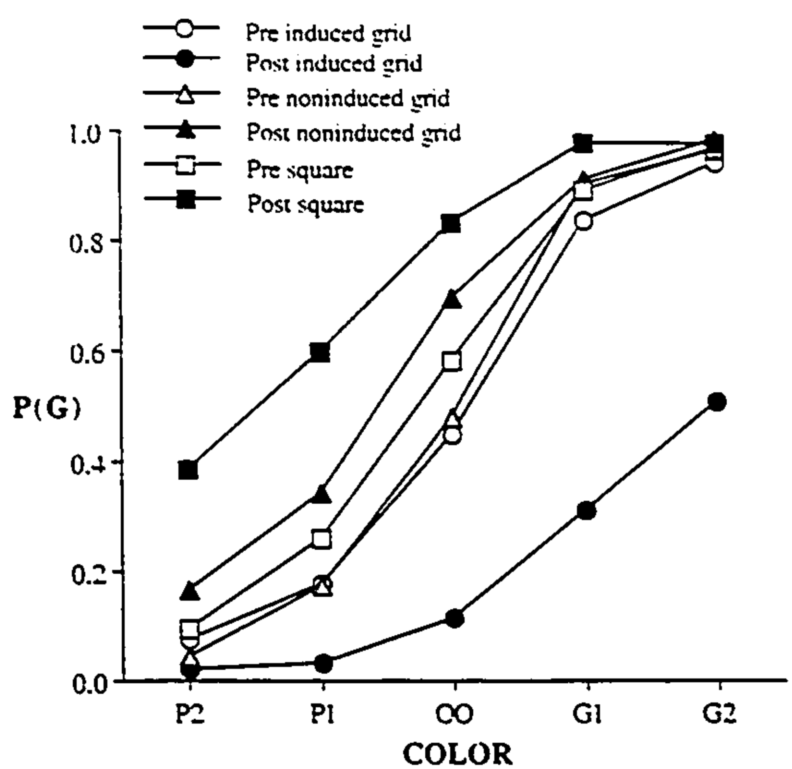
A


Pre induced grid
Post induced grid
Pre noninduced grid
Post noninduced grid
Pre square
Post square
1.0
0.8
0.6
0.4
0.2
0.0
P(G)
P2
P1
OO
G1
G2
COLOR

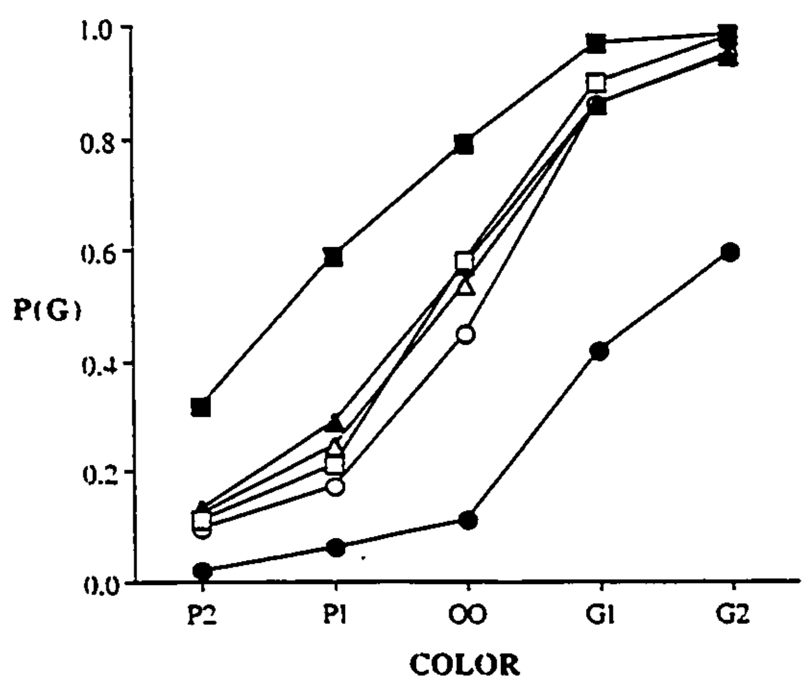
B


Pre induced grid (green)
Post induced grid (green)
Pre induced grid (magenta)
Post induced grid (magenta)
Pre square
Post square
1.0
0.8
0.6
0.4
0.2
0.0
P(G)
P2
P1
OO
G1
G2
COLOR

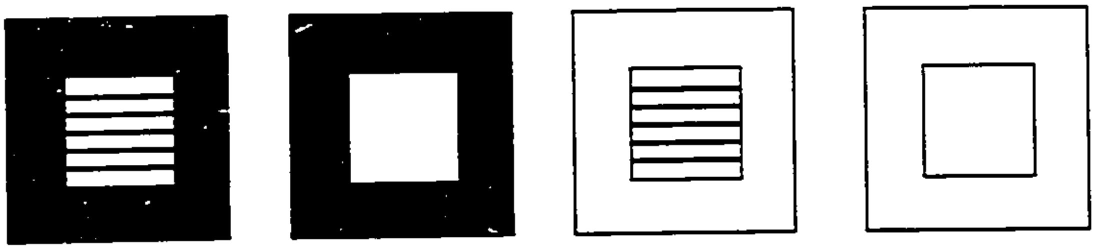
A


Pre induced grid
Post induced grid
Pre noninduced grid
Post noninduced grid
Pre square
Post square
1.0
0.8
0.6
0.4
0.2
0.0
P(G)
P2
P1
OO
G1
G2
COLOR

B


1.0
0.8
0.6
0.4
0.2
0.0
P(G)
P2
P1
OO
G1
G2
COLOR

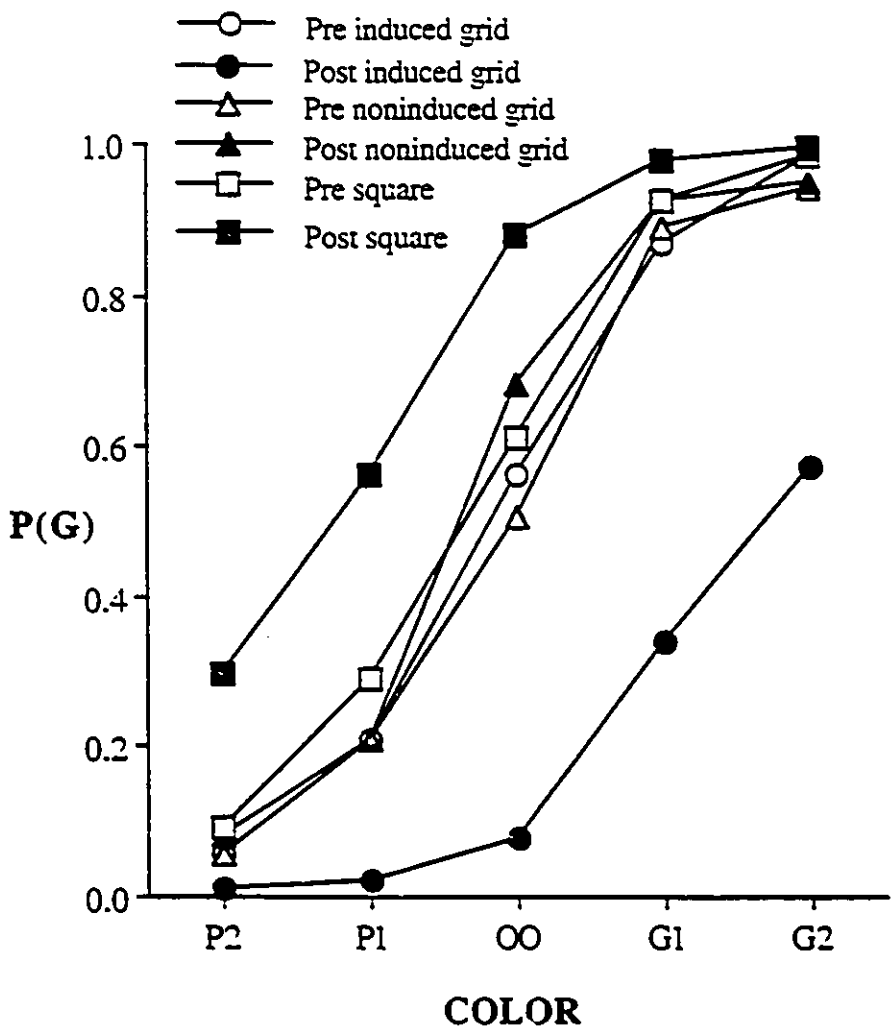
The Irrelevant Frames Induction Procedure

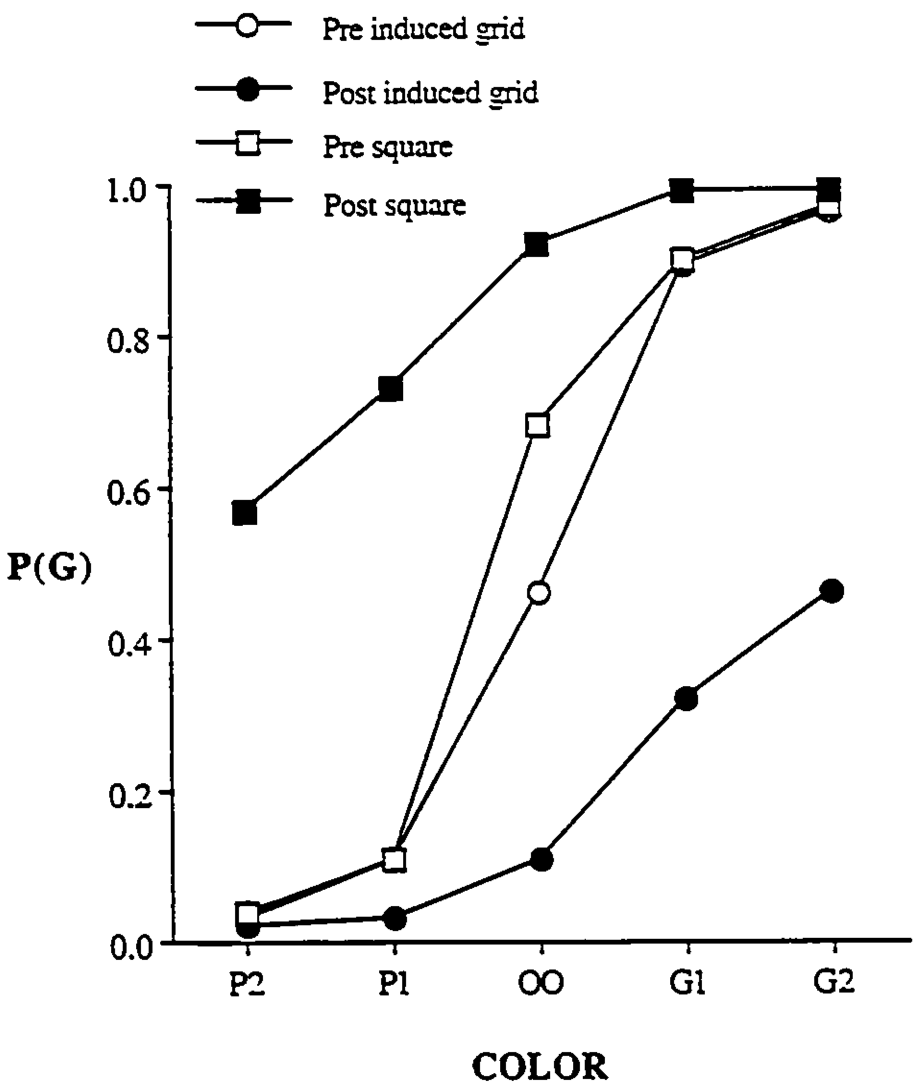


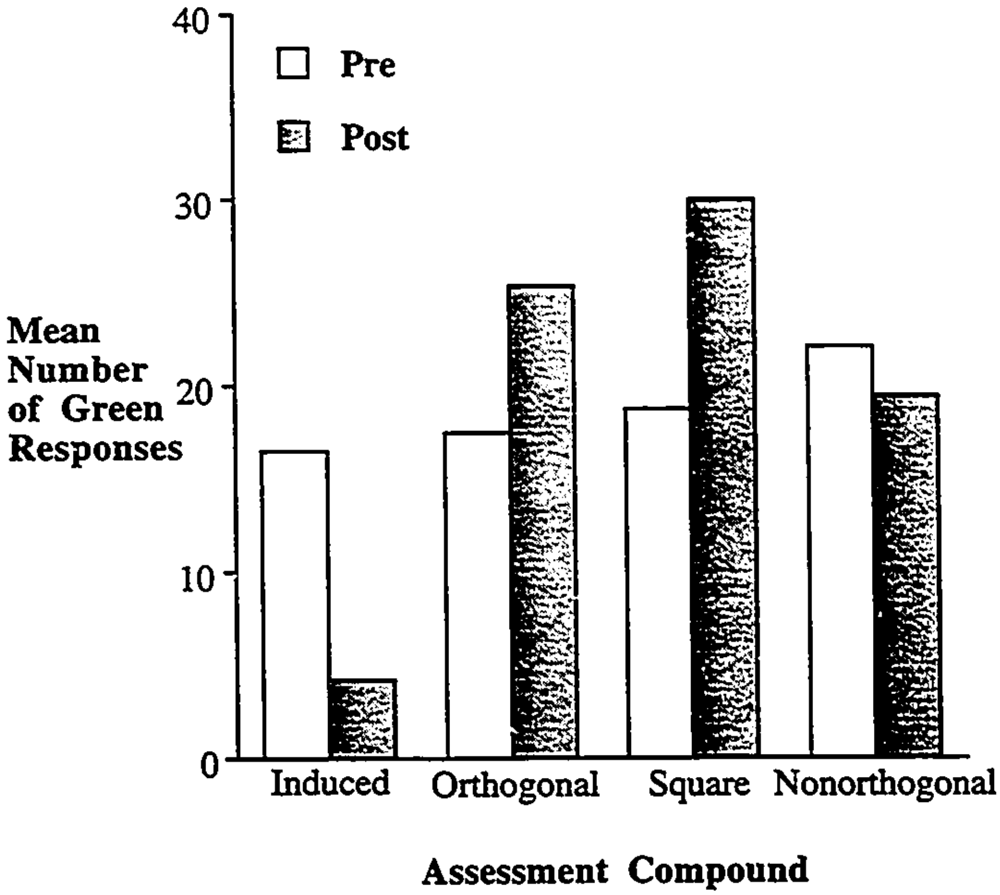
Green $GRID_h + FR_b + SQ$ | Magenta $FR_b + SQ$ | Green $GRID_h + FR_w + SQ$ | Magenta $FR_w + SQ$

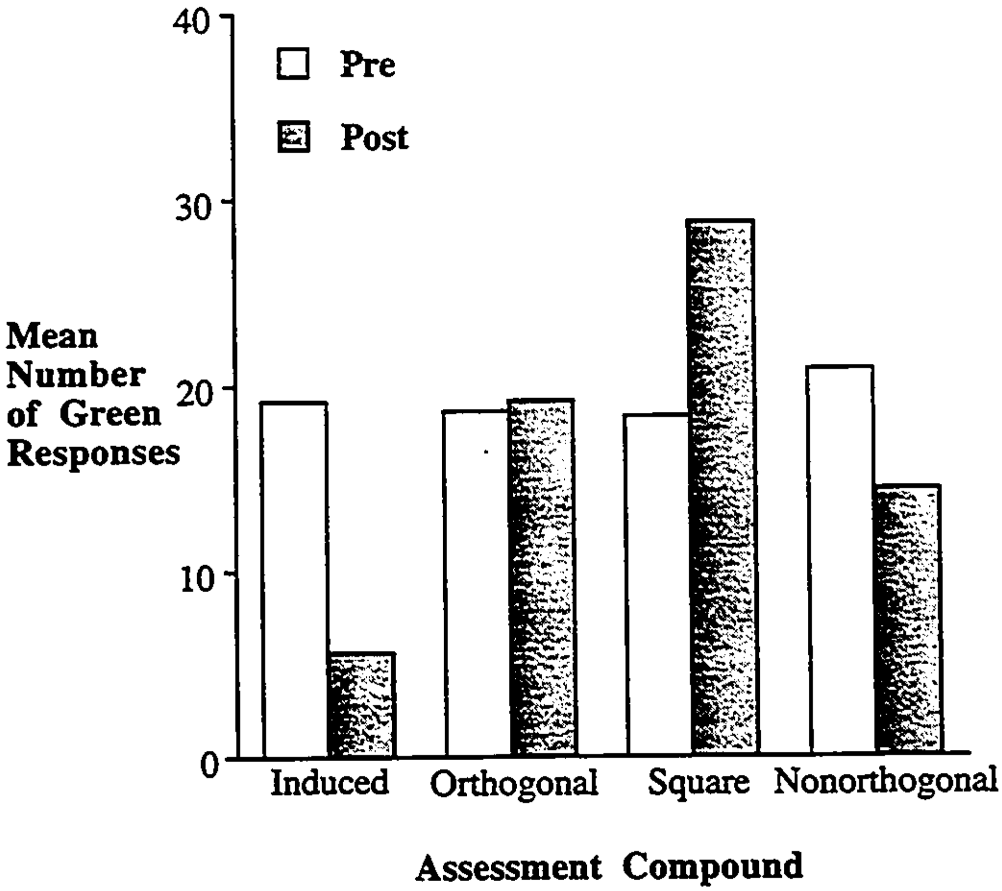
Assessment Compounds

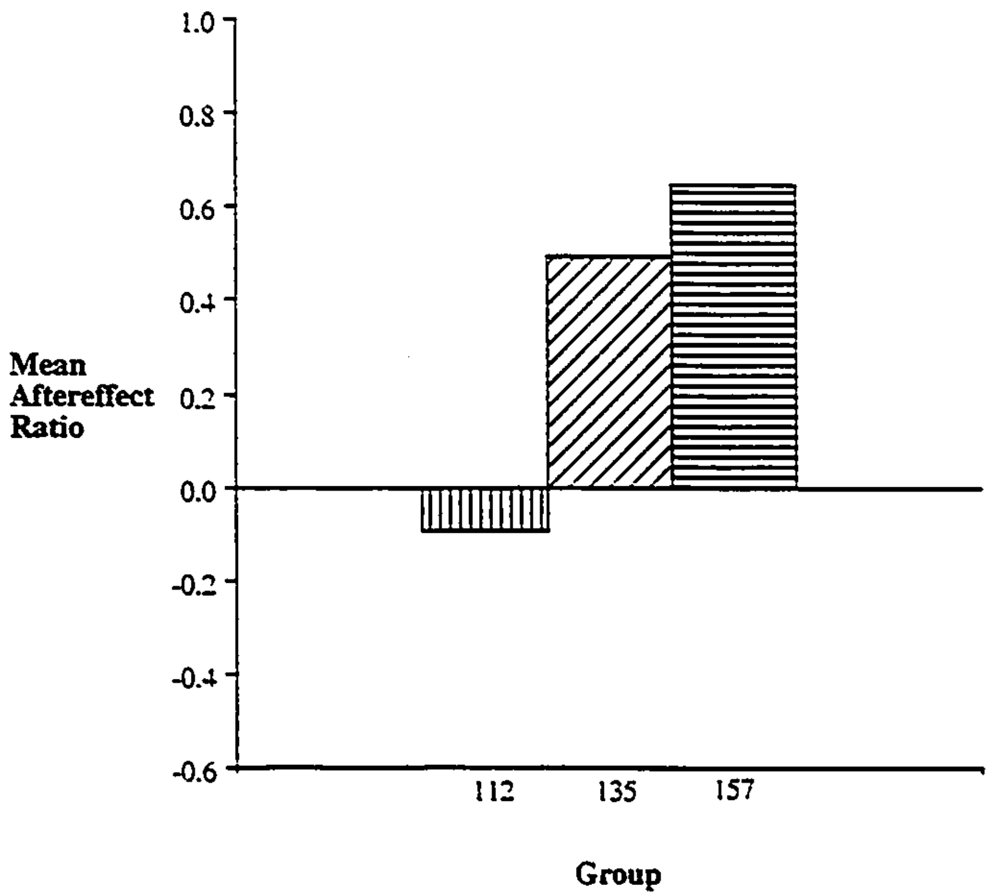
$GRID_h + FR_b + SQ$ | $GRID_v + FR_b + SQ$ | $FR_b + SQ$


Pre induced grid
Post induced grid
Pre noninduced grid
Post noninduced grid
Pre square
Post square
1.0
0.8
0.6
0.4
0.2
0.0
P(G)
P2
P1
OO
G1
G2
COLOR


Pre induced grid
Post induced grid
Pre square
Post square
P(G)
1.0
0.8
0.6
0.4
0.2
0.0
P2
P1
OO
G1
G2
COLOR


40
30
20
10
0
Pre
Post
Mean Number of Green Responses
Induced
Orthogonal
Square
Nonorthogonal
Assessment Compound


40
30
20
10
0
Pre
Post
Mean
Number
of Green
Responses
Induced
Orthogonal
Square
Nonorthogonal
Assessment Compound


1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
Mean Aftereffect Ratio
112
135
157
Group

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