# TEMPORAL INTERACTIONS AMONG OPPONENT-PROCESS HUES EMPLOYING A VISUAL MASKING PARADIGM

by

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# Abstract

This experimental series had as its main concern the investigation of certain assumed temporal and spatial interactions of an opponent-process theory of color vision. A visual masking paradigm was used, employing both forward and backward masking sequences. The results indicate that in a backward masking sequence, where the test stimulus follows the mask stimulus, greater masking occurred when the test and mask stimuli were of non-opponent hues. For the forward masking sequence the results were less clear. The degree of masking obtained was markedly less, and when it did occur it was generally greater for opponent than non-opponent pairings of test-mask hues. Test stimulus hues were ordered green, yellow, red, blue in terms of resistance to masking, this order being the same for both backward and forward masking sequences. A similar consistent ordering of the mask stimulus hues was not demonstrated. It is generally concluded that the results, while not conclusive, do provide some empirical support for an opponent-process theory of color vision.

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# Introduction

The general purpose of the research reported in this thesis was to investigate certain assumed temporal and spatial interactions of an opponent-process theory of color vision. An attempt was made to test the postulated temporal and spatial interactions of opponent-processes based on Hurvich & Jameson's (1957) restatement of Hering's original theory of color vision.

## Opponent-process theory - Hering Model

The opponent-process theory as originally stated postulates three independent variables which provide the basis for color vision. These three variables represent three pairs of processes interacting with three pairs of sensory qualities; red (+) - green (-), yellow (+) - blue (-), and the achromatic pair, black (+) - white (-). Each member of the individual pairs is mutually opposed to the other member of the pair in terms of the assumed underlying physiological processes. To differentiate between the opposed members the first member of each pair is labeled with a positive sign (+), and the second with a negative sign (-). In the absence of chromatic stimuli the opponent response systems are postulated to return to a state of equilibrium.

## The Hurvich & Jameson postulates

### (a) Temporal interactions

In addition to the above Hering postulates of mutual inhibition of opponent processes, Hurvich & Jameson (1957) have attempted to define the specific temporal interaction's occurring among these processes. It is proposed that momentary activity in one member of an opponent process precludes activity in the other; continued activity in that same member however, results in a decreasing tendency for its continued activity, and an increasing tendency for activity in the opponent member. For example, stimulation of the red process results in an initial inhibition of the green process, however with continued stimulation there is a decreasing tendency for the red response and an increasing tendency for the green response.

### (b) Spatial interactions

Not only are the visual responses modified by changes in time, but in addition, Hurvich & Jameson postulate a similar spatial interaction That is, an initial response in one member of an opponent process results in a momentary inhibition of responses in spatially adjacent processes. Continued activity in this member results in a decreasing tendency for its continued activity and an increasing tendency for activity in the spatially adjacent opponent process. Such spatial interactions are offered as explanation for the familiar color contrast phenomenon such as 'simultaneous color contrast' or 'contrast enhancement'.

## Psychophysical evidence

Experimental support for the postulated temporal interactions among opponent processes has been offered by Keston (1965). The purpose of Keston's investigation was to determine the changes in perceived color produced by the temporal succession of two brief, superimposed pulses of light, this procedure being termed 'temporal chromatic induction' by Keston. The interaction of two successive pulses of equal luminance and duration was studied as a function of pulse-duration and luminance. The stimuli consisted of a red flash followed by a near-white flash. Both pulses were presented to the same area of the retina. There was no dark interval between pulses. Pulse durations ranged from 10 - 250 msecs. and luminances were 21.0, 2.1 and 0.21 mL. Changes in perceived color were measured by subjective reports of hue and saturation. The results indicated that as the paired pulse-durations lengthened, reds became increasingly desaturated, then white, then finally blue-green. Keston proposes that his results are analogous to, and consistent with Jameson & Hurvich's (1961) findings that in spatial interactions affecting perceived color, induced responses are opponent to those of the inducing stimuli. A parallel may be drawn (although Keston admits to oversimplification) between his findings in temporal interactions of hues and those of Jameson & Hurvich in the spatial realm.

In their investigation of spatial interactions of perceived color, Jameson & Hurvich also have shown that an area of 'darkness' interposed between the focal area and the inducing area appeared to reduce induction effects. According to Keston, the introduction of a 'dark interval' in a temporal interaction situation does not appear to serve the same function. The dark interval (or interstimulus interval) may serve to enhance the degree of interaction, to decrease the interaction, or it may have no effect. In other words, the dark interval interacts with various other parameters (not specified) in determining perceived color in temporal interaction situations. It would appear that systematic investigation of these parameters is warranted in an attempt to define the nature and significance of temporal interactions in color vision theory.

Quite apart from the spatial and temporal interactive effects between members of the opponent processes, i.e. between R+ and G-, and between Y+ and B-, there appears to be important differences between the three paired processes. The three pairs of visual response processes appear to be independent of each other; that is, they exhibit differential response thresholds and follow differential rates of increase with increases in the strength of stimulation. According to Hurvich & Jameson (1957), the response thresholds of the three paired processes are a function of photochemical absorption activity or 'sensitivity': that is, in the achromatic (black-white) pair, the amount of photochemical absorption necessary to excite the achromatic white response is less than the amount of photochemical activity required to stimulate either the R+G- or Y+B- chromatic pairs. Similarly, the red-green system has a lower threshold than the yellow-blue system. Some support for such differential response thresholds may be obtained from "small field dichromasy" studies in which the eye behaves, with respect to stimuli that are very small in area (20' of visual angle) and of low intensity, in a manner similar to that of the congenital tritanope who can only discriminate reds and greens. This dichromatism for small light sources appears to support the view of Hurvich and Jameson that at levels (near threshold) which are sufficient to activate the red-green system, the yellow-blue system fails to respond.

With increases in levels of luminance the three paired systems also show differences in rate of response increase (Hurvich & Jameson, 1957). For example, the achromatic response increase is probably the most rapid of the three, resulting in desaturation of spectral stimuli at high intensity levels. The yellow-blue system, although exhibiting a higher response threshold as noted earlier, shows a more rapid rate of increase in response as luminance levels increase than does the red-green system. The differences in response increase with changes in illumination account for the decreasing saturation of hues with increasing illumination and the tendency for mixed hues to be more yellow or blue at high levels of illumination and more red or green at low illumination levels (Le Grand, 1957). Such hue shift phenomenon are known as the Bezold-Brucke effects.

Neurophysiological evidence

Central to the Hurvich and Jameson (1957) restatement of Hering's postulates is the concept of induced activity in spatially adjacent processes as outlined earlier. The work of H. K. Hartline and associates is especially important in providing a physiological viewpoint in this concept of lateral inhibition and excitation of adjacent neural events. Hartline (1956) has found that the discharge of impulses in any one optic nerve fiber in the *Limulus* ommatidia depends not only upon the stimulation of the specific receptor from which the neural fiber arises, but also upon the stimulation over the entire population of mutually interacting elements. Lateral inhibition and excitation is not only confined to invertebrates but has been investigated and confirmed in the vertebrates, including the frog (Barlow, 1953 a, b) and the cat (Kuffler, 1953).

The current status of physiological evidence for the existence of neural processes within the visual system which respond to specific wavelengths and intensities appears to support an opponent-process model in many respects. DeValois, Abramov and Jacobs (1966) conducted a detailed analysis of a population of single cells in the lateral geniculate nucleus (LGN) of the macaque monkey. On the basis of the obtained responses to monochromatic light these LGN cells were divided into two general classes:

(a) spectrally non-opponent cells responding to all wavelengths, and,

(b) spectrally opponent cells responding to certain portions of the spectrum. Four types of spectrally opponent cells were classified:

(i) red excitatory and green inhibitory (+R-G),
(ii) green excitatory and red inhibitory (+G-R),
(iii) yellow excitatory and blue inhibitory (+Y-B),
(iv) blue excitatory and yellow inhibitory (+B-Y).

Comparisons with psychophysical data appear to indicate that the spectrally non-opponent cells transmit brightness information; opponent cells however, appear to transmit information about color (DeValois, 1965). Subsequent research has confirmed these findings (DeValois, Abramov and Mead, 1967). In further neurophysiological analyses of the responses of cells in the macaque LGN, Abramov (1968) suggests possible associations between cone types in the retina and the spectrally opponent cells in the LGN. It appears that +R-G and +G-R cells are associated with cone pigments having absorption maxima at 535 and 570 millimicrons, also, +Y-B and +B-Y are associated with 445 and 570 millimicron cone types. These findings basically support a three pigment - neural opponent response model of the type proposed by Hurvich and Jameson (1957).

The Bezold-Brucke effect, referred to previously in the context of differential rates of response increase of opponent pairs based on psychophysical data, may now also be viewed within a physiological framework. Some hints as to the neurophysiological mechanisms underlying the Bezold-Brucke effect are seen in the opponent cell responses obtained by DeValois (1965) in the macaque LGN. More specifically, the manner in which the inhibitory (-) and excitatory (+) processes vary as a function of intensity can now be examined in terms of the above effect. In the +R-G cell population the excitatory phase is usually more sensitive at low intensities, with maximum excitatory responses occurring at 570 mμ. As intensity increases more and more inhibition from the -G process occurs. This inhibition tends to limit the increase in excitation in the 570-600 mμ range, and at some of these wavelengths increases in intensity may begin to produce a decrease rather than an increase in firing rate, in other words, the intensity response curve reverses its slope at high intensity levels. At the longer wavelengths (above 600 mμ) an increase in intensity produces a steady increase in firing rate with little or no inhibition from the -G process. As a result, as intensity increases there is a progressive shift in the maximum excitation in a +R-G cell from 570 to 600 mμ or more. Assuming that the +R-G cells are signalling "red" with an increase in activity, and "green" with a decrease in activity, then the perceived color changes that make up the Bezold-Brucke effect are as expected. As intensity is increased, longer and longer wavelengths are necessary to maintain a degree of perceived "redness", as intensity is increased, longer and longer wavelengths are also necessary to produce maximum firing rate of the +R-G cells. A similar argument may be applied to the shifts in response of the +G-R cells. Increasing the intensity of light from the green part of the spectrum necessitates a progressive shift toward shorter wavelengths to maintain the same perceived color, i.e. a low intensity light of 550 mμ may appear to have the same color as a high intensity light of 530 mμ.

It should be noted that the physiological studies under consideration have been conducted on infra-human species and that attempts to generalize to the psychophysics of human visual responses are naturally open to criticism. Evidence supporting such a generalization however, may be drawn from behavioral studies which have shown that the macaque monkey (for example), and man, have the same sensitivity to light and the same color vision (DeValois, 1965; Devalois and Jacobs, 1968). Biochemical evidence indicates a close correspondence between macaque photopigments and those of man (Marks, Dobelle and MacNichol, 1964).

## The experimental problem

In light of the support, obtained from both psychophysical and physiological data, for an interpretation of color vision in terms of an opponent-process system, this investigation had as its main concern the testing of hypotheses derived from the postulated spatial and temporal interactions of opponent-processes in color vision theory.

Since the problem to be investigated was these temporal interactions among opponent sensory qualities, an experimental paradigm was devised in which temporally sequential stimuli were presented in rapid succession and which yielded a measure of the interaction of these stimuli. These conditions were met in a visual masking paradigm in which inhibitory effects on a test-stimulus can be induced by either a preceding or subsequent 'masking' stimulus.

Visual masking is probably one of the most active areas in experimental psychology today, and according to Kahneman (1968) more studies of masking and associated phenomena have appeared since the most recent review of the field (Raab, 1963), than were cited in that review. Although the major theoretical issues in masking have not yet been resolved, its utility as a tool in vision research has been amply demonstrated. In spite of the widespread use of masking techniques in perception and allied fields, made apparent by both Raab (1963) and Kahneman (1968), the technique has not been employed to any great extent in investigations of temporal interactions of hues. However, it was felt that such a paradigm could be usefully employed in this investigation for the purposes referred to above.

## Experiment I: Backward Masking and Hue Interaction

The purpose of the first study was to investigate the temporal interactions of hues employing the visual masking paradigm. Hurvich and Jameson (1957) postulated that momentary activity in one member of an opponent process precludes activity in the other; continued activity in that same member, however, results in a decreasing tendency for its continued activity and an increasing tendency for activity in the opponent member. As an illustration, it can be proposed that excitation in a red or blue process results in an increasing tendency for activity in the opponent green or yellow members accompanied, or followed, by a decreasing tendency for continued red or blue activity (assuming continuous rather than momentary activity of the initial excitation).

In general, visual masking refers to a class of situations in which some measure of the effectiveness of a visual stimulus, i.e. a test stimulus, is reduced by the presentation of another (the masking stimulus) in close, specified temporal contiguity to it. When the mask stimulus follows the test stimulus in temporal sequence the situation is termed 'backward masking'; conversely, when the test stimulus follows the mask stimulus the situation is one of 'forward masking'. The test and mask stimuli may or may not overlap spatially. When the test and mask stimulus do not overlap spatially the cases of forward and backward masking are termed paracontrast and metacontrast respectively (Kahneman, 1968). This study (Expt. I) employed a backward masking paradigm where the mask stimulus follows the test stimulus in time, and tested the temporal interaction of an initial stimulus, the test stimulus, composed of the hues red, green, yellow or blue and a subsequent stimulus, the mask stimulus, composed of the same hues. Both opponent and non-opponent hues were paired in all combinations.

The specific experimental hypotheses for this study are as follows:

(1) There is a general inhibitory effect in the form of a reduction of the effectiveness of the test stimulus, consisting of red green yellow and blue letters, as a function of the masking stimulus. This reduction of the effectiveness (in terms of recognition) of the test stimulus or 'masking', is independent of the hue combinations with the mask stimulus.

(2) There is a differential inhibitory, or masking effect, quite apart from the general effect as hypothesized in (1) as a function of opponent or non-opponent relationships between the test and mask stimulus.

Prior to the main study outlined above a pilot series was undertaken, first, to determine recognition thresholds for all letter and hue combinations (A, T, U, red, green, yellow and blue) for each subject and second, to investigate certain variables in a masking study.

Thresholds were determined employing a subjective confidence rating, i.e. each subject attached a percentage estimate, from zero to one hundred percent, to the degree of confidence experienced in the identification of the particular test stimulus. From the results provided in the recognition trials a plot of 'confidence rating versus exposure duration of test stimulus' was then made for each subject. From these plots an exposure duration was chosen for each hue at a certain confidence rating value for that particular subject.

This selected exposure duration for a particular hue and subject was then employed as the test stimulus duration in the subsequent pilot masking study. In this pilot, the variables of interest were, the interstimulus interval, opponent hue pairing of test stimulus and mask stimulus, and letters. Interstimulus intervals of 0, 20, 40 and 80 msec were investigated, with a constant mask stimulus duration of 200 msec. The results of the pilot masking study then determined the interstimulus interval that was used in the main study.

## Method

### Subjects

Five male subjects, of average age 26 years, were selected on the basis of at least two criteria:

(1) 20/20 vision, as determined by the Orthorater tests for acuity,

(2) normal color vision, as determined by Dvorine color plates.

A sixth subject (female), although having met the above criteria, was not included with the above subjects. The subject's responses were considered to be too aberrant for inclusion.

### Apparatus

Presentation of stimuli was accomplished using the Scientific Prototype Model GB three-channel tachistoscope and timer. The light source for each field was Westinghouse 'Daylight' lamps (color temperature approximately $6600^{o}K$) designated as standard source 'C' as specified by the International Commission on Illumination (CIE).

The brightness of all stimuli in each field of the tachistoscope was measured using the Pritchard 'Spectra' photometer and flicker photometry. Corrections were made using Kodak neutral density filters thus ensuring equality of brightness at $8 \times 10^{-1}$ foot lamberts in all stimulus fields.

The tachistoscope eyepiece was modified to accommodate an iris diaphragm for use as an artificial pupil, this, in conjunction with a forehead restraint and chin-rest, ensured elimination from the field of view of all but the specific target stimulus.

## Materials

The test stimuli consisted of two separate components:

(1) 5" x 7" Kodalith negatives in the center of which were located the transparent letters A, T or U, and,

(2) Kodak Wratten narrow-band filters with the following characteristics:

  (a) Number 49, designated as blue, dominant wavelength 461 millimicrons.

  (b) Number 73, designated as yellow, dominant wavelength 576 millimicrons.

  (c) Number 92, designated as red, dominant wavelength 646 millimicrons.

  (d) Number 58, designated as green, dominant wavelength 538 millimicrons.

By selecting the appropriate transparency and filter twelve test stimulus conditions can be generated. The test stimulus letters subtended a visual angle of $0.5^{\circ}$.

The masking stimuli also consisted of two components:

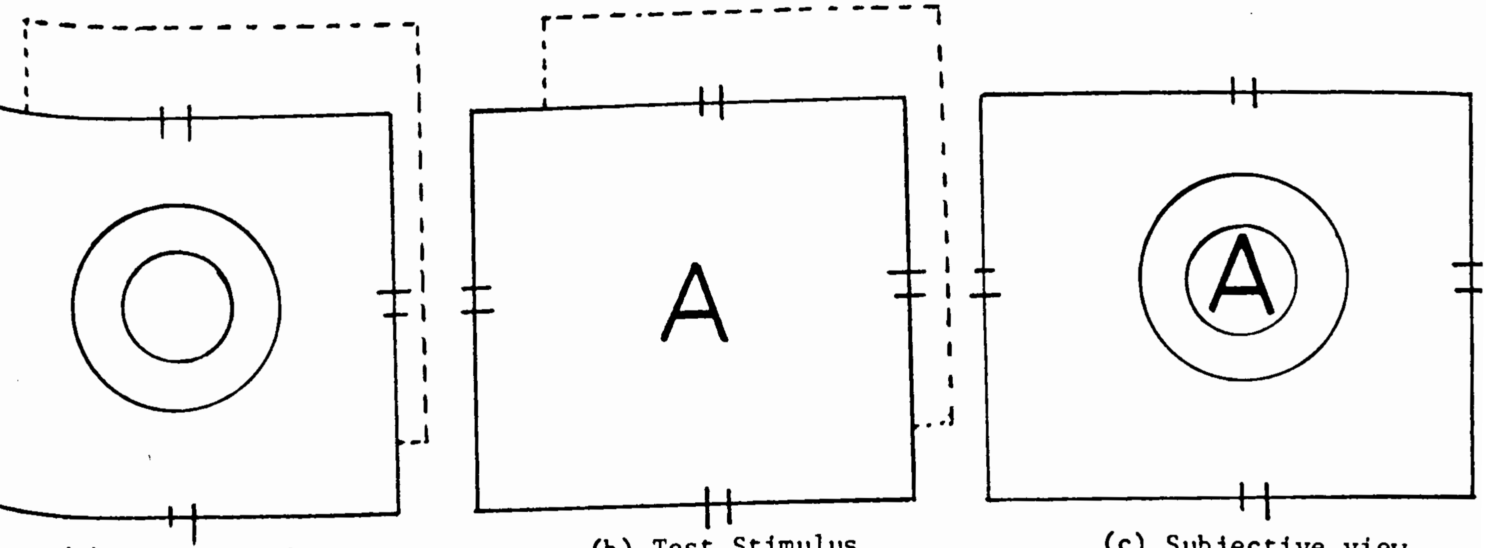
(1) a 5" x 7" Kodalith negative in the center of which is located a transparent annulus, and,

(2) Kodak Wratten filters, as described above.

The masking stimuli subtended a visual angle of $1.4^{\circ}$. A white pin-point light source served as a fixation point and was provided in the third field of the tachistoscope. Diagrammatic representations of the test and mask stimuli are shown in Fig. 1.

## Procedure

The first pilot study was conducted to determine identification thresholds for each hue and letter combination for each of the five Ss using a 'subjective confidence rating' method. A plot of 'confidence rating versus



(a) Mask Stimulus - Channel 2

(b) Test Stimulus - Channel 1

(c) Subjective view

Fig. 1. Diagrammatic representation of stimulus figures. Dotted line represents Kodak Wratten filter placed behind stimulus. Stimulus figures (annulus and letter) are actual size; stimulus frames (broken lines) are 5" x 7".

exposure duration of test stimulus' were obtained for each subject, permitting the selection of exposure durations corresponding to the 75% confidence rating level as the test stimulus duration in the subsequent experimental masking procedures.

Procedurally, the determination of identification thresholds for hue and letter combinations for each subject was as follows: after a period of dark adaptation (a minimum of 25 minutes) each subject's task was to identify the tachistoscopically exposed letter (A, T or U) and the hue (red, green, yellow or blue) at exposure durations of 0, 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90 and 100 milliseconds in random sequence. Instructions to the subject were as follows:

"Your task will be to report the identity of a test-stimulus presented in the field of the tachistoscope. The stimulus figure will consist of a letter of a certain hue. You are to report the letter and the hue, and at the same time attempt to estimate how sure you are in your identification and report this degree of confidence in terms of a percentage from zero to one hundred. For example, if you are completely sure you can identify a 'red A', then report, 'red A, 100%'. You can present the test stimuli at your own rate by pressing the switch provided. Between presentations be sure to maintain location of the fixation point provided in the center of the field".

From the results provided in these recognition trials, appropriate test stimulus durations were chosen for the subsequent masking study. In a second pilot-study in which interstimulus interval was varied, a 20 msec interstimulus interval was found to result in optimum masking.

The procedure for Expt. I did not differ greatly from that of the pilot recognition study. After a period of dark adaptation the subject's task was to identify the exposed letter (A, T or U) and the hue (red, green, yellow and blue) at the predetermined exposure duration, with the added complexity of a temporally subsequent masking stimulus (an annulus completely enclosing the test stimulus) of the hues red, green, yellow or blue. The duration of the mask stimulus was a constant 200 msec., the interstimulus interval, between test stimulus and mask stimulus, was a constant 20 msec.

Instructions to the subject were similar to those given above. Each trial, therefore, consisted of the following:

(1) Dark adaptation, (2) Instructions (omitted after the first trial), (3) verbal ready signal, (4) presentation of the test stimulus, (5) Interstimulus interval, (6) presentation of the mask stimulus (7) verbal report, including subjective confidence rating.

There were 48 measures for each subject with three letters, four mask stimuli hues and four test stimuli hues, with both opponent and non-opponent pairings. The data were analyzed in a subjects x 3 x 4 x 4 design. The experimental variables were letters (A, T and U), mask stimulus hue (red, green, yellow and blue) and test stimulus hue (red, green, yellow and blue).

## Results

Measures used in this analyses consisted of quantitative statements of confidence in the response, not the correctness or incorrectness of the response. It should be further noted that the number of incorrect responses made with a 100% confidence rating of any particular test stimulus were in fact minimal and are considered to be effectively negligible. Since all measures are subjective confidence ratings of recognition on a zero to one hundred per cent scale, a high rating represents less masking than a low rating. The means responses for test stimulus recognition (subjective confidence ratings) for each of the five subjects and the hues red, green, yellow and blue indicate a general consistency in the response of each subject, particularly with regard to responses made for each hue (see Appendix A). These data are interpreted as being sufficient indication for consistent responses to the four hues, and further, that there are no anomalous responses to individual hues.

The subjective confidence ratings of this first experiment were analyzed in a 5 x 3 x 4 x 4 analysis of variance. The source table and F values are presented in Table 1. The first hypothesis of a general inhibitory effect in the form of a reduction in the effectiveness of the test stimulus, or general masking effect, was confirmed. All mean ratings fell substantially below the 75% confidence level, indicating that masking was occurring. The mean subjective confidence rating for red test stimuli, across all conditions, was 41.0, the mean confidence rating for green test stimuli was 61.0, the mean confidence rating for yellow test stimuli was 52.5, and the mean confidence rating for blue test stimuli was 7.0. The difference in this effect on recognition between the above test stimulus hues is significant at the .01 level (F = 10.73, df = 3, 12). Mean differences between the four test stimulus hues are given in Table 2. Using the method of multiple comparisons between means (Hays, 1963: p.468) the mean differences between red and green, red and yellow, also red and blue test stimuli are found to be significant at the .05 level. The mean difference between green and blue test stimuli are significant at the .05 level, however the difference between green and yellow is not significant. Finally, the mean difference between yellow and blue test stimuli is significant at the .05 level.

## Table 1

## Analysis of Variance of Confidence Ratings as a Function of Letters, Test Stimulus Hue and Mask Stimulus Hue: Experiment I

| Source of Variation | df | MS | F |
|---|---|---|---|
| Mean | 1 | 3912.34 | |
| Subjects (S) | 4 | 174.39 | |
| Letters (L) | 2 | 13.01 | 1.54 |
| Test Stimulus Hue (T) | 3 | 337.33 | 10.73** |
| Mask Stimulus Hue (M) | 3 | 6.88 | 0.84 |
| S x L | 8 | 8.49 | |
| S x T | 12 | 31.41 | |
| L x T | 6 | 24.07 | 2.80* |
| S x M | 12 | 8.15 | |
| L x M | 6 | 4.81 | 1.33 |
| T x M | 9 | 14.63 | 1.26 |
| S x L x T | 24 | 8.59 | |
| S x L x M | 24 | 3.61 | |
| S x T x M | 36 | 11.62 | |
| S x T x M | 18 | 4.02 | 0.871 |
| S x L x T x M | 72 | 4.61 | |

*p<.05

**p<.01

Table 2

Difference in Mean Confidence Rating for,

a) All Pairs of Test Stimulus Hues, and

b) All Pairs of Mask Stimulus Hues:

Experiment I

a) Test Stimulus

| Hues | Red | Green | Yellow | Blue |
|---|---|---|---|---|
| Red | .... | .... | .... | .... |
| Green | 20.00* | .... | .... | .... |
| Yellow | 21.50* | 11.50 | .... | .... |
| Blue | 34.00* | 54.00* | 44.50* | .... |

b) Mask Stimulus

| Hues | Red | Green | Yellow | Blue |
|---|---|---|---|---|
| Red | .... | .... | .... | .... |
| Green | 7.33* | .... | .... | .... |
| Yellow | 0.50 | 6.83* | .... | .... |
| Blue | 3.66* | 2.67 | 3.16* | |

* Indicates significance at the .05 level, df = 3, using multiple comparison methods.

The mask stimulus hue main effect did not reach significance at the .05 level (F = 0.84, df = 3, 12). Mean differences between mask stimulus hues are also shown in Table 2. Mean differences between red and green, yellow and green, blue and green, and blue and yellow mask hues are significant at the .05 level, however, mean differences between red and yellow, and blue and green mask hues do not reach significance. Figure 2 presents the test stimulus and mask stimulus hue mean ratings for each of the four test and mask hues.

The main effect for test stimulus letters did reach statistical significance at the .05 level (F = 1.54, df = 2, 12).

The letter by test hue interaction reached significance (F = 2.80, df = 6, 24) at the 5% level. The significance of this letter by test hue interaction appears to be largely due to considerably reduced recognition of the red 'T' when compared with the other hue-letter combinations.

The second hypothesis of differential masking as a function of the opponent or non-opponent relationships between test and mask stimuli was only partially confirmed. The test stimulus by mask stimulus interaction (F = 1.26, df = 9, 36) does not reach significance of the .05 level. However, examination of the comparisons between means of the test-mask pairs, on the basis of opponent and non-opponent relationships, using the method of multiple comparisons between means (Hays, 1963), indicates that more masking i.e. less recognition, occurs with non-opponent pairs than with opponent test-mask pairs. These comparisons are shown in Table 3. For purposes of comparison test-mask pairs of the same hue, i.e. red-red, green-green, are omitted. Note that seven of the eight comparisons in Table 3 indicate greater masking occurring with non-opponent pairs, and six of these differences are significant at the .05 level, df = 9. One comparison

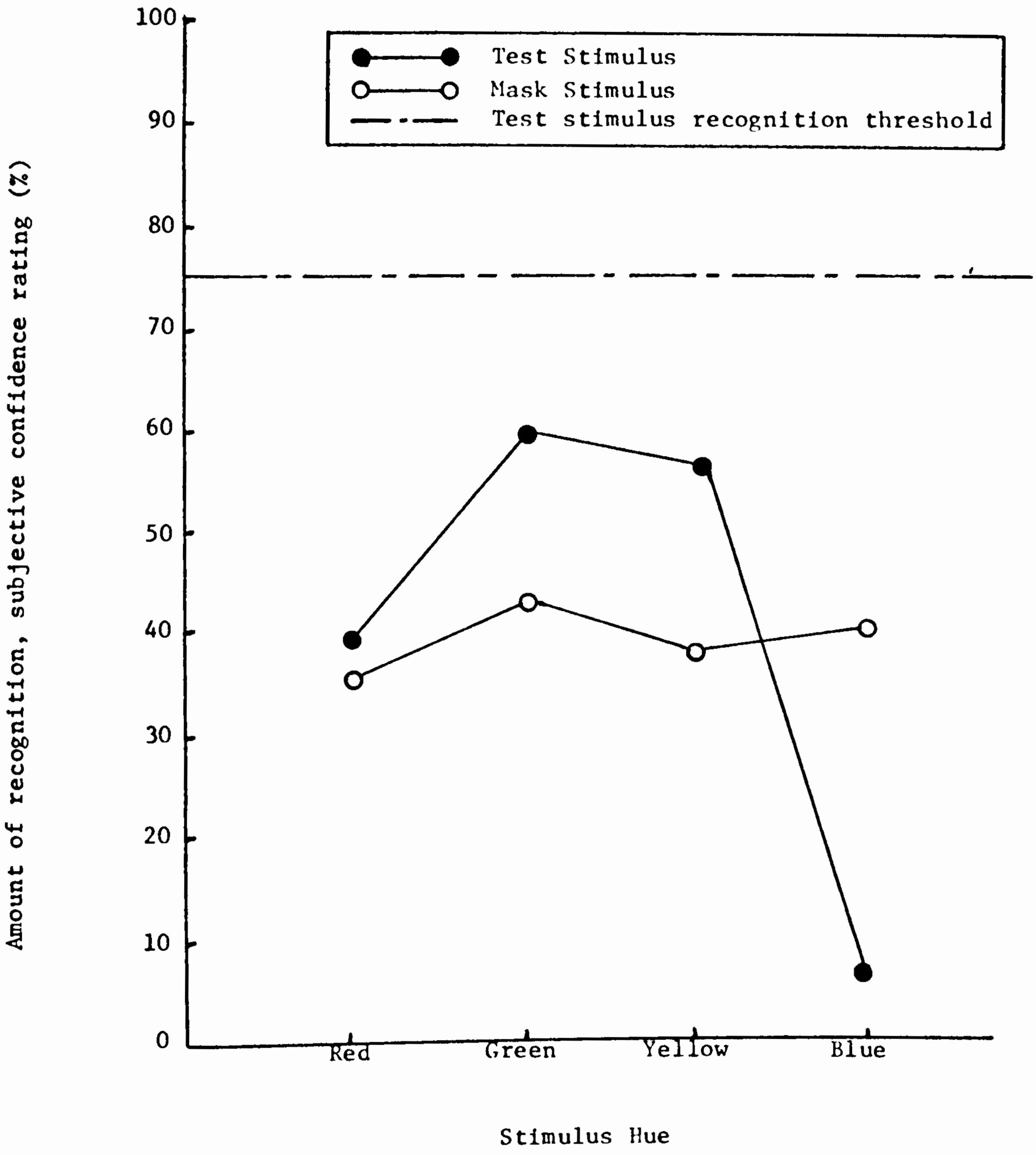


Figure 2. Amount of recognition, expressed as confidence ratings as a function of stimulus hue, for the test and mask stimulus in Experiment I.

### Table 3

### Comparisons Between Mean Confidence Ratings for Opponent and Non-opponent Pairs of Test-Mask Stimulus Hues: Experiment I

| Test-Mask Stimulus Hues | | Mean Confidence Rating | | Pair showing less recognition |
|---|---|---|---|---|
| Opponent | Non-opp. | Opponent | Non-opp. | Opp./Non-opp. |
| R-G | R-Y | 56.00 | 26.65 | Non-opp.* |
| R-G | R-B | 56.00 | 42.67 | Non-opp.* |
| G-R | G-Y | 56.00 | 64.67 | Opponent* |
| G-R | G-B | 56.00 | 50.67 | Non-opp. |
| Y-B | Y-R | 63.34 | 51.33 | Non-opp.* |
| Y-B | Y-G | 63.34 | 50.00 | Non-opp.* |
| B-Y | B-R | 15.34 | 4.00 | Non-opp.* |
| B-Y | B-G | 15.34 | 0.60 | Non-opp.* |

*Indicates significance at the .05 level, using multiple comparison methods.

(G-R/G-Y) indicated greater masking occurring with the opponent pair (significant at the .05 level). Figure 3 presents these test stimulus by mask stimulus data in graphic form expressed as test stimulus recognition (percent subjective confidence rating) as a function of mask stimulus hue for both non-opponent and opponent hue relationships.

## Discussion

Comparisons made between opponent and non-opponent test-mask pairs (Table 3) indicate a significantly greater differential masking effect in the direction of non-opponent pairs in 75% of these comparisons in spite of the non-significance of the overall test by mask interaction. This lack of significance results, in part, from a large mean difference between the G-R/G-Y pairs, this difference lying in the opponent (G-R) direction. The experimental finding of a greater masking effect in non-opponent test-mask pairs appears to support the underlying theoretical assumptions of an opponent-process theory of color vision. A more complete analysis and interpretation of these findings will be discussed in greater detail in the final summary and conclusions chapter.

Examination of the mean masking effects of the four hues, although not significant overall, does indicate some consistency in the ordering of the magnitude of these effects in terms of masking efficiency of the four hues. Masking efficiency is defined here as being the ability of the mask stimulus to effectively reduce recognition of the test stimulus as measured by the subjective confidence rating. The smaller the rating, the more efficient the mask. As shown in Figure 1, the red mask hue is seen as being the most efficient (37.5% recognition), followed by yellow (38.0%) and blue (41.1%) and finally green (44.8%). Similar ordering effects of the four test stimulus hues may be demonstrated. Ordering of the test stimulus hues may be made in

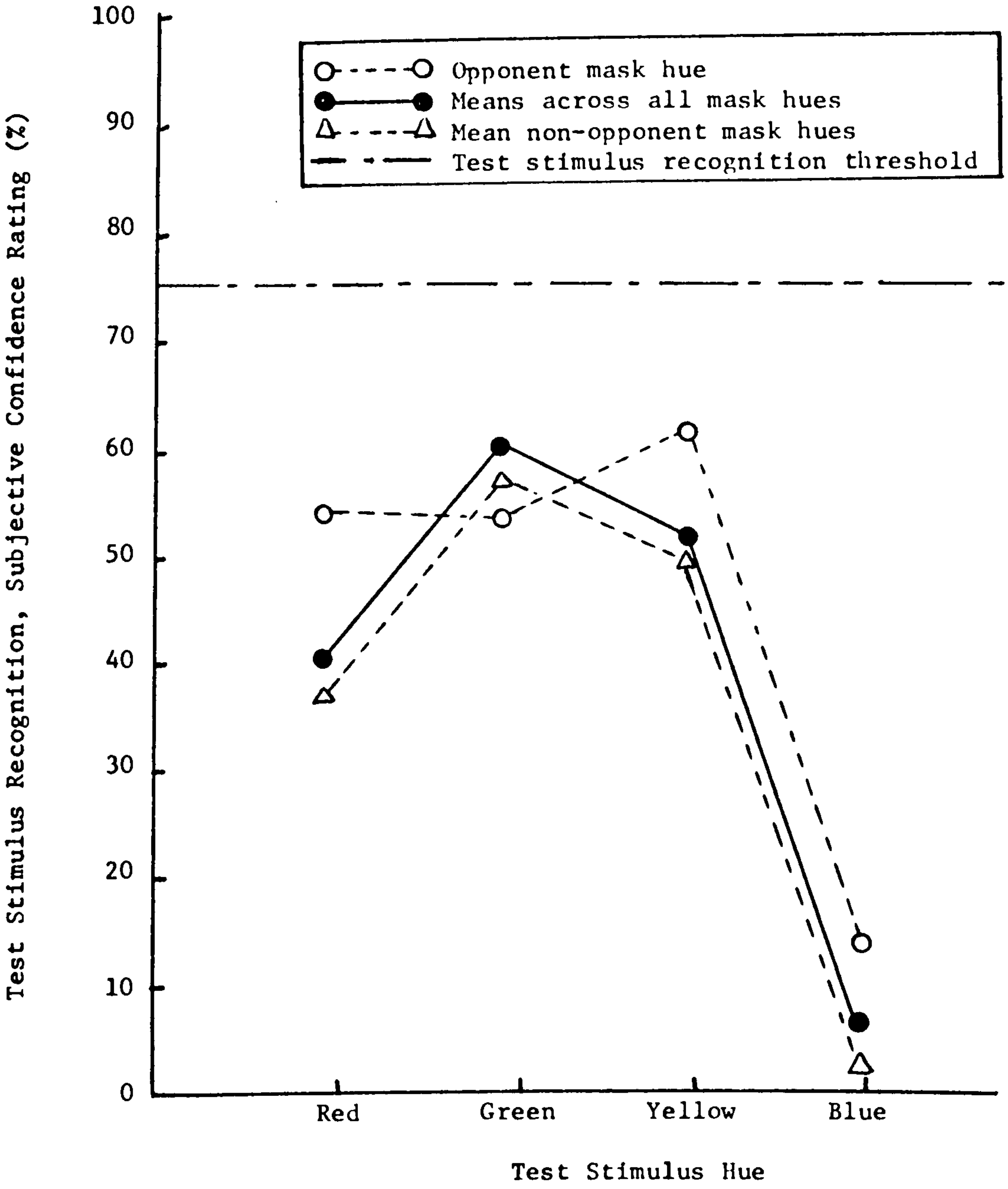


Fig. 3. Test stimulus recognition, expressed as confidence ratings, as a function of test stimulus hue, for each opponent mask hue, the average of each non-opponent mask hue, and for the average of all mask hues in Experiment I.

terms of test stimulus efficiency i.e. resistance of the test stimulus to masking effects. The overall test stimulus hue means are significant, as noted in the previous section, and as shown in Figure 1 the green test hue is most efficient (61.0% recognition), followed by yellow (52.5%) and red (41.0%), and finally blue (7.0%). Although the red, green, yellow and blue test stimuli were presented at temporal durations well above threshold, derived from recognition threshold determinations, the significant difference between the four test hue means appears to indicate a differential reduction in the effectiveness of the test stimuli as a function of the presence of a mask stimulus and its associated hue. This finding is substantiated to a large extent by the opponent and non-opponent comparisons previously discussed, in which non-opponent test-mask pairs demonstrated a greater differential reduction in the effectiveness of the test stimulus, or masking effect. Apart from the above considerations of the relations between test-mask pairs and their opponent properties, the means for the test and mask stimulus hues demonstrate that green is the most efficient test hue, but the least efficient mask hue. Yellow is equally as efficient as a test hue as it is a mask hue, however, red ranks third in efficiency as a test hue, but most efficient of all as a mask hue. Finally, blue ranks least efficient as a test hue, but ranks third as a mask hue.

The lack of a significant difference for letter means, across all hues, appears to indicate that contours, in the form of letters, did not contribute to any differential masking effects. The letters A, T and U appear to possess equal properties as test stimuli with respect to contour relationships and the circumscribing annular mask stimulus. This conclusion appears to be warranted in spite of the presence of a significant letter x hue interaction, this interaction in large part being due to anomalous confidence ratings for the red 'T' test stimulus.

## Experiment II: Forward Masking and Hue Interaction

In the previous section, Experiment I, it was hypothesized that differential masking of hues would occur as a function of the opponent or non-opponent nature of the mask and test stimulus hues in a backward masking paradigm. However, it can be hypothesized that the postulated temporal interactions of opponent processes may also occur in a forward or pro-active sequence as well as in a retroactive or backward sequence. It should be noted that in rapid presentations of successive stimuli, as in a masking situation, there are both backward and forward masking effects. At the present time there is little or no evidence to support either a proactive or retroactive temporal sequence for opponent hues. The purpose of this part of the study was therefore to examine proactive temporal sequences of both non-opponent and opponent hues, and to compare these findings with those of Experiment I.

In a forward masking paradigm the masking stimulus precedes the test stimulus in time, such a temporal sequence will be employed in this part of the study, and will test the temporal interaction of an initial stimulus, the mask stimulus, of the hues red, green, yellow or blue and a subsequent stimulus, the test stimulus, composed of the same hues. Both opponent and non-opponent hues were paired in all combinations.

The specific experimental hypotheses for this study are as follows:

(1) There is a general inhibitory effect in the form of a reduction of the effectiveness of the test stimulus, consisting of red, green, yellow and blue letters, as a function of the mask stimulus. This reduction of the effectiveness (in terms of recognition) of the test stimulus, or 'masking', is independent of the hue combinations with the mask stimulus.

(2) There is a differential inhibitory or masking effect, quite apart from

the general effect as hypothesized in (1), as a function of opponent or non-opponent relationships between test and mask stimulus.

(3) Both the general and differential masking effects, as hypothesized in (1) and (2), differ in magnitude in this forward masking sequence when compared with the magnitude of masking in the backward masking sequence.

## Method

### Subject

The same five subjects who participated in Experiment I were used in this experiment.

### Apparatus, Materials and Procedure

The apparatus, materials and procedure were identical to those used in Experiment I with the exception that the test stimulus was presented after the mask stimulus, i.e. in a forward masking paradigm.

## Results

As in Experiment I, the measures employed were quantitative statements of confidence in recognition of the test stimuli not measures of correctness or incorrectness. A high confidence rating indicates greater recognition, i.e. less masking, of the test stimulus, than a low rating. Mean responses for test stimulus recognition for each of the five subjects and the hues red green yellow and blue indicate a general consistency in the response of each subject particularly with regard to those responses made for each hue (see Appendix B). These data are interpreted, as in Experiment I, as being sufficient indication for consistent and reliable responses to the four hues, and that there are no anomalous responses to individual hues.

The confidence ratings of this second experiment were analyzed in a 5 x 3 x 4 x 4 analysis of variance. The source table and F values are given in Table 4. As before, all scores are subjective confidence ratings

Table 4

Analysis of Variance of Confidence Ratings as a Function of Letters, Test Stimulus Hue, and Mask Stimulus Hue: Experiment II

| Source of Variation | df | MS | F |
|---|---|---|---|
| Mean | 1 | 6933.75 | |
| Subjects (S) | 4 | 200.59 | |
| Letters (L) | 2 | 43.36 | 5.82* |
| Test Stimulus Hue (T) | 3 | 536.54 | 24.87** |
| Mask Stimulus Hue (M) | 3 | 5.92 | 0.70 |
| S x L | 8 | 7.44 | |
| S x T | 12 | 21.57 | |
| L x T | 6 | 15.46 | 2.733* |
| S x M | 12 | 8.36 | |
| L x M | 6 | 14.85 | 4.15** |
| T x M | 9 | 4.93 | 1.05 |
| S x L x T | 24 | 5.65 | |
| S x L x M | 24 | 3.57 | |
| S x T x M | 36 | 4.68 | |
| L x T x M | 18 | 10.36 | 1.58 |
| S x L x T x M | 72 | 6.55 | |

*$p<.05$

**$p<.01$

based on a ten to one hundred scale, a high rating indicates greater recognition, i.e. less masking of the test stimulus, than a low rating.

The first hypothesis of a general inhibitory effect in the form of a reduction in the effectiveness of the test stimulus, or general masking effect, was confirmed. An examination of the data shows that the mean test stimulus recognition (subjective confidence rating), across all hues, was 53.75%. The mean subjective confidence rating for red test stimuli, across all conditions, was 51.3, for green test stimuli, 76.3, for yellow test stimuli, 75.0 and for blue, 12.3. The difference in this effect on recognition between the above test stimulus hues is significant at the .01 level (F = 24.87, df = 3, 12. These results indicate an overall increase in test stimulus recognition, i.e. less masking, then was found in Experiment I. Specifically, on the average there is no masking for the green and yellow test stimuli.

Mean differences between the four test stimulus hues are shown in Table 5. The mean differences between red and green, red and yellow, and red and blue are significant at the .05 level. Mean differences between green and blue test stimuli are significant at the .05 level, however the green and yellow mean difference is not significant. The mean difference between yellow and blue test stimuli is significant at the .05 level. These significant mean differences between the four test hues are in accord with those differences found in Experiment I, in spite of the increase in recognition scores for the green and yellow test stimuli shown in this experiment.

The mask stimulus hue main effect did not reach significance at the .05 level (F = 0.708, df = 3, 12). Mean rating differences between mask stimulus hues are also given in Table 5. The mean difference between red and green masking hues is significant at the .05 level, but the remaining

### Table 5

### Difference in Mean Confidence Rating for
### a) All Pairs of Test Stimulus Hue, and
### b) All Pairs of Mask Stimulus Hues:
### Experiment II

a) Test Stimulus

| Hues | Red | Green | Yellow | Blue |
|---|---|---|---|---|
| Red | .... | .... | .... | .... |
| Green | 25.20* | .... | .... | .... |
| Yellow | 23.67* | 1.33 | .... | .... |
| Blue | 39.00* | 54.97* | 53.97* | .... |

b) Mask Stimulus

| Hues | Red | Green | Yellow | Blue |
|---|---|---|---|---|
| Red | .... | .... | .... | .... |
| Green | 6.34* | .... | .... | .... |
| Yellow | 5.00 | 2.34 | .... | .... |
| Blue | 2.67 | 3.67 | 2.33 | .... |

*Indicates significance at the .05 level, df = 3, using multiple comparison procedures.

hue differences are not significant. Figure 4 presents the test stimulus and mask stimulus mean ratings for each of the four test and mask hues. Recognition is expressed as percent subjective confidence ratings.

The main effect for test stimulus letters does reach statistical significance at the .05 level (F = 5.82, df = 2,8), reflecting lower confidence ratings for 'T' than for 'A' and 'U'.

The letter by test stimulus hue interaction reached significance at the .05 level (F = 2.73, df = 6, 24), this significant interaction again, as in Experiment I, appears to be due to reduced recognition of the red 'T' when compared with the other letter - hue combinations. The letter by mask stimulus hue interaction was also significant at the .05 level (F = 4.15, df = 6, 24), this interaction appears, in large part, to be due to reduced recognition of the green 'T' when used as a mask stimulus when compared with the remaining letter-mask hue combinations.

The second hypothesis of differential masking effects as a function of the opponent or non-opponent relationships between test and mask stimuli was not confirmed. The test stimulus by mask stimulus interaction does not reach statistical significance at the .05 level (F = 1.05, df = 9, 36). Examination of comparisons between means of the test-mask pairs, in terms of opponent and non-opponent relationships (shown in Table 6), indicates little consistency in the results. For purposes of comparison, test-mask pairs of the same hue are omitted. The results of these opponent-nonopponent comparisons show relationships in both directions and some, though not all, are significant at the .05 level. The R-G/R-Y comparison shows significant differences in the opponent directions, i.e. greater masking occurring in the opponent R-G test-mask pair. However, the G-R/G-Y comparison indicates greater masking in the non-opponent (G-Y) pair. Similar non-opponent mask-

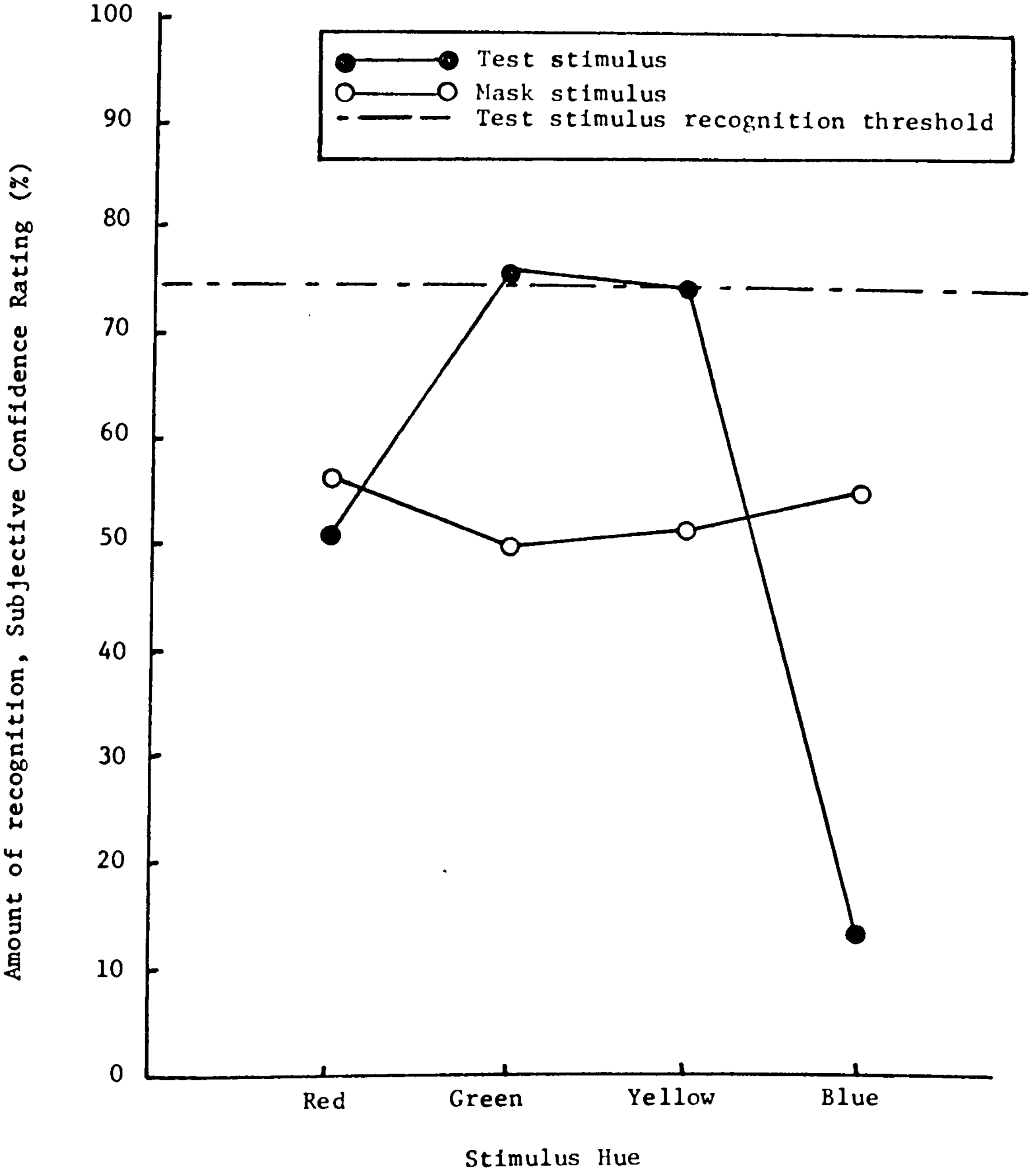


Fig. 4. Amount of recognition, expressed as confidence ratings as a function of stimulus hue for the test and mask stimulus in Experiment II.

## Table 6

## Expt. II: Comparisons Between Opponent and Non-opponent Test Stimulus-Mask Stimulus Pairs

| Test-Mask Stimulus Hues | | Mean Confidence Rating | | Pair Showing Less Recognition |
|---|---|---|---|---|
| Opponent | Non-opp. | Opponent | Non-opp. | Opp./Non-opp. |
| R-G | R-Y | 47.34 | 60.00 | Opponent* |
| R-G | R-B | 47.34 | 47.34 | Equal |
| G-R | G-Y | 76.67 | 70.67 | Non-opp.* |
| G-R | G-B | 76.67 | 80.00 | Opponent |
| Y-B | Y-R | 78.00 | 85.34 | Opponent |
| Y-B | Y-G | 78.00 | 67.34 | Non-opp.* |
| B-Y | B-R | 10.00 | 17.34 | Opponent* |
| B-Y | B-G | 10.00 | 8.00 | Non-opp. |

*Indicates significance at the .05 level, using multiple comparison procedures.

ing effects are also shown in the Y-B/Y-G pair. In total, four of the eight possible comparisons indicate greater opponent pair masking, three non-opponent and one comparison (R-G/R-B) shows no difference at all. Figure 5 presents the above test stimulus by mask stimulus data in the form of test stimulus recognition, percent subjective confidence ratings, as a function of mask stimulus hue for both non-opponent and opponent relationships.

The third hypothesis of both general and differential masking effects differing in magnitude in a forward or proactive masking sequence when compared with the magnitude of masking in the backward or retroactive masking sequence was confirmed. (The source table and F values are presented as a combined analysis in Table 7). The results show increased test stimulus recognition in the forward masking sequence (Expt. II) when compared with test stimulus recognition in the backward masking sequence (Expt. I), where F = 7.7, df = 1, 4. The mean test stimulus confidence rating, across all conditions, for the forward masking sequence was 52.29%, and for the backward masking sequence mean test stimulus confidence rating was 41.41%.

The letter by test-stimulus hue interaction in the combined analysis is also found to be significant at the .05 level (F = 4.15, df = 6, 24), as is a letter by mask hue interaction (F = 4.16, df = 6, 24). An additional significant interaction - the mask condition by mask hue interaction (F = 3.49, df = 3, 12) - occurs in this combined analysis of variance, reflecting very similar confidence ratings for the green mask hue (46.5 in backward masking, 48.6 in forward masking) than for red, yellow and blue mask hues in the two masking conditions.

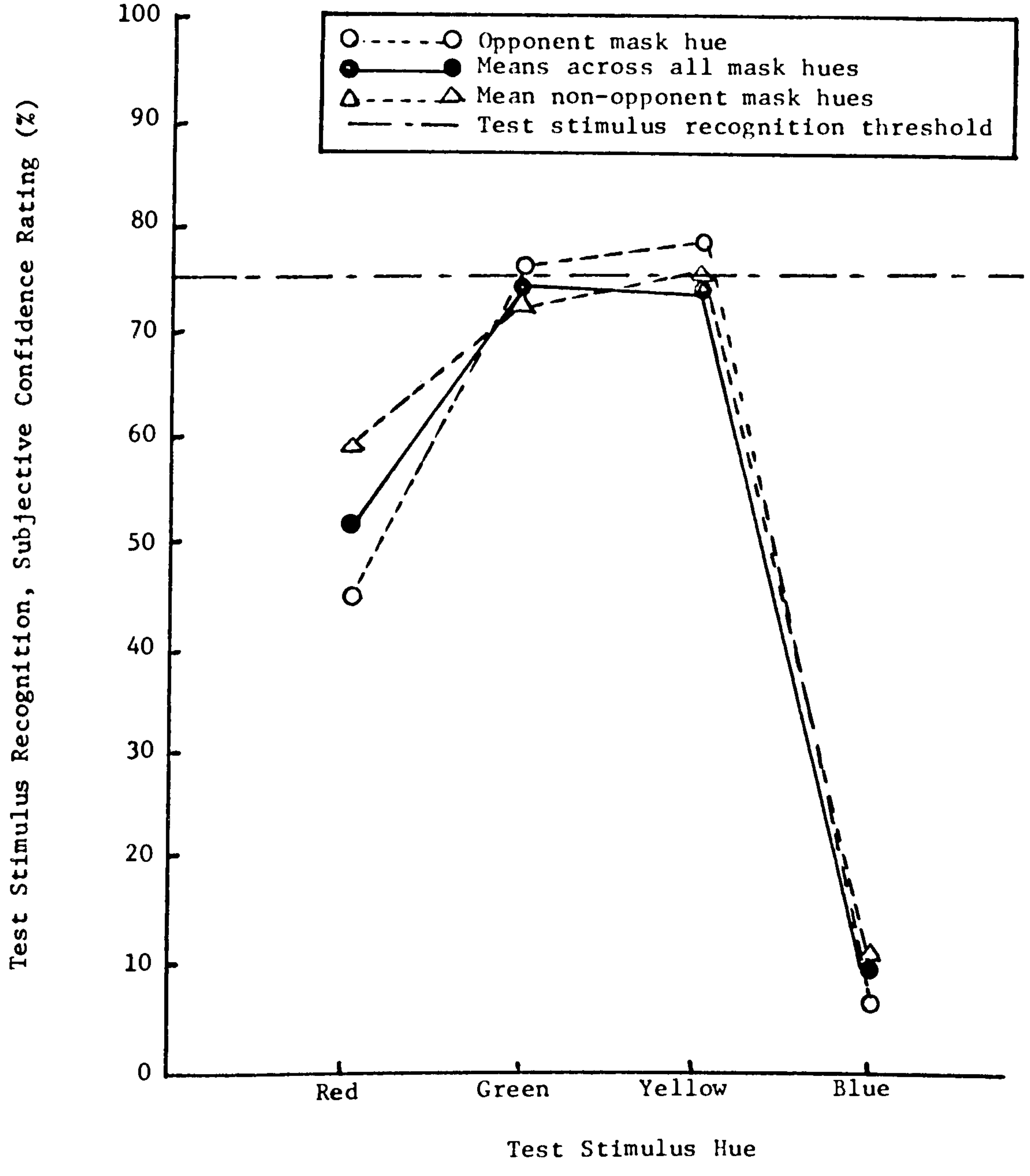


Fig. 5. Test stimulus recognition, expressed as confidence ratings, as a function of test stimulus hue, each opponent mask hue, for the average of each non-opponent mask hue, and for the average of all mask hues in Experiment II.

Table 7

Analysis of Variance of Confidence Ratings as a Function of Letters, Test Stimulus Hue, Mask Stimulus Hue, and Forward vs. Backward Masking: Experiment II

| Source of Variation | df | MS | F |
|---|---|---|---|
| Mean | 1 | 10537.50 | |
| Subjects (S) | 4 | 391.23 | |
| Letters (L) | 2 | 32.78 | 1.83 |
| Test Stimulus Hue (T) | 3 | 914.46 | 16.58** |
| Forward vs. Backward Masking (C) | 1 | 141.91 | 7.70* |
| Mask Stimulus Hue (M) | 3 | 1.35 | 0.11 |
| S x L | 8 | 17.96 | |
| S x T | 12 | 55.12 | |
| L x T | 6 | 29.13 | 4.15** |
| S x C | 4 | 18.45 | |
| L x C | 2 | 2.18 | 0.25 |
| T x C | 3 | 11.51 | 1.25 |
| S x M | 12 | 11.46 | |
| L x M | 6 | 17.24 | 4.16** |
| T x M | 9 | 7.97 | 1.01 |
| C x M | 3 | 10.55 | 3.49* |
| S x L x T | 24 | 7.00 | |
| S x L x C | 8 | 8.61 | |
| S x T x C | 12 | 9.14 | |
| L x T x C | 6 | 4.82 | 1.03 |
| S x L x M | 24 | 4.14 | |
| S x T x M | 36 | 7.83 | |

Table 7 (Cont'd)

Analysis of Variance of Confidence Ratings as a Function of Letters, Test Stimulus Hue, Mask Stimulus Hue, and Forward vs. Backward Masking: Experiment II

| Source of Variation | df | MS | F |
|---|---|---|---|
| L x T x M | 18 | 7.60 | 1.23 |
| S x C x M | 12 | 3.01 | |
| L x C x M | 6 | 7.66 | 2.139 |
| T x C x M | 9 | 8.26 | 1.642 |
| S x L x T x C | 24 | 4.65 | |
| S x L x T x M | 72 | 6.17 | |
| S x L x C x M | 24 | 3.58 | |
| S x L x C x M | 36 | 5.03 | |
| L x T x C x M | 18 | 1.93 | 0.449 |
| S x L x T x C x M | 72 | 4.32 | |

*p<.05

**p<.01

## Discussion

It was hypothesized that opponent hue test-mask pairs would exhibit a systematically different masking effect than would non-opponent hue test-mask pairs. The results indicate that this hypothesis was not confirmed. In fact, only four out of the eight comparisons made in Table 3 show greater masking in opponent pairs, and only two of these opponent comparisons are statistically significant. Of the four remaining comparisons it was shown that three indicated greater masking for non-opponent pairs, and the fourth showed no difference. In the previous experiment (Expt. I), the results indicated that, in general, greater masking of the test stimulus occurred with non-opponent hues in test-mask pairs. The only difference between Experiments 1 and 2 lies in the temporal sequence of the test and mask stimulus. The conflicting results obtained in the second experiment are, it appears, probably due to the proactive masking sequence of the test and mask stimuli. Concomitant with these conflicting comparisons found in the forward masking sequence is the noticeably increased level of recognition of the test stimulus, i.e. weaker masking effect. In fact, no masking was obtained with green and yellow test stimulus hues. The data suggest that with a proactive or forward temporal sequence of test and mask hue a weaker masking of the test stimulus occurs resulting in a less well-defined functional relationship between the test-mask pair and the opponent or non-opponent sensory qualities of the hues. A more complete discussion and interpretation will be provided in the final summary and conclusions chapter.

Examination of the mean masking effects of the four mask hues, although not significant overall, does show some ordering in terms of masking efficiency of these four hues. As before, the smaller the subjective confidence rating, the more efficient the mask. As shown in Figure 4, the green mask hue shows the highest efficiency (50.16%), followed by yellow (52.50%), and blue (54.83%), and finally red (57.50%). These ordering effects are somewhat different when compared with those of Expt. I. In the first experiment the mask hue order was red, yellow, blue and green, in this experiment the order is changed, i.e. green, yellow, blue, red. Yellow and blue maintain their relative positions, however, red and green have transposed the first and fourth position, green now being the most efficient mask hue and red the least.

Similar comparisons between ordering effects of the four test stimulus hues may be made. The overall test stimulus hue means are significant as the results have shown, and as shown in Figure 1 the green test hue is most efficient in resisting masking effects (76.34% recognition) followed by yellow (75.0%), then red (51.34%) and finally blue (12.34%). This order is preserved in both Expt. I and this experiment and appears to demonstrate that in both forward and backward masking the probability of recognition of the test stimulus letters decreases from a maximum with a green test hue through yellow and red to a minimum with blue.

## Summary and Conclusions

This series of experiments had as their main concern the investigation of certain assumed temporal interactions of an opponent process theory of color vision employing a visual masking paradigm. The opponent-process theory, as originally postulated by Hering and later restated by Hurvich and Jameson, proposes that there are three independent variables which subserve both chromatic and achromatic vision, i.e. red-green, yellow-blue and black-white processes. Furthermore, each member of the individual pairs is mutually opposed to the other member of the pair in terms of the assumed underlying physiological processes. This opponent activity is assumed to be reflected in the temporal interactions of the opponent hues. It has been proposed that momentary activity in one member of an opponent process precludes activity in the other, continued activity in that same member however, results in a decreasing tendency for its continued activity, and an increasing tendency for activity in the opponent member.

Since the problem to be investigated was these temporal interactions among opponent hues, an experimental paradigm had to be employed in which temporally sequential stimuli could be presented in rapid succession. These conditions were met in a visual masking paradigm in which inhibitory effects on a test stimulus were induced by either a preceding or subsequent stimulus, the mask stimulus.

The first experiment in this series investigated the temporal interaction of opponent and non-opponent hues in a backward masking sequence, where the mask stimulus follows the test stimulus in time, and was designed to test the hypothesis that apart from a general inhibitory effect in the form of a reduction in the effectiveness of the test stimulus, there would be a differential masking effect as a function of the opponent or non-opponent relationships between the test and mask stimulus. The first hypothesis, of a general inhibitory or masking effect of the test stimulus, was confirmed. Mean recognition across all hue conditions, as indicated by confidence ratings, was 40.37%, using a test stimulus duration which allowed 75% recognition in trials made prior to Experiment I. The second hypothesis, of differential masking effects as a function of the opponent sensory qualities between mask and test stimulus, was not as clearly confirmed. Although the test hue by mask hue interaction in the analysis of variance of confidence ratings did not reach significance, comparisons made between the test-mask pairs on the basis of non-opponent and opponent relationships did show significantly reduced recognition, i.e. increased masking, with non-opponent test-mask pairs rather than with opponent pairs in six out of eight comparisons made. Related to this hypothesis was the assumption of an increase in activity in one member of an opponent hue pair with a concomitant momentary decrease in activity in the other member; however, continued activity of this member results in a decreasing tendency for activity in the opponent member. It was assumed that the temporal durations of the test stimulus and mask stimulus were of short enough duration to be 'momentary' in the sense that Hurvich & Jameson use the term. Since greater masking (reduced recognition) was observed in non-opponent than in opponent pairs of hues, it seems reasonable to conclude that the minimal masking of opponent hues arose out of a situation where the test stimulus, defined as 'momentary', is characterised by an increase in activity of the hue, with the associated reduction in activity of the other member of the pair. The mask stimulus, of the opponent hue to the test stimulus, can be defined as 'continuous' with respect to the test stimulus, and is characterised by an increasing tendency for activity in the opponent member, i.e. the test stimulus hue. This increase in activity is assumed to be sufficient for a reduction in masking effect, i.e. more efficient test stimulus in a backward masking situation, hence non-opponent hue masking is predominant. It is suggested that in the forward masking sequences, although overall masking was reduced, the opposite condition may occur, that is, opponent-hue masking is more predominant.

The preceding assumptions are all based on one further postulate of opponent-process theory, that is, the occurrence of opponent induction processes that make a response in any local area of the visual field dependent not only on the local stimulation in that area, but also on activities in surrounding visual regions. This last assumption has considerable importance since the test and mask stimuli did not occupy the same retinal region but were, in fact, separated spatially, the test stimulus being circumscribed by the annulus of the mask stimulus. The two stimuli were separated, both spatially and temporally, by a 'dark' region. It can be suggested here that manipulation of these spatial and temporal variables, including the duration of the mask stimulus, might prove to be fruitful areas in further support of an opponent-process theory of color vision.

The second experiment again hypothesized a general reduction in the effectiveness of the test stimulus as a function of the mask stimulus, independent of the hue combinations. The temporal sequence between test and mask hue was a proactive or forward masking sequence. Again it was predicted a differential masking effect would occur as a function of the opponent and non-opponent relationship between the test-mask pair. The first hypothesis of a general masking effect, across hues, was confirmed, the mean test stimulus recognition was 53.75% (46.25% masking). When compared with the first experiment it can be concluded that a weaker masking effect, or increased recognition, took place in the forward masking sequence. This observation is confirmed in the combined analysis of forward versus backward masking. The hypothesis of differential masking effects in opponent and non-opponent hue pairs was not confirmed. Four of eight comparisons made between opponent and non-opponent test-mask pairs indicated greater opponent pair masking; of the remaining four comparisons, three showed greater masking in the non-opponent pairs, and in the fourth, no difference was demonstrated. It seems reasonable to conclude on the basis of the foregoing that with a proactive mask-test sequence there is a consequent reduction in masking effect which is further reflected in the lack of any definite relationship between the opponent hues, mask and test stimulus. It appears that, the stronger the masking effect, the more explicit the relationship becomes with regard to opponent hue and non-opponent hue test-mask pairs.

Of further interest are the means for the four hues as test and mask stimuli particularly with regard to the order of test and mask efficiency. For both backward and forward masking conditions the green test hue was most efficient in resisting masking effects, followed by yellow, red and blue. This ordering effect varies considerably with the results obtained by Teft (1969) whose four test hues were ordered, in terms of their resistance to masking effects, from blue, red, green to yellow. For Teft, blue is the most efficient hue in terms of resistance to masking effects; however in this experimental series, blue is the least efficient hue in this respect. Differences in experimental methods however, make any comparisons between these two studies less than conclusive.

The unusually increased reduction in recognition of blue hue-letter combinations should probably be regarded with some suspicion. In spite of the fact that duration thresholds for the four hues were determined prior to the experimental series using recognition procedures, blue test stimuli were masked to a considerably greater extent than the other three hues.

This raises the question of why should blue test stimuli, in this experimental situation, be more prone to masking than the other hues? A suggested solution may lie in the degree of contrast present between the test stimuli and the opaque black background. As noted above, the order of efficiency, in terms of resisting masking, was green, yellow, red and blue, with blue being the least efficient, i.e. most easily masked test stimulus hue. Comments by the subjects indicated that blue appeared to be highly saturated when compared with the other hues, particularly green and yellow. This suggests that a low contrast condition existed between blue and the black background when compared with yellow and a black background. Such a low contrast condition, as described above, might account to a large extent for the reduction in recognition of the blue test stimuli along with any concurrent masking effects due to the presence of an initial or subsequent masking stimulus

In general, it may be stated that the results of this experimental series, while not conclusive, do appear to provide some empirical support for an opponent-process theory of color vision. Furthermore, the results do tend to support earlier findings of chromatic backward masking. The extent of masking varies significantly with not only the particular test and mask hues employed, but also with the temporal sequence of the test and mask stimulus, i.e. a backward or forward masking sequence.

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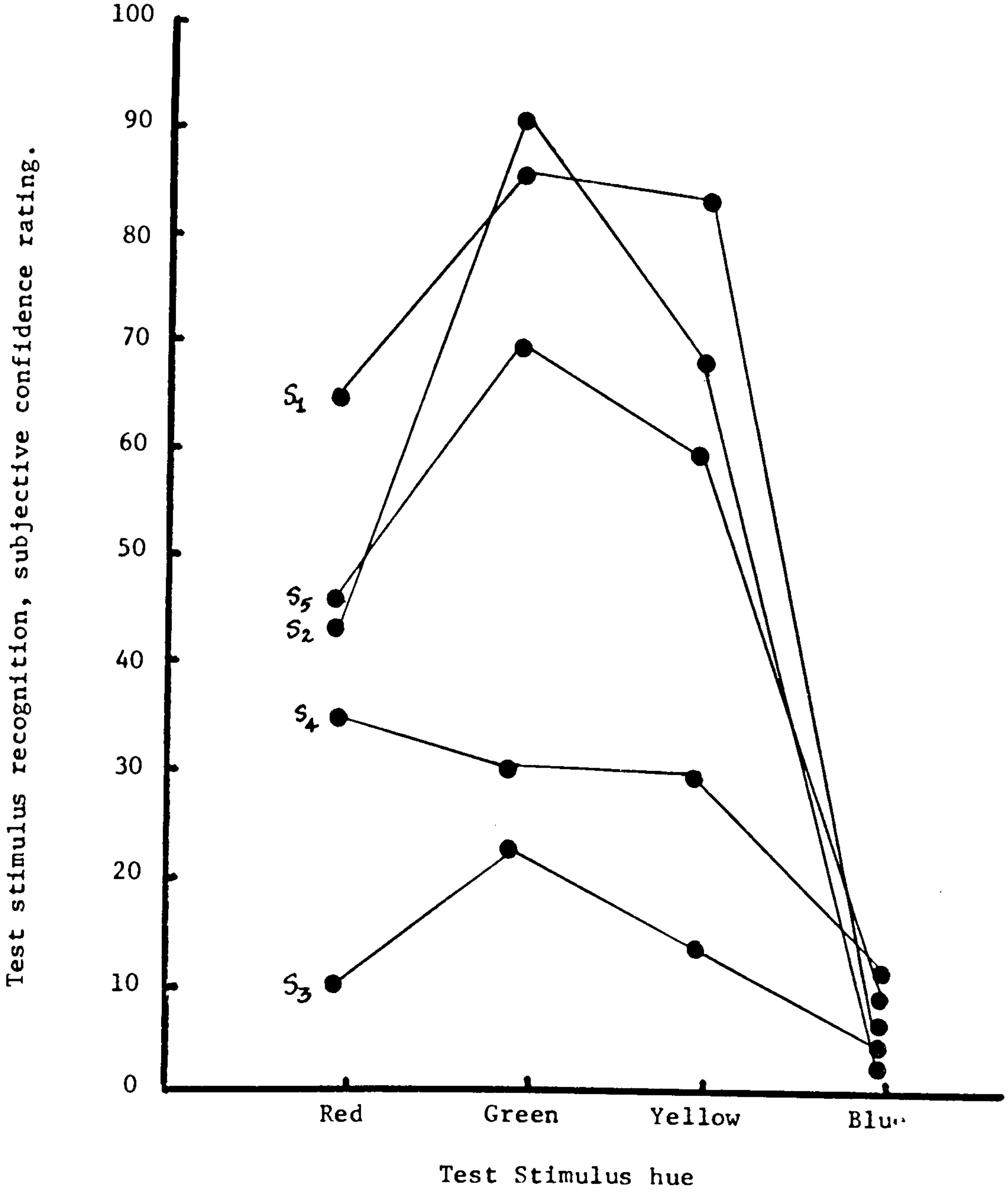
# Appendix A

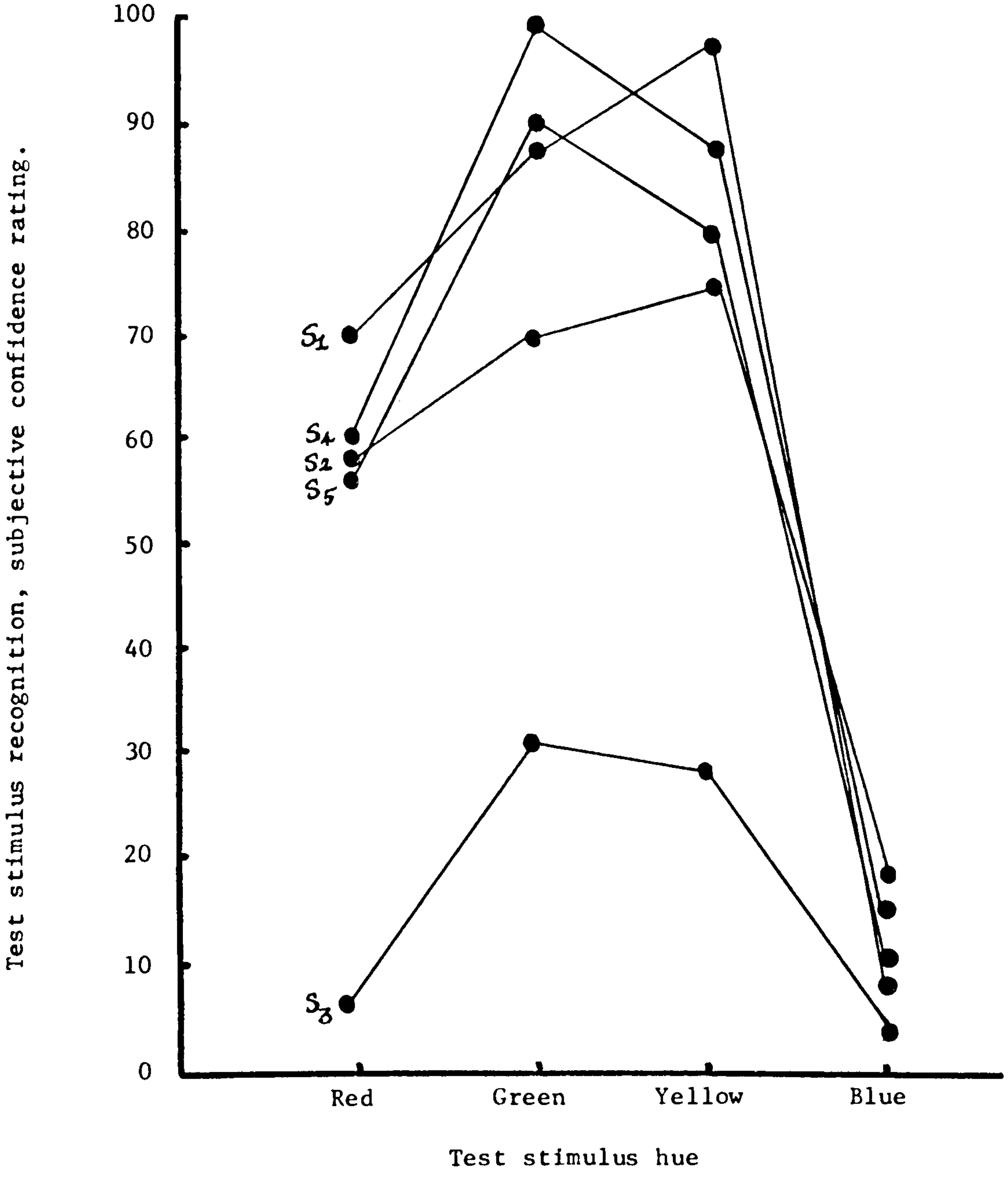
Figure of mean test stimulus recognition, subjective confidence rating, for each of five subjects for the hues red, green, yellow and blue (Backward masking condition).



Mean test stimulus recognition, subjective confidence rating, for each of five subjects for the hues red green yellow and blue (backward mask condition).

# Appendix B

Figure of mean test stimulus recognition, subjective confidence rating, for each of five subjects for the hues red, green, yellow and blue (forward masking condition).



Mean test stimulus recognition, subjective confidence rating, for each of five subjects for the hues red, green, yellow and blue (forward mask condition).