Threshold Temporal Integration of Chromatic Stimuli

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Abstract—We measured calorimetric purity thresholds as a function of stimulus duration for seven wavelengths between 430 and 650 nm. Purity thresholds were measured in a hue substitution mode. The purity-duration function showed decreasing purity as duration was increased to about 640 msec. Functions for different wavelengths could be fit by a fixed chromatic template displaced on the purity axis. Increment thresholds as a function of duration were measured for white and chromatic lights added to a homogenous white stimulus field. The “white” function showed no integration beyond 160 msec and was fit by an achromatic template. The wavelength functions were not parallel; wavelengths at the spectral extremes showed longer integration times, similar to the purity-duration functions. Increment data could be fit by a vector sum of chromatic and achromatic templates.

Chromatic mechanisms Colorimetric purity Hue substitution Temporal integration

Introduction

Psychophysical methods have been used extensively to investigate the temporal properties of the human cone photoreceptors and cone-fed neural pathways. The existing literature emphasizes the following three theoretical generalizations.

1. Temporal resolution is poorer or temporal integration greater for the short-wavelength cone than for the middle- and long-wavelength cones

These ideas were suggested by studies that use selective chromatic adaptation and the two-color threshold methods of Stiles (1978) to attempt isolation of single cone mechanisms. Brindley et al. (1966) found a peak value of critical flicker frequency (CFF) for Stiles’ Π₁ mechanism that was about three times lower than that for the Π₁, and Π₁, mechanisms. Green (1969) also reported reduced CFF (a lower cut-off frequency) for the “blue” system which he attributed to depressed modulation sensitivity at all temporal frequencies relative to that observed for “green” and “red” mechanisms. Kelly (1974), in attempting to measure temporal contrast sensitivity functions for the cone mechanisms, found both a lower cut-off frequency and a lower frequency of peak sensitivity for the “blue-sensitive” mechanism. Krauskopf and Mollon (1971) and Uetsuki and Ikeda (1971) used variants of the Stiles two-color technique in estimating critical duration for single pulses of light, a measure that is reciprocal to CFF (Matin, 1968). They reported longer values of critical duration for “short-wavelength mechanisms” or Π₁, Π₁, vs Π₁, and Π₁, mechanisms. (But see Mollon, 1982 and Krauskopf and Williams, 1981. Also see the Discussion section of this paper.)

2. Isolated chromatic (neural) systems have poorer temporal resolution or longer temporal integration than the achromatic systems

The evidence for this hypothesis comes from various approaches. de Lange (1958) and Kelly and van Norren (1977) obtained temporal contrast sensitivity functions for red and green sinusoidal waveforms presented 180 deg out of phase. This red-green “isoluminance” stimulus produced a low-pass contrast sensitivity function. In comparison the same stimuli presented in phase to give pure luminance flicker produced a band-pass contrast sensitivity function with a higher cut-off frequency. Bowen et al. (1977) measured two-pulse discrimination (threshold interval between two just-resolvable pulses) for spectral targets presented either as luminance increments or decrements (discrimination by achromatic mechanisms) or in “hue substitution” (chromatic targets exchanged for equiluminous white fields, favoring discrimination by purely chromatic mechanisms). Two-pulse thresholds were generally longer (temporal resolution was poorer) for hue substitution pulses than for incremental and decremental stimuli except at the spectral extremes. Dain and King-Smith (1981) measured threshold-duration functions under conditions designed to favor detection by the red-green opponent mechanism (674 test on a 556 nm adapting field). Critical duration for these conditions was significantly longer than for detection by the achromatic systems (isochromatic 556 nm test and background).

3. The isolated red-green and blue-yellow chromatic systems are similar in their temporal properties.

We make this inference based upon our analysis
of published data. For example, plots of contrast sensitivity vs frequency for equiluminous red-green (Wisowaty, 1981) and blue-yellow (Wisowaty and Boynton, 1980) counterphase flicker have identical asymptotic slopes. Similarly, contrast sensitivity functions to temporal modulation of colorimetric purity (Walraven et al., 1958) have the same high frequency slope when plotted against square root frequency. Both results imply equivalent resolution properties for the chromatic processing systems. Further, Bowen (1981) showed that while visual onset and offset latency to hue substitution pulses were wavelength-dependent, the overall visual response duration (the algebraic difference between onset and offset latency) remained constant for stimuli of different wavelengths.

The present study takes a new approach to the problem of measuring the temporal response characteristics of chromatic mechanisms, and the resulting data bear upon the three hypotheses cited above. We have obtained measures of the colorimetric purity threshold for a mixture of white and spectral light which is exchanged with an equiluminant steady white field. Threshold purities necessary for detection are determined as a function of the duration of the exchange. As indicated above, this type of chromatic stimulus presentation has been called hue substitution. Hue substitution is intended to isolate the response of chromatic neural mechanisms. In addition to measuring purity thresholds for hue substitution presentations, we have also obtained measures of luminance thresholds for incremental spectral lights and a "white" light in order to assess the relative contributions of chromatic and achromatic mechanisms to the detection response.

METHODS

Equipment

Our equipment was a four-channel, computer-controlled optical system. Light was sampled from a xenon arc lamp in two directions. One path served as a "colored-light" channel: the light was collimated for insertion of interference and neutral filters and wedges and then re-imaged on a d.c. servo-controlled circular neutral density wedge. The light was then imaged into an integrating sphere. The other path was split to form three "white-light" channels. One beam (the desaturant channel) passed through a second d.c. servo-controlled neutral density wedge and then was combined with the colored-light channel at the entrance to the integrating sphere. These two channels allowed selection of equiluminant mixtures giving colorimetric purities ranging from 0.0008 to 0.985. Before the entrance of the integrating sphere was a shutter (Uniblitz, Vincent Associates) with reflective blades. The second white-light channel passed through color-compensating and neutral filters and was reflected from the front of the shutter into the integrating sphere. The chromaticity coordinates of the white light were \( \lambda = 0.3134, \ \mu = 0.3363 \). (For a description of the chromaticity calibration procedure, see Burns et al., 1982.)

A field-stop was placed at the exit of the integrating sphere to give a 1.2 deg field. The third white-light channel passed through color-compensating and neutral filters and then was reflected from this field stop to produce a 4' white surround. A lightly-frosted glass diffuser was placed in front of the field stop to blur its edges. The observer viewed the field directly.

The colored light was produced by three-cavity interference filters (Ditric Optics). The nominal wavelengths of peak transmission were 430, 450, 480, 500, 530, 570, 600 and 650 nm.

Calibrations

Color-compensating and neutral filters were used to make the three white-light channels metamic. All three were of equivalent luminance when the desaturant channel's computer-controlled wedge was at its transparent position; this luminance was 1 cd/m² (about 15 effective trolands when viewed with the natural pupil. Le Grand, 1968).

The d.c. servo-controlled wedges were driven by 11 bit D/A converters. The overall repeatability of the angular position of the wedges was better than 0.3 deg (worst case, 0.003 density unit). The wedges were calibrated at each of 83 wedge positions using an EG&G Model 550 radiometer/photometer with its BCD output sent to a Z-80 based microcomputer. The average relative transmission of the wedge as a function of position was stored on floppy disk. We repeated the calibration of the colored light channel for each interference filter used in the study.

A photomultiplier was used to calibrate the shutter. Shutter transients were eliminated by adjustment of optical components. We used shutter timing determined by our XY Basic computer language. We wanted nominal shutter durations of 5 msec increasing by factors of two to 2560 msec and we set these by trial and error. We were within 2 msec for each duration except at the lowest duration; 8 msec was the shortest duration that could be achieved using XY Basic.

Procedures

The experiment was run under computer control. The experimenter selected the wavelength and set of durations for a given trial block. Up to nine durations were used in a block.

For purity thresholds in hue substitution, the wavelength was chosen and the computer selected the white-light and appropriate colored-light calibration data. Starting with the lowest transmission of the colored-light wedge, the lowest available colorimetric purity was calculated, followed by a set of purity steps increasing in logarithmic steps of 0.097. Thirty-two steps were available. Using the calibration data, the necessary wedge voltages were calculated for each desired purity step.
At the start of the trial block both computer-controlled wedges were in their transparent position. We blocked the colored-light channel, removed the frosted glass and controlled the shutter by a function generator to check that no visible white-light transient occurred when the shutter opened at a low repetition rate. We then replaced the frosted glass and blocked the desaturant channel. An additional manual wedge was used to adjust the colored-light channel to equivalent luminance with the white-light channel by heterochromatic flicker photometry. Three matches were made; the repetition rate on the function generator was adjusted to allow a precise match. When all channels were matched in luminance, the shutter was returned to computer control.

For incremental thresholds, the desaturant channel's wedge was set at its transparent position to give a 1 cd/m² background. The appropriate colored-light channel calibration data were selected and necessary wedge control voltages calculated for logarithmic increment steps of 0.097. The white-light channels were balanced as described previously and heterochromatic flicker photometry was performed for the selected wavelength.

The computer program was in three parts. First, we checked that the range of durations was appropriate. Next, we measured thresholds using a staircase procedure with randomly interwoven durations. The initial purity was in the middle of the range and the step size was 1/4 of the range. The direction of each subsequent step was determined by the observer's response. After a reversal, the step size was halved until a reversal in response occurred for a unit step (0.097 log difference). In the third part, starting with the threshold "yes" response, randomly interwoven staircases in unit steps were run until either 5 or 10 response reversals were obtained.

Observers

Two of the authors, both with normal color vision and normal visual acuity, served as observers. Observer R.W.B. ran two trial blocks of five reversals per session. His data represent two or three replications at each wavelength for a total of 20 or 30 reversals per duration. Observer V.C.S. ran one trial block of ten reversals at each wavelength.

RESULTS

The logarithm of threshold colorimetric purity log \( \frac{L_c}{L_u + L_c} \) is plotted as a function of stimulus duration in Fig. 1. For all wavelengths, purity decreases as exposure duration increases until about 640 msec and then levels off. The slopes of the functions show a gradual change with duration increase. At the shortest durations of 8–20 msec, the slopes show approximate reciprocity. Above 20 msec, there is a more gradual change in the purity until the asymptote is approached. Data for the two observers are similar. The functions for the different wavelengths are of similar shape but are displaced on the purity axis. The highest purities are required for 570 nm, the lowest for 430 nm. Thresholds could not be obtained below 80 msec for 570 nm but were obtained at 8 msec for 430 and 450 nm, confirming an earlier study of duration thresholds for hue substitution stimuli (Pokorny et al., 1979).

The solid and dashed lines in Fig. 1 represent a set of theoretical predictions derived to test whether the data for different wavelengths can be described by a common template. We assumed that chromatic temporal processing can be described as a linear low-pass filter. We based our choice of filter on the data of Wisowaty (1981) representing the temporal response of an isolated "red-green" chromatic pathway. Wisowaty and Boynton (1980) published data for an isolated "blue" mechanism response whose high frequency response shows similar slope to the "red-green" chromatic response.

Relative modulation sensitivity for an nth-order linear filter can be written

\[
\log M = n \log(2\pi c) - n/2 \log(4\pi^2(f^2 + c^2))
\]

where \( M \) is percent modulation, \( f \) is frequency (Hz).
Fig. 2. The three panels demonstrate the procedure used to obtain a threshold template. The top panel shows linear low-pass filters for chromatic (solid line) and achromatic (dashed line) processing [equation (1)]. The middle panel shows the corresponding impulse functions [equations (2) and (2a)] and the bottom panel shows the corresponding threshold templates [equation (3)].

$K$ is a normalizing constant, $n$ is the number of stages, and $c$ is the corner frequency (Hz) (Fig. 2, top panel). An impulse response for a minimum phase linear filter may be described by the equation

$$I(t) = \left( \frac{t^n e^{-2\pi c t}}{n} \right)$$

This function $I(t)$ can be normalized by dividing by its maximal value which occurs at time $(n - 1)/2\pi c$

$$I_n(t) = I(t)/I[(n - 1)/2\pi c]$$

where $t$ is in msec and $n$ and $c$ are as defined above (Fig. 2, middle panel). To model a threshold response we assumed that the observer acts as a peak detector (Roufs, 1972). We used a discrete convolution procedure to obtain the response $R(J)$ at discrete times $J$ for different duration stimuli using the equation

$$R(J) = \sum_{K=0}^{2560} \sum_{J=0}^{K} A(K) I_n(J - K)$$

where $J$, $K$ were discrete times sampled at 5 msec intervals for $J$ varying from 0 to 2560 msec and $K$ from 0 to $J$; $A(K)$ was the stimulus step defined as unity for $K$ less than the stimulus duration and zero elsewhere; and $I_n(J - K)$ was the normalized impulse response function given by equation (2a) evaluated at times $J - K$. We then assumed that threshold would be proportional to the reciprocal of the peak response at each duration. Based on the Wisowaty (1981) and Boynton and Wisowaty (1980) data, the number of stages ($n$) determined by the slope of the high frequency component, could have a value of 5 or 6. The choice of corner frequency $c$ determines the range of the curve. We used a 5 stage 5 Hz corner frequency filter. The bottom panel of Fig. 2 shows the predicted log threshold for the filter.

The chromatic response template was fit by a least-squares procedure to the data for each wavelength allowing only scaling on the vertical axis. Table 1 shows the average residual least square at the minimum for each wavelength for both observers. The average residuals ranged from 0.0011 to 0.0053 and did not show systematic wavelength variation. The data are replotted in Fig. 3, to show the deviations from the template. For observer V.C.S., the data points distribute about the template except for 320 msec for which many points fall below the template. For observer R.W.B., data at 160 and 320 msec distribute above the template and those above 640 msec distribute below the template. To a first approximation, our purity threshold data are all fit by the same chromatic response template.

The 2560 msec data are shown as a function of wavelength in Fig. 4. For both observers, the results appear like plots of colorimetric purity measured as the first step from white. Wright's (1946, p. 164) average of three studies of least colorimetric purity is shown for comparison.

The second set of data, for incremental stimuli, were obtained on the 1 cd/m² light background. The coloured light channel was varied to obtain thresholds. The maximal purity was therefore 0.5. Data were obtained both for a white light condition and for several wavelengths. Figure 5 shows thresholds as a function of duration. Again, threshold decreases as duration increases. However, the functions are no longer parallel. The white light and 570 nm functions have reached an asymptote by 160 msec. The function for 500 nm shows a continued decrease to about

<table>
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<th>Wavelength</th>
<th>V.C.S.</th>
<th>R.W.B.</th>
</tr>
</thead>
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<td></td>
<td></td>
</tr>
<tr>
<td>430</td>
<td>0.0022</td>
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</tr>
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<td>0.0016</td>
</tr>
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<tr>
<td>600</td>
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<tr>
<td>white</td>
<td>0.0029</td>
<td>0.0018</td>
</tr>
</tbody>
</table>
Fig. 3. Threshold calorimetric purity data replotted to show deviations from the chromatic template of Fig. 2.

320 msec and the functions for 430 and 650 nm show asymptotes at 640 msec.

The solid line drawn through the “white” data represents an achromatic response template derived in the same way as described for the chromatic response template. The achromatic response template was derived from a 5 stage, 12.6 Hz corner frequency linear filter* (see Fig. 7) A least-squares fit of the achromatic template to the “white” function showed residual error scores of 0.0029 for V.C.S. and 0.0018 for R.W.B. (Table I).

In Fig. 5, the increment data for various wavelengths were predicted by combining chromatic and achromatic templates. This was possible since both data sets share the same metric, the amount of light transmitted by the colored channel wedge necessary for detection. The predicted functions (solid and dashed lines) were obtained by vector summation of the chromatic sensitivity templates of Fig. 1 with the achromatic template of Fig. 5. No free vertical scaling was allowed. Fits for observer V.C.S. are close to the data with exception of the 450 nm data which shows a 0.1 log unit vertical scaling difference. Data for R.W.B. are also close to the predictions.

The increment data represent a procedure similar to that of King-Smith and Carden (1976) and may be replotted in their format. The difference between the white function and the other increment functions represents the additional sensitivity derived by using narrow-band light. Figure 6 shows these differences at fixed durations for observer V.C.S. plotted relative to the Judd (1951) revised V′(λ). The functions are similar to the King-Smith and Carden (1976) data in showing increased sensitivity at the spectral extremes for long duration pulses.

DISCUSSION

Several aspects of the results should be emphasized:

(1) The same purity vs duration function is obtained at all wavelengths if the signal to be detected is a purely chromatic one.

This result clarifies certain discrepancies in the literature on wavelength effects on temporal integration. In particular, if the stimulus is selected so as to favor detection by chromatic mechanisms and if luminance mechanisms do not affect the detection response, no effects of wavelength on temporal processing are observed.† Identical temporal integration functions are merely scaled vertically along the threshold purity axis according to trichromatic purity discrimination. This finding is consistent with the hypothesis that the red-green and blue-yellow chromatic systems have similar temporal integration properties.

(2) The purity−duration function for an incremental achromatic stimulus shows shorter temporal integration than do the functions for hue substitution signals.

This finding extends the generality of various studies (e.g. Dain and King-Smith, 1981) which claimed longer temporal integration for chromatic mechanisms relative to achromatic mechanisms.

(3) Temporal integration for incremental chromatic stimuli is determined jointly by chromatic and achromatic systems.

We are able to model the purity−duration functions for chromatic increments at various wavelengths by a vector combination of the achromatic function and the appropriate chromatic function. Such an approach is arbitrary but vector summation has been used successfully to predict brightness of spectral lights (Guth et al., 1969). In fact, for most
wavelengths, the choice of combination formula is not critical. The chromatic data (Fig. 1.) at 530 nm for V.C.S. and 500 nm for R.W.B. lie close to the increment white data (Fig. 5). Figure 7 shows the increment data for these wavelengths plotted with three types of combination rule: most sensitive, vector summation, and linear summation. The data lie closest to the vector summation prediction, but for both observers show similar deviations. The data are not sufficiently precise nor the models sufficiently different for a firm conclusion.

We chose to model our data with two low-pass filters of identical slope but different corner frequencies. A band-pass filter for the achromatic function could also be used, and would give an identical template for an appropriate choice of parameters. Similarly a pair of low-pass filters subtracted to give band-pass characteristics and added to maintain low-pass characteristics (e.g. Burbeck and Kelly, 1980; Kelly, 1983) can also give an identical pair of templates. When such pairs of filters are matched in amplitude, they differ in high-frequency resolution. However these same sets of filters with appropriate vertical scaling all converge at high frequencies. The lower integration range of the achromatic filter results from its reduced modulation range. In general, there is no way a priori to determine the relative positions of the chromatic and achromatic filters and thus to compare resolution capabilities of the two mechanisms.

Our data do however, allow an explicit comparison of chromatic and achromatic sensitivity at least for our experimental conditions. The depth of chromatic modulation from white depends on wavelength, being greatest at the spectral extremes and least at 570 nm. At 570 nm purity thresholds are less sensitive than increment thresholds at all durations. The available chromatic modulation depth is much less than the achromatic, and we expect temporal processing to be poorer at all frequencies. At 600 and 500–530 nm the purity thresholds are approximately the same as the achromatic at long durations. For these wavelengths, chromatic and achromatic modulation depths are the same. However the purity thresholds are less sensitive at short durations, implying that chromatic temporal processing is poorer at high frequencies. At the spectral extremes, purity thresholds are more sensitive than achromatic threshold at all durations. For these wavelengths, the available chromatic modulation depth is greater than the achromatic. Chromatic temporal processing is superior at low frequencies and slightly superior or equivalent at high frequencies. Thus depending on the chromaticity range investigated, the chromatic mechanism may show poorer or equivalent high-frequency resolution.

Fig. 4. The logarithm of reciprocal threshold colorimetric purity for a 2560 msec stimulus plotted as a function of wavelength. Circles and dashed lines show data of observer V.C.S.; squares and dashed lines show data of observer R.W.B. The solid line is Wright's (1946) average of least colorimetric purity. The data have not been scaled vertically.

Fig. 5. Luminance thresholds plotted as a function of duration (msec). The solid and dashed lines are derived from vector summation of the achromatic template with the chromatic templates fitted to data shown in Fig. 1. The top panel shows data for observer V.C.S.; the bottom panel shows data for observer R.W.B.
Fig. 6. Increment data recalculated to show relative sensitivity as a function of wavelength. The difference between chromatic increment and white templates are plotted relative to the Judd (1951) relative luminous efficiency function (solid line). Different circles represent different durations; higher sensitivity is associated with longer durations. The top panel gives data for observer V.C.S. and the bottom panel data for observer R.W.B.

It must be emphasized that we used modulation from white. When pairs of wavelengths are used (Kelly, 1974; Wisowaty and Boynton, 1980; Wisowaty, 1981) the modulation range will depend on the available chromaticity range. Modulation from white favors short wavelengths at the expense of the mid-spectrum. In comparison, chromaticity modulation from mid-to-long spectrum lights allows a larger modulation range for mid-spectrum lights. Nevertheless, chromatic processing at mid-spectrum still shows lower resolution capability. Based on our data however, chromatic processing can show equivalent resolution provided a sufficient chromaticity range is available.

How may our results be reconciled with the assertion that temporal resolution is poorer or temporal integration greater for short-wavelength cones than for middle- and long-wavelength cones (point 1 of the Introduction)? We first accept the postulate that isolated short-wavelength mechanisms only act through a chromatic processing channel while isolated middle- and long-wavelength mechanisms input to either achromatic or chromatic processing channels (Guth et al., 1968; Mollon and Krauskopf, 1973; Smith and Pokorny, 1975; Tolhurst, 1977; Boynton, 1979; Stromeyer et al., 1979; Eisner and MacLeod, 1980). Given this, it then becomes clear that the reported longer temporal integration of the "isolated" short-wavelength cones (Krauskopf and Mollon, 1971; Uetsuki and Ikeda, 1971) is merely an expression of the different integration properties of achromatic and chromatic neural systems. Further, use of bright yellow adapting fields to isolate short-wavelength cone response (e.g. Brindley et al., 1966; Green, 1969; and Kelly, 1974) may serve to reduce modulation sensitivity even more (Wisowaty and Boynton, 1980). Thus the hypothesis of inherently "slow" short-wavelength cones is called into question.

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REFERENCES


