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Recognition Thresholds for the Spectrally Opponent Neural Network in the Human Visual System

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RECOGNITION THRESHOLDS FOR THE SPECTRALLY OPPONENT NEURAL NETWORK IN THE HUMAN VISUAL SYSTEM

Douglas H. Smith
RECOGNITION THRESHOLDS FOR THE SPECTRALLY OPPONENT NEURAL NETWORK IN THE HUMAN VISUAL SYSTEM

Douglas H. Smith

December, 1976

Submitted in partial fulfillment of Masters and Baccalaureate degree requirements of the Photographic Science and Instrumentation program at Rochester Institute of Technology, Rochester, New York. Dr. Gerhard W. Schumann, Director of Graduate Studies. Advisors: Dr. Robert T. Kintz, Eastman Kodak Company, Dr. Gerhard W. Schumann, Rochester Institute of Technology

ABSTRACT

Recognition thresholds for an alphanumeric resolution test object of differing target/background chromaticities and equal luminosities were determined. Combinations of the four psychologically unique hues were studied, and those pairs corresponding to the green-red and yellow-blue opponent neural systems were found to give the highest visibilities. Equivalent achromatic contrasts for each of the presented color pairs were determined, and comparison of the results with achromatic data of other researchers shows clearly that the spectrally opponent neural network in the human visual system is much less efficient in processing spatial information than is the spatially opponent (achromatic) neural network.
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I. INTRODUCTION

I-1. The Problem

To date, investigations in the realm of chromatic information transmission in the human visual system have been limited. Most research has dealt with the physical characteristics of the cone mechanisms themselves; spectral sensitivities, pigment bleaching rates, and threshold contrasts for colored gratings on adaptive fields of differing chromaticity and higher luminance level having been determined for each (Stiles, 1949; Brown and Wald, 1964; Marks, Dobelle, and MacNichol, 1964; Rushton, 1966; Green, 1968; Kelly, 1973; Cavonius and Estevez, 1975). Some studies of the function of the visual neural system are also evident (DeValois, 1965a; Wiesel and Hubel, 1966; DeValois, Abramov, and Jacobs, 1966), but little has been said concerning the spatial frequency information transmission capabilities of the human chromatic system as a whole. This study directs itself to that end.

I-2. The Human Color Vision System - An Overview

Thomas Young (1807) was the first to formulate a modern theory of trichromacy for human color vision. He suggested that three primary color sensations (red, green, and violet), separately and in combination, were responsible for the myriad of colors perceived by the visual system. His work was elaborated by Helmholtz (1866), who incorporated the theory into his Handbuch der Physiologischen Optik. Their work, combined with
that of Max Schultz (1866), who determined that color vision was due exclusively to the response of cones in the retina, led to the postulation of the existence of three types of cones differing in spectral sensitivities. Extensive investigations by Stiles (1949), Rushton (1963, 1964, 1966), Brown and Wald (1964), and Marks, Dobelle, and MacNichol (1964) have proved the postulation correct and spectral sensitivity functions for the three cone types have been determined.

Considerable evidence exists to suggest that in addition to the three classes of photo-receptors (cones) present in the retina, the phenomena of human color vision requires a complex neural system to compare and contrast the output from the different receptor types. A very important property intrinsic to the photopigments contained within the cones of the retina is that they give the same type and size of response to any captured photons regardless of the wavelength of the incident light. According to Rushton, et al (1973), this so-called Principle of Univariance can be stated: "The (inherent) response of a receptor depends upon its effective quantum catch, but not upon what quanta are caught". Each receptor type responds to light of almost any wavelength according to its spectral sensitivity. From this, it can easily be seen that chromatic information is lost within the initial visual response; the receptors, by themselves, cannot be responsible for color vision.

Two opponent neural organizations within the human visual system are thought to be responsible for separating and processing visual information received by the photo-
receptors into luminance and chromatic components. Research in sensory physiology has shown that virtually every neuron in the sensory pathway has a combination of excitatory and inhibitory influences exerted upon it, and will increase or decrease its firing rate (from some median level) upon exposure to the proper stimulus. This spontaneous firing rate of afferent neurons serves as a carrier frequency around which signals are modulated, with both increases and decreases from this frequency relaying information about the stimulus (DeValois, 1965a; Vander, Sherman, and Luciano, 1975; DeValois and DeValois, 1975). Achromatic luminance information is believed handled in this manner by a spectrally non-opponent neural network and wavelength information by a spectrally opponent neural network. Both mechanisms apparently aim at increasing the specialization of single neural cells (in the direction of spatial form as opposed to diffuse light, and color as opposed to white light) (Barlow, 1953; Kuffler, 1953; DeValois, 1965b; Wiesel and Hubel, 1966; DeValois, 1972).

Precortical neural units subservient to the spectrally non-opponent network exhibit typical antagonistic center-surround receptive field organization, with 'on' centers and 'off' surrounds (or the converse thereof) of like spectral sensitivity. Such cells are color blind and are capable of processing achromatic information only (DeValois, Jacobs, and Jones, 1962; Jacobs, 1965). Neural cells responsible for the spectrally opponent system, on the other hand, possess a center-surround organization with spectral sensitivities for excitatory centers and inhibitory surrounds differing from one another (Gouras,
1968; DeValois and Pease, 1971). Four types of spectrally opponent cells are thought to exist at the lateral geniculate level (red excitative—green inhibitive, green excitative—red inhibitive, blue excitative—yellow inhibitive, and yellow excitative—blue inhibitive), and it is believed they difference the responses of the red- and the green-sensitive cones, and the combination of the red—plus green—(yellow) and the blue-sensitive cones (DeValois, 1965; DeValois, Abramov, and Jacobs, 1966; Walraven and Bouman, 1966; and Abramov, 1968). The red-green and blue-yellow systems within the spectrally opponent organization form the basis for the so-called psychologically unique hues; those colors (red, yellow, green, blue) which appear to the visual system to be fundamental in nature.

Because of the inherent differences in receptive field organization, the spatial tuning (at the lateral geniculate level) of the two opponent networks is thought to be quite different. Whereas the spectrally non-opponent network is optimally responsive to small, incremental (or decremental) stimuli (Kuffler, 1953; DeValois, 1972), the spectrally opponent network will best fire to large, uniform fields (DeValois, Smith, Karoly, and Kitai, 1958; Wiesel and Hubel, 1966; Gouras, 1968; Ingling and Drum, 1973). A cell with green-sensitive excitatory center and red-sensitive inhibitive surround would be optimally excited by a uniform green spot covering its entire receptive field, since a green spot at its center would cause maximum excitation and green in the surround would elicit minimum inhibition (DeValois and DeValois, 1975). A small green spot with
red surround, on the other hand, would prove a very poor stimulus, since both excitation and inhibition would be taking place simultaneously. For this reason, color discrimination ceases when the spatial frequency of the stimulus becomes high enough to cause color changes within the response field of a spectrally opponent cell. Granger and Heurtly (1973) have shown that this cessation occurs at spatial frequencies greater than 20 cpd.

Investigations involving observer response to 'pure' chromatic stimuli (in the absence of luminance information) have been limited. Most researchers have made use of periodic sine- and square-wave gratings in their studies, and consequently, very little information regarding the processing capabilities of the human chromatic visual system to tasks of greater inherent complexity than grating detection is available. Shade (1958) was the first to use sine-wave gratings of equal luminance and varying chromaticity in an effort to isolate and study the 'color' channel in human vision. He found a loss in the low frequency end of the measured sine-wave response functions, and postulated the existence of a high-pass band filter in the color processing system, similar to that found in the luminance channel. Subsequent researchers (van der Horst, de Weert, and Bouman, 1967; van der Horst and Bouman, 1969; Granger and Heurtly, 1973; Kelly, 1974) failed to find this low frequency loss, and found instead a flat response, indicating that the color discriminating process responds optimally to large, uniform, low frequency stimuli. These findings are consistant with the response field organizations discussed.
earlier. Patel (1967) and van der Horst, et al (1967) also found that as the over-all luminance level is decreased, neural integrative interaction of the chromatic channel increases, thereby causing an increase in threshold.

Investigations by Wagner, MacNichol, and Wolbarsht (1960) and Wiesel and Hubel (1966) have shown that the spectrally opponent cells are capable of serving not only the spectrally opponent neural network, but the spectrally non-opponent neural network as well. These precortical units (which comprise over 70% of the population of the precortical neural cells in the human visual system (DeValois and DeValois, 1975)) can handle chromatic information and luminance information simultaneously, and will give the same response to small, incremental (luminance) stimuli as they will to large, uniform chromatic fields (of appropriate wavelength). This necessitates further processing at neural levels higher than the lateral geniculate nucleus. To date, there has been very little investigation dealing with the color responses of cortical cells, but the evidence available suggests that LGN color information is fed into: (1) cortical color-specific channels that separate chromatic and luminance information, and (2) cortical multiple-color channels that sum over several chromatic inputs to extract contour (form) information (Gouras, 1968; Hubel and Wiesel, 1968).

Daw (1968) was the first to discover so-called double-opponent, color specific cells in the monkey
striate cortex. These cells have concentric center-surround organization as do LGN cells, but in addition, possess a large far surround of opposite spectral response characteristic to that of the near center-surround. Therefore, a cell with green-sensitive excitative center and red-sensitive inhibitive surround would have a red-excitative, green-inhibitive far surround and would be maximally responsive to a green on a red background. These cells have also been observed by Hubel and Wiesel (1968) and Michael (1973) in separate studies.

I-3. Use of Fourier Analysis in Vision Research

Research over the past twenty-five years has placed much emphasis on the use of Fourier transforms, and the resulting modulation transfer function, as a means of specifying the physical performance of optical systems. The basic concept of Fourier analysis states that any periodic stimulus, of any waveform, can be analyzed into a series of sinusoidal waves composed of the fundamental frequency and harmonics (integer multiples) thereof. Inversely, Fourier synthesis states that by combination of a fundamental frequency with an appropriate series of harmonics, any periodic waveform can be reconstructed. This implies that if the response of a linear system to a series of sine-waves of known amplitude, frequency, and phase can be discerned, then the response of that system to any periodic waveform can be found. The system in question must be isotropic and homogeneous over the range of investigation, and must be free from phase shifts (Ganz, 1975).
Interest in using this procedure to describe the imaging properties of the human visual system has, of late, been made evident by several independent researchers. Although the response of the visual system has been shown to be non-linear (Campbell and Robson (1968) and Kelly and Magnuski (1975) have found evidence of a multiplicity of frequency-tuned channels in the system, and Richards (1964) has shown that failure of chromatic additivity at low luminance levels is due to non-linearity of the chromatic channel), the assumption of linear superposition over limited dynamic ranges can be made (Dodwell, 1975). The transmission of spatial and temporal information in the visual system can be measured (to some extent) by the visibility of sine- and square-wave gratings as verified by the findings of Shade (1958), DePalma and Lowry (1962), Campbell and Robson (1968), van der Horst (1969), Cornsweet (1970), and Kelly (1972).

The alphanumeric characters contained in the RIT target used in this study all possess three parallel (horizontal) bars similar to those of a tri-bar target. Whether or not the three cycles incorporated in each alphanumeric can be assumed to approximate an infinite square-wave grating (as one is tempted to do) is the subject of some contention. Hoekstra, et al (1974) found that visual sensitivity increased with the number of bars in the grating until a certain 'critical value' \( n = 7 + 1 \) at photopic luminance levels was reached. Kelly (1965) showed three bars to be inadequate in representing an infinite grating, and Barakat and Lerman (1967) found that a "3-bar test object is a poor approximation to an infinite target, while a 7-bar target is an excellent approximation if the central region of the image is used".
Visual thresholds in the present investigation will be reported in cycles per degree in order to conform with standard practice, and will also be given in terms of the spatial angle subtended by the alpha-numeric at the observer's eye. It is recognized by the author that the cycles per degree reported herein probably do not correspond to the cycles per degree reported by previous authors using approximations to infinite (periodic) gratings.

I-4. Inherent Target Uncertainty

Interest in the use of visual acuity targets possessing inherent uncertainty has surfaced in recent years. Whereas sine- and square-wave gratings merely require the observer to respond in a 'yes - no' manner (the grating is either present or absent), a target of greater complexity (possessing a higher degree of uncertainty) requires a psychological judgement on the part of the observer ("What has been seen?"). In their study of the influence of target shape on visual acuity, Villani and Innocenti (1970) theorized that visual perception of Landolt rings, double break rings, 'U', and various (unspecified) letters of the alphabet involved higher neural processing than that required for pure optical resolution. Fox (1957) suggested that as the complexity of the visual task increases (from grating detection to perception of targets possessing some degree of uncertainty), the importance of the contour of the stimulus as an information carrier increases. This point of view is supported by Perrin (1960), who surmised that the criterion of interest
in higher visual tasks is some (as yet unspecified) property of the microdensitometer trace of the edge of the image.

Donaldson and Gough (1967) determined a set of six equally recognizable alphanumerics (2,3,5,8,9,E), and from this, five (2,3,5,8,E) were chosen for use in the RIT Alphanumeric Resolution Test Object (Archer, 1974). Each of the four quadrants of the test object consists of 26 three-character groups ranging in size from 1 line/mm to 18 lines/mm, the progressive change in size following the sixth root of two. Each of the quadrants is individually randomized. (This presents some difficulty in that any observer using the target cannot read all 26 groupings for any given experimental condition. Therefore, the characters actually seen by the observer are not truely random (Bobb, 1975).)

This target has been chosen for use in the present study despite claims that the alphanumerics used are not equally recognizable (Bobb, 1975), and are not truely random in their distribution. It is felt by this author that the advantages gained by its use (inherent uncertainty, a reasonably close approximation to equal recognizability) will outweigh the shortcomings.

The following is a documentation of the use of the RIT Alphanumeric Resolution Test Object in determining recognition thresholds for the human 'color channel'.
II. METHODOLOGY

II-l. Apparatus

The apparatus used in this study was a modified version of that employed by Bobb (1975) in his investigation of identification thresholds (see Figure #1). A high-efficiency tungsten-iodide bulb (General Electric #1958; 150w, 28v) provided mixed white light. This was mounted inside a cardboard housing, thereby necessitating a fan-forced ventilation system to dissipate the generated heat. An Ashland axial flow fan was used for this purpose. The light was collimated using a Wollensak 6" f/2.5 Raptar lens positioned one focal length from the source. Due to the large physical dimensions of the lamp filament (it did not approximate a point source), a pinhole was placed in close proximity to it, and auto-collimation techniques employed on this new source. Once accomplished, the pinhole was removed and the source assumed collimated.

Two cube beamsplitters used to separate and recombine the image and background beams measured two inches to the side and had transmission/reflection coefficients of approximately 0.35. (In other words, they transmitted/reflected about 35% of the light incident upon them.) The image beam in the apparatus was formed by the transmitted light from the first beamsplitter and the background beam by the reflected light.
The remainder of the apparatus is described by Bobb (1975).

Figure #1
Schematic diagram of test apparatus.
The image forming beam fell incident upon a diffuser of opal glass at window #1. Immediately against the diffuser was a polarizer, made of Polaroid Corporation's HN-38 material (chosen for its 'flatness' across the visual spectrum), and a series of mounts constructed to allow for the convenient insertion and removal of appropriate neutral density and Wrottan filter packs. All filters were positioned on cardboard holders, individually notched for identification purposes under dark conditions. The test target was positioned to the outside of all filters at this window, as shown in Figure #1.

The background beam was reflected by two first-surface mirrors after reflection from the first beamsplitter (see Bobb, 1975) and was incident upon an opal glass diffuser at window #2. A second polarizer (Polaroid HN-38), oriented 90° to the axis of the first, and mounts for neutral density and Wrottan filters were present as in window #1.

The second beamsplitter recombined the image and background beams (which were now cross-polarized) by reflecting the background beam from window #2 onto the reflective surface of the test target at window #1, and then transmitting both beams from the test target to the viewing aperture. A third polarizer (also Polaroid's HN-38 material) was mounted on a revolving platter with axis of rotation passing through the center of the aperture. Rotation of the polarizer caused the luminance reaching the eye from one beam to decrease, while that
from the other beam increased, thereby affording a means of equating the luminances of both. A pointer attached to the platter indicated the angle of rotation at any desired luminance setting.

The entire apparatus was baffled within a light-tight housing. All testing was performed in total darkness.

II-2. Filtration

A. Wrattan Filter Packs

Four Wrattan filter packs were prepared for use in presenting the four psychologically unique (color) hues to the observer. Table #1 and Figures #2 - #5 show the combinations used. As is evident from the graphs, the hues are sufficiently separated (in terms of spectral separation of the dominant wavelengths) to allow the use of wideband Wrattan filters. As previously mentioned, the filter combinations were mounted on cardboard holders, the holders having been notched for identification purposes.

<table>
<thead>
<tr>
<th>PSYCHOLOGICALLY UNIQUE HUE</th>
<th>DOMINANT WAVELENGTH</th>
<th>WRATTAN FILTER(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>470 nm</td>
<td>#48</td>
</tr>
<tr>
<td>Green</td>
<td>530 nm</td>
<td>#55 + #64</td>
</tr>
<tr>
<td>Yellow</td>
<td>580 nm</td>
<td>#22 + #57</td>
</tr>
<tr>
<td>Red</td>
<td>650 nm</td>
<td>#92</td>
</tr>
</tbody>
</table>

TABLE #1
Wrattan filter combinations used to present approximations to the psychologically unique hues.

13.
Figure #2
Blue; Wrattan Filter #48

Figure #3
Green; Wrattan Filters #55 & #64
Figure #4
Yellow; Wrattan Filters #22 & #57

Figure #5
Red; Wrattan Filter #92
B. Neutral Density

A constant luminance level was maintained over all test situations by means of appropriate neutral density filtration. Average luminance measurements were made of each color pair at the so-called 'minimum border' condition (see section on minimally distinct border), and these measurements used to make the calculations given in Table #2. Measurements were made with a Spectra Pritchard Photometer.

<table>
<thead>
<tr>
<th>TRANS/REF</th>
<th>( I )</th>
<th>BLUE/YELLOW</th>
<th>ND</th>
<th>EFFECTIVE LUMINANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue/Yellow</td>
<td>.180 fL</td>
<td>1.000</td>
<td>0.0</td>
<td>.180 fL</td>
</tr>
<tr>
<td>Blue/Red</td>
<td>.193 fL</td>
<td>1.072</td>
<td>0.0</td>
<td>.193 fL</td>
</tr>
<tr>
<td>Red/Yellow</td>
<td>.237 fL</td>
<td>1.317</td>
<td>0.1</td>
<td>.188 fL</td>
</tr>
<tr>
<td>Blue/Green</td>
<td>.280 fL</td>
<td>1.556</td>
<td>0.2</td>
<td>.177 fL</td>
</tr>
<tr>
<td>Yellow/Red</td>
<td>.290 fL</td>
<td>1.611</td>
<td>0.2</td>
<td>.183 fL</td>
</tr>
<tr>
<td>Green/Red</td>
<td>.300 fL</td>
<td>1.667</td>
<td>0.2</td>
<td>.189 fL</td>
</tr>
<tr>
<td>Green/Yellow</td>
<td>.323 fL</td>
<td>1.794</td>
<td>0.3</td>
<td>.162 fL</td>
</tr>
<tr>
<td>Red/Green</td>
<td>.417 fL</td>
<td>2.317</td>
<td>0.4</td>
<td>.166 fL</td>
</tr>
<tr>
<td>Yellow/Green</td>
<td>.537 fL</td>
<td>2.983</td>
<td>0.5</td>
<td>.170 fL</td>
</tr>
</tbody>
</table>

**TABLE #2**
Neutral density used to maintain constant over-all luminance for all color combinations.

II-3. Minimally Distinct Border

The criterion of a minimally distinct border between two juxtaposed fields of differing chromaticity was used to equate the luminances of the various color pairs tested. Investigations by Boynton and Kaiser
(1968), Boynton (1973), Myers, Ingling, and Drum (1973), and Guth and Graham (1975) have shown that luminances determined by this method are additive in nature (obeying Abney's Law of Additivty), whereas brightnesses derived from heterochromatic brightness matching are not (additive). It has been suggested that this discrepancy exists because of an inherent difference in the neural processes involved; border detection surmised to be a function solely of the luminance channel in the human visual system, and brightness discrimination depending on both luminance and chromatic channels. Ingling and Drum (1973) have shown that the receptive field organizations of both the chromatic and achromatic neural units are such that a border will be enhanced only if a luminance difference exists. A pure chromatic contrast will not produce enhancement, and the border will appear at a minimum.

A minimally distinct border would be achieved when an equal effect on the luminance channel is produced by both fields being compared. It is therefore conceivable that at the minimum border setting, both fields might not appear equally bright. This has, in fact, been detected; the less saturated of the two fields under test appearing less bright. It has been proposed (Boynton and Kaiser, 1968) that activation of the photoreceptors by appropriate external stimuli activate chromatic and achromatic 'elements' in the visual neural system. Upon activation, these elements are assumed to produce an increment of one unit of brightness and one unit of chromaticness or 'whiteness' (depending on the class of elements involved). Minimally distinct border is thought to occur when the number of

15.
the number of achromatic elements in both fields is equal. Accordingly, a saturated field will appear brighter because of the greater number of chromatic elements activated.

In this study, a bipartite field having precisely juxtaposed borders was used to present randomly chosen color pairs. A first-surface mirror was mounted on a cardboard support in such a way that it occupied one-half of a rectangular field. The remaining half field was cut away, leaving the straight edge of the mirror to serve as a border between the two (see Figures #6a and #6b). When this construction was positioned in the apparatus as shown, two side-by-side regions of differing spectral composition (as determined by the Wrattan filter packs used in window #1 and window #2) were viewed. Adjustment of the relative luminances of both channels was made (by rotation of the polarizing filter near the viewing aperture) until the border appeared minimum. This setting was noted on a degree scale located near the revolving platter. The procedure was repeated (by the author) for all color combinations, the results obtained assumed to be the points of equal luminance for the various color pairs. Repeatability of the author's border discrimination judgement was determined by making average luminance measurements of the bipartite field at each of the minimum border settings on three separate days. A Spectra Pritchard Photometer, equipped with a 2° collection aperture and spectral sensitivity corrected to that of the standard CIE photopic visibility curve, was used to make the readings. Results are given in Table #3.
**Figure #6a**
Bipartite field.

**Figure #6b**
Bipartite field as used in apparatus for determination of minimum border.
<table>
<thead>
<tr>
<th>TRANS/REF</th>
<th>DAY #1</th>
<th>DAY #2</th>
<th>DAY #3</th>
<th>x</th>
<th>s</th>
<th>SETTING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue/Yellow</td>
<td>.17 fl</td>
<td>.16 fl</td>
<td>.21 fl</td>
<td>.180 fl</td>
<td>.026</td>
<td>59°</td>
</tr>
<tr>
<td>Blue/Red</td>
<td>.18</td>
<td>.20</td>
<td>.20</td>
<td>.193</td>
<td>.012</td>
<td>50°</td>
</tr>
<tr>
<td>Red/Yellow</td>
<td>.24</td>
<td>.22</td>
<td>.25</td>
<td>.237</td>
<td>.015</td>
<td>75°</td>
</tr>
<tr>
<td>Blue/Green</td>
<td>.24</td>
<td>.28</td>
<td>.32</td>
<td>.280</td>
<td>.040</td>
<td>40°</td>
</tr>
<tr>
<td>Yellow/Red</td>
<td>.25</td>
<td>.25</td>
<td>.37</td>
<td>.290</td>
<td>.069</td>
<td>70°</td>
</tr>
<tr>
<td>Green/Red</td>
<td>.30</td>
<td>.29</td>
<td>.31</td>
<td>.300</td>
<td>.010</td>
<td>79°</td>
</tr>
<tr>
<td>Green/Yellow</td>
<td>.32</td>
<td>.33</td>
<td>.32</td>
<td>.323</td>
<td>.006</td>
<td>79°</td>
</tr>
<tr>
<td>Red/Green</td>
<td>.38</td>
<td>.45</td>
<td>.42</td>
<td>.417</td>
<td>.035</td>
<td>69°</td>
</tr>
<tr>
<td>Yellow/Green</td>
<td>.54</td>
<td>.52</td>
<td>.55</td>
<td>.537</td>
<td>.015</td>
<td>63°</td>
</tr>
</tbody>
</table>

**TABLE #3**

Determination of average luminance levels for each color combination.

(The author chose to equate the fields rather than allowing individual observers to do so, since it was realized that border minimization must be practiced to be repeatable. To an untrained observer, the fact that minimum border does not necessarily occur when the fields are equally bright might prove confusing. The author's vision was assumed to be representative of 'normal' (no color defects) color vision.)
II-4. RIT Alphanumeric Resolution Test Object

One quadrant of the RIT Alphanumeric Resolution Test Object was photo-etched onto the surface of a Kodak metal-clad (chromium) glass plate (see Figure #7). The target was contact printed such that the alphanumeric characters were etched away and the background remained reflective. The characters (2, 3, 5, 8, E) were randomly composed in groups of three ranging in size from one line per mm for the largest to approximately 18 lines per mm for the smallest. The progressive change (in size) from one line to the next was by the sixth root of two. Table #4 lists the alphanumerics by rows as they appeared in the target, along with corresponding spatial frequencies. Also given are the frequencies encountered by the observer, based on an object distance of 250 mm.

Figure #7
RIT Alphanumeric Resolution Test Object.
Not to scale.

18.
### TABLE #4

<table>
<thead>
<tr>
<th>LINE</th>
<th>ALPHANUMERIC CHARACTERS</th>
<th>TARGET (lines/mm)</th>
<th>OBSERVER (cycles/degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>E 2 E</td>
<td>1.000</td>
<td>4.3630</td>
</tr>
<tr>
<td>1</td>
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<td>5.4975</td>
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<td>10.9949</td>
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<tr>
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<td>E 5 2</td>
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<td>17.4534</td>
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<td>4.4898</td>
<td>19.5908</td>
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<td>5 3 2</td>
<td>5.0397</td>
<td>21.9899</td>
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<tr>
<td>15</td>
<td>2 5 3</td>
<td>5.6569</td>
<td>24.6828</td>
</tr>
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<td>E 8 2</td>
<td>6.3496</td>
<td>27.7055</td>
</tr>
<tr>
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<td>8 E 5</td>
<td>7.1272</td>
<td>31.0984</td>
</tr>
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<td>E 3 8</td>
<td>8.000</td>
<td>34.9068</td>
</tr>
<tr>
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<td>2 3 5</td>
<td>8.9797</td>
<td>39.1815</td>
</tr>
<tr>
<td>20</td>
<td>8 E 5</td>
<td>10.0794</td>
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<td>11.3137</td>
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<td>55.4111</td>
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<td>14.2544</td>
<td>62.1968</td>
</tr>
<tr>
<td>24</td>
<td>3 5 E</td>
<td>16.000</td>
<td>69.8136</td>
</tr>
<tr>
<td>25</td>
<td>3 2 E</td>
<td>17.9594</td>
<td>78.3631</td>
</tr>
</tbody>
</table>

Alphanumeric test target character order. Corresponding spatial frequencies on target and at observer's eye (based on 250mm object distance) also given.

### II-5. Procedure

Each observer in this study was determined to have normal color vision in a preliminary test designed to screen for color defects using HCC Pseudoisochromatic...
Plates. The plates contained simple geometric shapes of various hue and saturation combinations superimposed over a random neutral (grey) dot pattern. The observer viewed each of five plates and traced the shapes seen with a soft brush. A person with normal color vision should be able to see and trace all the presented geometric shapes.

The alphanumerics to be presented and the format of the target were carefully reviewed with the observer prior to testing. The observer was instructed that only the characters 2, 3, 5, 8, E would be allowed as valid responses, and he was told that he would be required to alternate the order in which each row of three alphanumerics was read. (It was explained that prior to each color combination presented, the experimenter would choose the reading order by saying out loud: "3 - 2 - 1", "1 - 3 - 2", "1 - 2 - 3", etc., and each row would then be read in that order. The left-most character in each row was said to occupy position #1, the middle character position #2, and the character on the right position #3.) It was further explained that the observer was to read each row in succession until he could no longer recognize the alphanumerics. Also pointed out was the physical break in the target between the 6th and 7th rows.

The observer was dark adapted for a period of 20 min. prior to experimentation. Studies by Hecht, Haig, and Chase (1937) and Rushton and Henry (1968) have shown that pigment regeneration in fully bleached cones is 95% complete after a 10 minute dark adaptation period.
A longer time was chosen for this study as an added precaution.

At the commencement of actual experimentation, the observer was seated before the apparatus and instructed to place his chin on the chin-rest provided. He was told to use only one eye for the entire experiment, the choice of which being left to the individual. If the observer normally wore corrective lenses, he was told to view the target both with and without them and decide which afforded clearer vision. (Several near-sighted persons found their glasses to be a hindrance when viewing the target. Presumably, this can be attributed to the short viewing distance of 250mm used.)

The observer was shown (in random order) each of the nine color combinations listed in Table #5, and his response to each was recorded by the experimenter. Data collection sheets were prepared for this purpose. In addition, each observer was required to view and respond to the target presented in a high-contrast, achromatic (black and white, positive) mode.

<table>
<thead>
<tr>
<th>TARGET/BACKGROUND</th>
<th>POLAROID SETTING</th>
<th>NEUTRAL DENSITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue/Red</td>
<td>50°</td>
<td>0.0</td>
</tr>
<tr>
<td>Blue/Yellow</td>
<td>59°</td>
<td>0.0</td>
</tr>
<tr>
<td>Red/Yellow</td>
<td>75°</td>
<td>0.1</td>
</tr>
<tr>
<td>Green/Red</td>
<td>79°</td>
<td>0.2</td>
</tr>
<tr>
<td>Yellow/Red</td>
<td>70°</td>
<td>0.2</td>
</tr>
<tr>
<td>Blue/Green</td>
<td>40°</td>
<td>0.2</td>
</tr>
<tr>
<td>Green/Yellow</td>
<td>79°</td>
<td>0.3</td>
</tr>
<tr>
<td>Red/Green</td>
<td>69°</td>
<td>0.4</td>
</tr>
<tr>
<td>Yellow/Green</td>
<td>63°</td>
<td>0.5</td>
</tr>
</tbody>
</table>

TABLE #5
Color combinations presented.
III. RESULTS AND DISCUSSION

III-1. Recognition Threshold

Determination of observer recognition threshold values was achieved by a method similar to that employed by Bobb (1975) in his investigation of identification thresholds. In the present study, recognition threshold was defined as the spatial frequency corresponding to the first row of the first pair of consecutive target rows in which two or more alphanumeric recognition errors occurred. The choice of this criterion was somewhat arbitrary, since Bobb showed that aside from a constant lateral shift along the spatial frequency axis (of a spatial frequency versus contrast sensitivity graph), the method of threshold determination chosen was inconsequential. Thresholds were obtained for each observer at each color combination, the results being reported in cycles per degree.

III-2. Analysis of Variance

An analysis of variance was performed on the recognition threshold data in an effort to determine factor significance. Three factors were tested (color pairs, character reading order, observer group (see next section)), and the results are given in Table #6. With an alpha-risk of 0.01, it was determined that 'color pairs', 'observer group', and the interaction between the two were all significant. 'Character reading order', on the other hand, was found to be not significant, thereby indicating that the author's decision to vary
the order in which each observer read the alphanumerical characters had no adverse effects on the results.

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>SS</th>
<th>DF</th>
<th>MS</th>
<th>F-RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>133.6954</td>
<td>8</td>
<td>16.7119</td>
<td>8.9193</td>
</tr>
<tr>
<td>B</td>
<td>4.6326</td>
<td>5</td>
<td>0.9265</td>
<td>0.4945</td>
</tr>
<tr>
<td>C</td>
<td>113.8686</td>
<td>1</td>
<td>113.8686</td>
<td>60.7730</td>
</tr>
<tr>
<td>AB</td>
<td>136.0331</td>
<td>40</td>
<td>3.4008</td>
<td>1.8150</td>
</tr>
<tr>
<td>BC</td>
<td>8.2822</td>
<td>5</td>
<td>1.6564</td>
<td>0.8840</td>
</tr>
<tr>
<td>AC</td>
<td>58.0521</td>
<td>8</td>
<td>7.2565</td>
<td>3.8729</td>
</tr>
<tr>
<td>error</td>
<td>74.9468</td>
<td>40</td>
<td>1.8737</td>
<td></td>
</tr>
</tbody>
</table>

A - color pairs  
B - character reading order  
C - observer group

Table #6  
Analysis of variance. Color pairs, observer group, and the interaction between the two are significant with an alpha-risk of 0.01.

III-3. Bimodality of Observer Response

While 'color pairs' and 'character reading order' are straightforward in interpretation, the factor labeled 'observer group' warrants further explanation at this time. During the initial data collection phase of this investigation, it was noticed by the author that the observers' responses to the red target on green background seemed to be bimodally distributed (see Figure #8). Based on the consideration that bimodality of observer color vision differences had been reported
by several previous authors (Judd, 1949; Talbot, 1952; Rubin, 1961; Richards, 1967), it was decided to separate the observers in this study into two groups. Those with red/green responses distributed about the lower of the two means were said to comprise the 'low-response group', and those with responses distributed about the other (higher) mean were said to comprise the 'high-response group'. These groupings were maintained for all color pair combinations.

III-4. Tested Color Pairs

Nine color pair sets, consisting of combinations of four different target colors (red, yellow, green, blue) and three background colors (red, yellow, green), were studied. (Blue was not used as a background color because of low luminance levels in the background beam of the apparatus.) Table #7 lists the averages and standard deviations of threshold responses for the low-response group, the high-response group, and the two groups combined for each of the nine color pairs. (The two response groups were approximately equal in size, the low-response group having 13 members and the high-response group, 16.) A series of t-statistics were computed to determine significant differences in mean threshold response values between the low- and high-response groups. Assuming an alpha-risk of 0.01, it was found that the two groups are in fact different for five of the nine combinations presented (green target/red background, red target/green background, blue target/yellow background, yellow target/red background, and yellow target/green background). Low- and high-response
group means for the achromatic target configuration were determined to be not significantly different, thereby indicating that every observer's acuity in a black and white (non-chromatic) situation (at a viewing distance of 250mm with an RIT Alphanumeric Resolution Test Object) could be assumed to be statistically alike. Hence, response group differences cannot be attributed to differences in (luminance channel) acuity.

<table>
<thead>
<tr>
<th></th>
<th>G/R</th>
<th>R/G</th>
<th>B/R</th>
<th>B/Y</th>
<th>Y/R</th>
<th>Y/G</th>
<th>B/G</th>
<th>R/Y</th>
<th>G/Y</th>
<th>ACHRO</th>
</tr>
</thead>
<tbody>
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<td>H</td>
<td>10.03</td>
<td>10.94</td>
<td>9.68</td>
<td>10.30</td>
<td>9.06</td>
<td>8.81</td>
<td>7.31</td>
<td>7.84</td>
<td>7.07</td>
<td>28.53</td>
</tr>
<tr>
<td></td>
<td>1.97</td>
<td>2.00</td>
<td>2.13</td>
<td>2.66</td>
<td>2.05</td>
<td>1.78</td>
<td>1.59</td>
<td>2.12</td>
<td>1.98</td>
<td>5.79</td>
</tr>
<tr>
<td>L</td>
<td>8.55</td>
<td>7.20</td>
<td>8.33</td>
<td>7.65</td>
<td>7.10</td>
<td>6.80</td>
<td>6.79</td>
<td>6.35</td>
<td>6.62</td>
<td>24.07</td>
</tr>
<tr>
<td></td>
<td>0.80</td>
<td>1.10</td>
<td>1.48</td>
<td>1.65</td>
<td>1.27</td>
<td>1.37</td>
<td>1.39</td>
<td>2.21</td>
<td>1.27</td>
<td>4.59</td>
</tr>
<tr>
<td>C</td>
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<td>9.51</td>
<td>9.21</td>
<td>8.95</td>
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<td>2.43</td>
<td>1.98</td>
<td>1.82</td>
<td>1.50</td>
<td>2.10</td>
<td>1.76</td>
<td></td>
</tr>
</tbody>
</table>

* * NS * * * NS NS NS NS

\textit{t-test on means; alpha = 0.01}

H = High Response Group
L = Low Response Group
C = Combined Data

\textbf{Table #7}

Threshold response values for the nine presented color pairs.
Data in cycles per degree.
Figure #9 statistically ranks the data for each observer group by placing confidence intervals about the means. This graphical representation shows the same general trend for both the high- and low-response groups; maximum threshold response values being reported for the green/red, red/green combinations, and minimum values for the red/yellow, green/yellow combinations. Thresholds for the low-response group tend to be less than those for the high-response group at each presented color combination, although at only five of the color pairs are the two groups statistically different, as stated previously.

Talbot (1952), Rubin (1961), and Richards (1967) have reported dichotomous differences among color normals with respect to (1) binocular synthesis of yellow, and (2) spectral location of unique green, and have found that an individual's response to one may be used to predict his response to the other. The data here presented is in apparent agreement with these findings; the five statistically different color pairs contain either yellow or green or both. The remaining color combinations containing yellow and/or green proved not significantly different, but it must be pointed out that the RIT target, in conjunction with the apparatus used in this study, was capable of measuring spatial frequencies no less than 4.36 cycles per degree. As is evident from Figure #9, the blue/green, red/yellow, and green/yellow combinations lie very close to this cut-off frequency; both high- and low-response groups have reached (or nearly so) their asymptotic limiting values.
Figure #9
Confidence intervals placed on means of high- and low- observer response groups.
The over-all trend shown by both response groups is more clearly displayed in the graph of combined data (Figure #10). Because of their relative closeness to the cut-off frequency, the individual response groups exhibit a liberal noise level which is lessened considerably in combination (due to larger sample sizes). A maximum average threshold value of 9.5 cpd is shown for the green/red, red/green combinations and a minimum value of 6.9 cpd for the red/yellow, green/yellow combinations. The achromatic threshold for both groups combined was 26.3 cpd, considerably higher than the chromatic thresholds. This result is consistent with the color vision theory presented earlier, chromatic acuity proving lower than achromatic because of the response field organizations involved at the lateral geniculate nucleus.

Note: (The author feels justified in combining the two response groups since they both exhibit the same over-all ranking trend, and because the confidence intervals for both groups can be seen to overlap for all but one of the presented color pairs. The unusually large separation of the groups at the red/green combination is most likely artificial; the two groups were originally determined by the bimodal red/green distribution.)

III-5. Color-Pair Visibility Groups

Figure #11 presents the data for both observer response groups and the combined data as analyzed by
Figure #10
Confidence intervals placed on means of combined data.
Low-Response Group

Increasing Visibility

High-Response Group

Increasing Visibility

Combined Data

Increasing Visibility

Figure #11
Duncan's Multiple Range Test.
0.05 Significance Level.
Duncan's Multiple Range Test. As expected, the inherent noise of the response groups alone, especially that of the low-response group, confounds the results of the test, making a separation of statistically alike color pairs very difficult. (The fact that the low-response group lies closer to the cut-off frequency than does the high-response group is the probable reason for the higher noise level.)

The combined data, on the other hand, shows clearly three 'visibility' groups based on the threshold response values of the presented color pairs. With a confidence of 95%, green/red, red/green, blue/red, and blue/yellow have been shown to be statistically alike, as have green/yellow, red/yellow, and blue/green. The first group will hereafter be referred to as the 'high-visibility' group, and the second, the 'low-visibility' group. The yellow/green and yellow/red combinations appear to serve as transition pairs between these two groups.

It is interesting to note that three of the four color pairs comprising the high-visibility group are those corresponding to the red-green and blue-yellow opponent neural systems. This would be expected from the evidence presented by Daw (1968), Hubel and Wiesel (1968), and Michael (1973) on the existence of double opponent-color cells in the visual cortex. These cells are optimally responsive to red on green, green on red, blue on yellow, and yellow on blue, and therefore account for the higher visibility of these corresponding color pairs.
The fourth color combination included in the high-visibility group (blue/red) is presumably here because of the large spectral separation of blue and red, thereby creating a high 'color contrast'. Boynton and Greenspon (1972) and Ingling and Drum (1973) have shown that uncontrolled eye movements cause successive chromatic contrast of an edge separating two hues which lie on opposite sides of one of the neutral points of either the red-green or blue-yellow chromatic channels. Because the observers in this investigation were allowed to scan the target at will, successive chromatic contrast is the probable cause of the high visibility of the blue/red combination.

Two color pairs (green/yellow, red/yellow) proved statistically different (in terms of visibility) from their respective opposites (yellow/green, yellow/red), a result which is not fully understood at the present time. The color-vision theory presented thus far does not seem to predict this outcome; opposites should be equally visible.

Several factors inherent to the experimental procedure used in the present study could have contributed to this somewhat confusing result. The overall luminance level (approx. 0.2 fL) of the presented color pairs was in the low photopic range, and it is conceivable that participation of rhodopsin in the photoreceptors at this level had a confounding effect (Richards, 1964).

Another factor possibly influencing this result was the manner in which the color pairs were balanced for luminance. The author's vision was assumed 'normal'
and was used to equate luminance levels of the color combinations presented by taking advantage of the minimum border technique. Bimodality of observer responses to unique green and binocular synthesis of yellow as reported by Richards (1967) could cause certain color pairs to be 'unbalanced' (not equally luminous) for some observers in this study.

Experimental procedure can only partially explain the statistically different visibilities found for the green/yellow – yellow/green and red/yellow – yellow/red color pairs, however. As is evident from the graph of combined data, higher visibility is reported for the yellow target/green background and yellow target/red background than for their respective counterparts. In both cases, greater visibility occurred when yellow was employed as the target color. Perhaps the unequal distribution of target to background area (approx. 40% alphanumerics and 60% background) has some (undetermined) effect.

III-6. Chromatic Contrast

Figures #12 through #15 are graphical representations of 'chromatic contrast' versus target visibility for the nine color pairs. (Chromatic contrast, in this context, is taken to mean spectral separation of the alphanumerical and background colors.) The data is grouped both by background color and target (alphanumerical) color, and two representations of each (spectral location and spectral separation) are given. The results show that as the spectral separation between alphanumerical color and background color increases, target visibility
Figure #12
Alphanumeric color versus target visibility (spatial frequency at threshold). Data grouped in terms of background color.
Figure #13

Background color versus target visibility (spatial frequency at threshold). Data grouped in terms of alphanumerical color.
Figure #14
Spectral separation of alphanumeric and background colors versus target visibility (spatial frequency at threshold). Data grouped in terms of background color.
Figure #15
Spectral separation of alphanumeric and background colors versus target visibility (spatial frequency at threshold). Data grouped in terms of alphanumeric color.
increases. This is consistent with the findings of Boynton and Greenspon (1972) and Ingling and Drum (1973) concerning successive chromatic contrast discussed earlier. The data also seems to indicate that once spectral separation between colors is sufficient to insure the inclusion of a chromatic neutral point, target visibility levels off to an asymptotic value. (The neutral point for the blue-yellow system lies very close to green (520 nm) and the neutral point for the red-green system lies to the short wavelength side of yellow (570 nm) (Ingling, Scheibner, and Boynton, 1970).)

III-7. Equivalent Achromatic Contrast

An equivalent achromatic contrast for each of the presented color pairs in this study was determined using a method developed by Boynton (1973). In his investigation, Boynton evaluated several borders formed by various color pairs (at the minimum border condition) in terms of the achromatic contrast necessary to produce a border of equal distinctness. He also asked his observers to subjectively rate the borders on a scale of zero (no border) to seven (very distinct border). From this, the relationship shown in Figure #16 was found.

Tansley and Boynton (1976) determined a multidimensional scaling in Euclidean space of subjectively judged differences (border distinctness) among all possible pairs of 36 non-spectral colors (Figure #17). Straight line distances between points was found to be highly correlated with border distinctness. The 36 colors used were specified in terms of their CIE chromaticity coordinates and are
Figure #16

Subjective border distinctness versus equivalent achromatic contrast. (Boynton, 1973)

Figure #17

Multidimensional scaling in Euclidean space of subjective border distinctness for all possible combinations of 36 non-spectral colors. (Tansley and Boynton, 1976)
given in Table #8. (Also given, in the bottom section of the table, are the coordinates of the four psychologically unique hues presented in this study. A 3200°K Tungsten source was assumed for the calculations.)

Using the information given, the location of the unique hues on the Euclidean scaling of Tansley and Boynton was determined, and from the straight line distances separating them, subjective border distinctness derived. This in turn was applied to the relationship shown in Figure #16, and an equivalent achromatic contrast for each color pair obtained. Figure #18 presents this data in the form of spatial frequency (cpd) versus log(1/contrast). Results of Bobb (1975) and Campbell and Green (1965) have also been included for comparison. As is readily evident, all data sets fall on straight lines of approximately equal slope, displaced laterally along the spatial frequency axis. The spatial frequency range of the color data is much smaller than that of the achromatic data of Bobb and Boynton and Green, but the change of spatial frequency with contrast can be seen to be equivalent. This suggests that the method of equivalent achromatic contrast for evaluating pure chromatic borders is a valid one.

III-8. RIT Alphanumeric Resolution Test Object

Table #9 lists the frequency of presentation of each character in the RIT Alphanumeric Resolution Test Object, along with the frequency of correct versus incorrect observer responses for each. A total of 5600 characters was presented during the course of this study, and as is evident from the table, all
Table #8

C.I.E. chromaticity coordinates for the 36 non-spectral colors presented in Figure #17. (Tansley and Boynton, 1976) Psychologically unique hues used in this study listed at the bottom of the table.

<table>
<thead>
<tr>
<th>Stimulus</th>
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<th>y</th>
<th>λ(nm)</th>
</tr>
</thead>
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<tr>
<td>2</td>
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<td>.18</td>
<td>532</td>
</tr>
<tr>
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<td>.17</td>
<td>.03</td>
<td>533</td>
</tr>
<tr>
<td>5</td>
<td>.23</td>
<td>.74</td>
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Blue  .13  .06  470
Green .14  .71  530
Yellow .49  .50  580
Red   .72  .28  650
Equivalent achromatic contrast derived for color data plotted versus spatial frequency. Achromatic contrast data of Bobb (1975) and Campbell and Green (1965) included for
### Presented Alphanumerics

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**Table #9**

Frequency of presentation of RIT Alphanumerics versus observer response. Top figure represents total number of responses, bottom figure, the respective fraction of column.
characters were not presented an equal number of times. The figure '3' represented 24% of the 5600 characters whereas '8' represented only 16%. This is in agreement with the findings of Bobb (1975), who found a presentation frequency of 23% for '3' and 15% for '8'. The remaining characters fall between these two extremes.

The recognizability of each alphanumeric character was also investigated, and it was found that contrary to the assertion of Donaldson and Gough (1968), the characters were not equally recognizable. '2' received the greatest number of correct observer responses (correctly recognized 90% of the time) while '8' received the least (correctly recognized 74% of the time). Bobb's data exhibited the same trend, although his percentages of correct responses were somewhat lower than those given here (85.6% for '2' and 67.6% for '8'). This can be accounted for by the additional observer response category allowed by Bobb; he permitted observers' responses to contain alphanumerics other than those presented.

A tabulation of the average information transferred by each target character is given in Table #10. This data is good only for the system as a whole (the experimental apparatus used in the study in conjunction with the human visual system) and efforts to separate the two would prove most difficult. Therefore, the average information transfer of 1.26 bits per target character calculated is applicable to this system only, and the RIT target used with another set-up could very easily produce different information transmission calculations.
<table>
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<th>INFORMATION</th>
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<tbody>
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<td>ALPHANUMERIC</td>
<td>TRANSFER (BITS)</td>
</tr>
<tr>
<td>E</td>
<td>1.18</td>
</tr>
<tr>
<td>2</td>
<td>1.31</td>
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<tr>
<td>3</td>
<td>1.09</td>
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<td>5</td>
<td>1.45</td>
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<tr>
<td>8</td>
<td>1.34</td>
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</table>

average information transfer = 1.26 bits

Table #10
Information transfer for each RIT alphanumeric.

IV. CONCLUSIONS

IV-1. Bimodality of Observer Response

Bimodality of observer response to color combinations containing green and/or yellow was found to be a significant factor in this study. Two observer response groups were determined on the basis of threshold response data (bimodal distribution) obtained for the red target/green background, and were found to be statistically different from one another for five of the nine color-pair combinations tested. The two groups proved to be
not significantly different for the blue/green, red/yellow, and green/yellow combinations, presumably because of their close proximity to the target-apparatus cut-off frequency. The fourth color combination at which the two response groups were found to be not significantly different was the blue target on red background, a result that tends to support the findings of Talbot (1952), Rubin (1961), and Richards (1967). In separate studies, they reported dichotomous differences among observers for the spectral location of unique green and binocular synthesis of yellow, but found no such differences among observers for blue or red.

IV-2. Color-Pair Visibility Groups

Color-pairs corresponding to the red-green and blue-yellow opponent neural systems (ie. red/green, green/red, blue/yellow) exhibited response thresholds higher than those of the remaining color combinations. This is consistent with color-vision theory, which predicts optimum response for red on green, green on red, blue on yellow, and yellow on blue, due to the operation of double-opponent, color-specific neural cells in the visual cortex (Daw, 1968; Hubel and Wiesel, 1968; Michael, 1973). Thresholds for the red target/green background, green target/red background, and blue target/yellow background were found to be statistically alike, with an average value of 9.30 cpd. The blue target/red background was also included in this high-visibility group; the spectral separation of red and blue being great enough to encourage successive chromatic contrast.
Boynton and Greenspon (1972) and Ingling and Drum (1973) found successive chromatic contrast between colors of sufficient spectral separation to insure the inclusion of a neutral point of either the red-green or blue-yellow opponent chromatic systems.

Response values for the green/yellow, red/yellow, and blue/green combinations were also found to be statistically alike, with an average value of 6.95 cpd. These three color pairs were said to comprise the low-visibility group. A difference of only 2.35 cpd was found to separate the high- and low-visibility groups, indicating that the chromatic visual system operates over a very limited range of spatial frequencies. As expected from theory, the chromatic system is not an efficient carrier of spatial information.

IV-3. Observer Accomodation

Several observers noted that the presented alphaneumerics seemed to 'drift' in and out of focus, thereby increasing the difficulty of the recognition task. This phenomenon is not completely understood at the present time, although there is reason to believe that it might be caused by the lack of luminance information in the target. Researchers have shown the importance of the stimulus contour as an information carrier (Fox, 1957; Perrin, 1960; Yonemura, 1974). If the assumption is made that the contour conveys spatial information in terms of luminance gradients (as might be expected, due to the existance of contrast-enhancing Mach bands), one can appreciate the observer's dilemma in this study.
Because of the equi-luminous target and background, luminance gradients did not exist. If it is again assumed that the eye's accommodation is somehow controlled by the information-carrying luminance gradients of the stimulus, the eye's wandering focus in this investigation can be understood.

IV-4. Equivalent Achromatic Contrast

Boynton's method of determination of equivalent achromatic contrast for chromatic stimuli (Boynton, 1973; Tansley and Boynton, 1976) has been shown to yield meaningful results. A graphical representation of spatial frequency versus log (1/contrast) for the chromatic data of this study showed a linear relationship closely resembling that exhibited by the achromatic data of Campbell and Green (1965) and Bobb (1975). The chromatic data was seen to lie on the low frequency side of the achromatic data, indicating that at any contrast level, the chromatic neural system is a much less efficient carrier of spatial frequency information than is the achromatic system.

IV-5. Recommendations for Future Study

It is felt by this author that further investigations of the human 'color' channel at higher luminance levels would yield meaningful results. Also, a scheme for directly comparing achromatic and chromatic contrasts at different over-all luminance levels should be looked into. A revised apparatus, possibly containing two light sources, would have to be developed for this.
V. ACKNOWLEDGEMENTS

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