

An Investigation of Color Memory as a Function of Hue, Saturation, Lightness and  
Observer Imagery Vividness for Blue, Green and Orange Test Hues

By

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(Abstract)

Fifty-two college-aged observers participated in an experiment assessing color memory via a PowerPoint '97 computer display program which varied one of the three dimensions of hue, saturation and lightness at a time. Consistent with previous research, errors were greater for the lightness conditions followed by saturation, and least for hue conditions. Additionally, a signal detection analysis indicated that  $d'$  was greatest for the hue conditions, less for saturation and lowest for lightness conditions. There were also significant but unpredicted differences in response criterion which may reflect task difficulty. Scores on the Vividness of Visual Imagery Questionnaire (Marks, 1973) were, in general, not correlated with performance on these color memory tasks, inconsistent with previous research. The role of complexity of neuronal circuitry, the significance for opponent-process, trichromatic and retinex color vision theories and the relationship to Sokolov's model of color memory were discussed. Also, it was concluded that investigators of color memory using a computer display are well-advised to calibrate the monitor with a colorimeter because the internal computer units may be unreliable indexes of changes in hue, saturation and lightness.

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An Investigation of Color Memory  
as a Function of Hue, Saturation, Lightness  
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There has been little research which investigated memory for color and its subjective, perceptual dimensions; namely, hue, saturation and lightness. Hue varies with the actual physical wavelength of light reflected, saturation refers to the physical purity of the waveform (the purer, the more perceptually saturated), and lightness (also inaccurately referred to as brightness and/or whiteness) refers to the physical intensity of the waveform (Hurvich, 1981; Schiffman, 1996; Wasserman, 1978). In the present study, memory for hue, saturation and lightness across various test hues for both high and low imagers (there are some data which indicate a difference between these on color memory tasks - discussed below) was investigated. Also, an analysis of two research methodologies for the study of color memory was included. What follows is a discussion of the anatomy and physiology of color vision, theories of color vision, color memory and the differentiation of color memory from memory color, a description of signal detection theory and a description of a pilot study performed by the present investigator.

Brief Survey of the Anatomy and Physiology of Color Vision

The anatomy and physiology of color vision is essential to the understanding of memory for color as memory must involve activation of neural circuits. The first stage of

color processing in the visual system is undoubtedly at the level of the retina and receptors. It has long been understood that there are at least three types of pigments in the cones of the retina, each differentially most sensitive to certain wavelengths of light. The L-cone pigment is maximally sensitive to longer wavelengths (around 560 - 570 nm), while the M-cones and S-cones are maximally sensitive to medium wavelengths ( 535 nm) and shorter wavelengths ( 445 nm), respectively (Abramov & Gordon, 1994; Merbs & Nathan, 1992; Mollon, 1982; Neitz, Neitz & Jacobs, 1991; Schnapf, Kraft & Baylor, 1987). Also at the level of the retina are the X ganglion cells (also called P ganglion cells). These cells convey color information (as well as perform some color processing including red-green, yellow-blue and black-white opponency) to the parvocellular division of the lateral geniculate nucleus (LGN) of the thalamus (Abramov & Gordon, 1994; DeValois & DeValois, 1993; DeValois & Jacobs, 1984; Mollon, 1982).

It is in the LGN, where one finds a preponderance of color opponent cells which are red-green, blue-yellow, or black-white. From the LGN the tracts make their way via the optic radiations to the occipital lobe of the brain where further color processing takes place. Investigators performing studies with primates found that the visual areas (V1 - V4) are responsible for the processing of color information (Livingstone & Hubel, 1984). These areas contain the color-processing blob cells which have various forms of receptive fields and opposing antagonisms. Also, it has been found that these areas are reciprocally connected to one another (Livingstone & Hubel, 1984).

By far, most color processing occurs in an area called V4. While most of the

anatomical work on the structure of the visual cortex has been accomplished with monkeys, there have been some recent fMRI studies assessing the nature of the human visual centers, as well. In humans, fMRI studies have indicated that this area lies on the lateral aspect of the fusiform gyrus. Additionally, it appears that there may be a retinotopic organization to the human V4, at least for representation of superior and inferior visual fields (McKeefry & Zeki, 1997). Further studies using human fMRI have indicated possibly three stages of cortical processing in the visual areas of the brain for color (Zeki & Marini, 1998). The first stage is thought to be accomplished exclusively in V1 and V2 and concerns itself with registering the presence, intensity, and differences among wavelengths of light. Secondly, V4 carries out processing which may regulate color constancy apart from memory and learning (Land s [1964] retinex algorithms - see below). Finally, beyond V4, the inferior temporal and inferior frontal lobe may be processing information about object colors (associating colors with specific objects making use of learning and memory). The parietal lobe processes information about movement of objects and is not relevant to a discussion of the processing of color. It is interesting to note that the hippocampus was activated when observers viewed normally-colored objects (Zeki & Marini, 1998) as well as V4, suggesting a memory component. There is also some evidence that lightness (and maybe both saturation and lightness) are subserved by two different processing mechanism by the visual centers of the brain, although those mechanisms have not been specified (Burns & Shepp, 1988; Mullen & Losada, 1994).

## Theories of Color Vision

Two widely accepted theories of color vision include the trichromatic theory and the opponent process theory. The trichromatic theory was developed by Young and Helmholtz (Young preceding Helmholtz) and, as the name implies, suggested that all color appearance is the result of relative levels of activity in three broadly sensitive processes which overlap in their sensitivity (Helmholtz, 1961; Young, 1961). The trichromatic theory has received much support from physiological evidence (at least at the retinal level) and psychophysical studies of color matching. The theory stated that the experience of any color is the result of the differential pattern of activation in the three cone systems. Subsequently, the existence of three specific cone pigments roughly equivalent to the red (approximately 570 nanometers [nm] ), green (approximately 535 nm), and blue (approximately 445 nm) hues have been identified, lending credence to the trichromatic theory (Abramov & Gordon, 1994; Merbs & Nathan, 1992; Mollon, 1982; Neitz, et al., 1991; Schnapf, et al., 1987).

Another widely accepted theory of color vision is the opponent-process theory of Hering (1961). Hering envisioned not a trichromatic, but a tetrachromatic theory of color vision which included four primary colors arranged in opposing pairs (red-green and yellow-blue plus black-white or lightness). This theory was based upon the observations of red-green color weak individuals who could still perceive yellow leading to the inclusion of yellow as a primary, rather than a red-green mixture (Hering, 1961; Hilgard, 1987). Hering also noticed the color zones of the retina wherein the retina is most

sensitive to reds and greens at and around the fovea, sensitive to blues and yellows as it moves into the periphery, and sensitive only to black and white (achromatic) in the extreme periphery of the retina. This, along with the observation that individuals never report a reddish-green or bluish-yellow (and vice versa) color, led Hering to the conclusion of opposing pairs of color sensitive cells as important to the perception of color (Hering, 1961; Hilgard, 1987). Also, the successive and simultaneous color contrast demonstrations provided more evidence for a red-green and yellow-blue opponency (e.g., fixating on a homogeneous red stimulus for a fixed duration, then looking away to experience a green after image).

There is ample physiological evidence to support the opponent process theory. Cells have been found in the lateral geniculate nucleus of the thalamus and in the cortex which respond in an opposing manner for red-green, yellow-blue and white-black (DeValois & DeValois, 1993; DeValois & Jacobs, 1984; Livingstone & Hubel, 1984). These cells have receptive fields which may operate on a center-surround antagonistic basis wherein the center of the receptive field may be excited by one of the pair of opposing colors (e.g., red, yellow or white) while the area surrounding the center is inhibited by its opposite (e.g., green, blue or black). Some opponent cells do not display the exact center-surround arrangement but are antagonistic nonetheless. It appears, then, that opponent process theory has much physiological support at the level of the cortex.

A color phenomenon which opponent process theory has difficulty with is color constancy (as did trichromatic theory). Whereas Helmholtz used the concept of

unconscious inference to explain color constancy, Hering developed the idea of memory color. The concept of memory color suggests that individuals have a mental representation of the colors of objects (e.g., apple is red, orange is orange, banana is yellow) and these representations provide the basis for color constancy (color remains the same despite illumination differences [in bright versus dim light]).

Although the trichromatic and opponent process theories of color vision are the most widely accepted, there are others, two of which are the Ladd-Franklin evolutionary theory and Land's retinex theory. Ladd-Franklin's (1973) evolution-based theory considered the phylogenetic development of the color visual system. According to Ladd-Franklin, any theory of color vision must meet the minimum requirements of: 1) acceptance of three primaries (red, green and blue) which can be combined to start the retinal process (her theory was at the retinal level), 2) that yellow and white are of utmost importance as they can be monochromatic as well as due to mixing of other colors, 3) the order of development of the color vision sense must be incorporated and 4) the non-occurrence of reddish-green and bluish-yellows must be accounted for. In the Ladd-Franklin theory it is accepted that the three primaries of red, blue and green exist; however, she also placed yellow and white in a special class. This is because the mixing of red and green does not result in a reddish-green color, but a yellow color and white can be produced through mixing red, green and blue or by mixing yellow and blue.

In order to explain these findings, Ladd-Franklin (1973) created an evolutionary developmental theory of color vision. Her theory considered the first stage of the

development of color vision to be achromatic. This system only perceives white (lightness). At a later stage in evolutionary development, the white system was split into a blue and a yellow system, which when combined form white. Even later in evolutionary development (stage III) the yellow system split into a red system and a green system, along with the leftover blue system. When the red system and green system combine, they revert back to yellow. This theory is also supported by the color zones of the retina and conditions of color weakness. The fovea was probably the last stage of evolutionary development and is sensitive to red and green. Further out in the periphery of the retina, there is sensitivity to blues and yellows, and in the outermost parts of the retina sensitivity is to white only. The perception of black, according to Ladd-Franklin results from a zero sensation state equivalent to silence in hearing. Thus, Ladd-Franklin's theory appears to receive support from the known color zones of the retina. Additional support comes from the observation that certain primitive primates and other more primitive mammals tend to display a type of dichromatism (although the exact colors of the dichromacy may be different) that is consistent with an earlier stage of evolutionary development proposed by Ladd-Franklin (Thompson, 1995).

In the late 1950s, Land carried out a series of experiments whose results were quite puzzling given the theories of color vision discussed so far. Land (1959a, 1959b) demonstrated that the full array of colors could be achieved through the mixture of only a long wave source and a short wave source. His experiments consisted of presenting a black and white photograph which was simultaneously taken through a long wavelength

filter and short wavelength filter. Then the photographs were presented together with a long wave filter over the long wave photograph and a short wave filter over the short wave photograph. The resulting picture was a color photograph showing all colors in the visual spectrum. Obviously, this posed problems for the theories discussed thus far as they required the mixing of at least three primaries.

Given these results, Land formed the retinex theory of color vision which essentially states that color is derived from a computational comparison of lightness of stimuli and their surrounding areas by three retinal-cortex (hence the term retinex) units which roughly correspond to long-, medium- and short-wave lengths (Land, 1964, 1986; Land & McCann, 1971; Thompson, 1995; Zeki, 1993). First, each retinex unit determines a lightness scale through computational comparisons within its waveband (long, medium or short). Then these three lightness scales are compared (again through a computational analysis) to result in a color perception. Most intriguing is that this occurs regardless of the illumination of the stimuli, hence explaining color constancy. Succinctly, color is the result of a comparison of comparisons. It results from the final computational comparison of the lightness scales for each retinex unit which have been constructed from computational comparisons of lightness from stimuli within that retinex unit (Zeki, 1993).

Many of Land's experiments incorporated a stimulus design known as a Mondrian, which consists entirely of different colored patches of uniform reflectance, separated by distinct edges (Blake, 1985). Land believed that this stimulus situation

depicts greater ecological validity since individuals rarely see monochromatic light outside of the laboratory (color matching procedures). Using this Mondrian image, investigators have written computer programs to simulate the retinex computations (Blake, 1985) and demonstrated color identity under different illumination conditions (color constancy) in goldfish (Ingel, 1985).

Although the retinex theory is intriguing, there are criticisms. Brainard and Wandell (1986) failed to replicate Land's findings with the retinex algorithm concluded that the retinex algorithm is inadequate as an explanation of color constancy. Another criticism of the retinex theory is that there is no determination of where in the brain the computational comparisons take place (Thompson, 1995). Early in the development of the retinex theory, Land made no conclusions in this regard other than to indicate that the comparisons are made somewhere in the retina or cortex (retinex) (Land, 1964). However, in an experiment using a split brain patient, Land and others (Land, Hubel, Livingstone, Perry & Burns, 1983) demonstrated that the cortex is necessary for the comparison (particularly the second one [comparisons of the generated lightness scales]). They presented one band of wavelengths to one hemisphere and another to the other hemisphere and found that the split brain subject perceived little or no color. However, caution is advised in interpreting and generalizing these results as it was a case study.

In summary, though the Ladd-Franklin evolutionary theory and Land's retinex theory are important, the only theories in most textbooks are the trichromatic and opponent process theories. There are probably several reasons for this, the primary one

being the overwhelming physiological evidence for the trichromatic (existence of three different spectrally tuned photopigments) and opponent process theories (existence of opponent cells in the retina, thalamus and visual cortex). Neither Land nor Ladd-Franklin had a serious academic affiliation from which they could influence future students and promote their theories. Land was founder of the Polaroid Corporation and some of his publications were in popular magazines (e.g., Fortune magazine) Also, his theory contradicted the current theories based on Newton's definition of color and the visual spectrum. Land's (1986) theoretical position was that wavelength had nothing to do with color and that it was the result of various lightness comparisons. Christine Ladd-Franklin, on the other hand, studied during a time when women were not allowed Ph.D.s. She did not receive hers until 40 years after completion of all the requirements for the degree (Hilgard, 1987). Ladd-Franklin also lacked a serious academic affiliation from which to promote her ideas and many of the places where she performed her research did not put her on salary because she was a woman (Furumoto, 1992). However, both of these theories deserve some recognition in texts which purport to discuss color vision.

#### Memory Color vs. Color Memory

Various research efforts have emphasized memory color, but typically ignore color memory. Much of the research performed on color memory is actually on memory color, but mis-named color memory. Memory color refers to a concept developed by Hering (Hurvich, 1981; Wasserman, 1978) to describe the phenomenon of color constancy. Basically, memory color refers to a memory of the color of familiar objects

(apples are red, bananas are yellow, oranges are orange) which is then adopted by the perceptual system to give color constancy (the perception that the color of objects remains constant across differing amounts of illumination). Color memory, however, refers to the memory for actual color - unrelated to or not specifically in conjunction with a particular object.

### Memory Color

The researchers in one study investigating memory color assessed hue, value (brightness/lightness) and chroma (saturation) effects on memory colors of objects and preferred colors of objects (Siple & Springer, 1983). These investigators found that, for hue and brightness (but not saturation), memory color and preferred color were more accurate to the actual color of the objects. Indeed, subjects' memory and preferred colors for objects were reliably more saturated than the actual color of the objects. Furthermore, they found that when the contextual information (shape, form) about the objects was removed, the results were the same. This led them to conclude that memory for colors of objects is coded independent of shape and form.

Using focal and non-focal colors (focal colors being colors from the Munsell Book of Colors (1915) which are supposedly more salient [Heider, 1972], thus better remembered) either appropriately or non-appropriately (e.g., purple tree and pink ocean, among others) in specific contexts, Ratner and McCarthy (1990) demonstrated that focality was nonsignificant while appropriateness was significant. Memory was more accurate under conditions of appropriateness than non-appropriateness. In addition,

Ridley (1987) demonstrated that when comparing subjects' color matches to a circle and an object (tomato or clover) both of the same color, the matches to the objects consistently were either redder (for the tomato) or greener (for the clover) than to the circles of the same color. These results were interpreted from a linguistics viewpoint in that the language (tomato or clover) applied to the object caused the color matches to approach best instances of primary color terms (red or green) rather than to average object colors (the average color of a tomato or clover). Interestingly, the standard colors of either the object or circle were estimated average object colors - meaning that the subjects' memory for the actual color presented was grossly inaccurate (according to the investigator, because of linguistics).

In an earlier investigation of memory color, Adams (1923) concluded that the memory for color of familiar objects becomes more saturated if the visible area is small. Other investigators have also found that this is true for larger visual areas (Fisher, Hull, & Holtz, 1956). Herring and Bryden (1970) demonstrated a memory color effect which varies as a function of exposure times to familiar objects (an apple, in this case). They found that an exposure time of 300 msec elicited a stronger memory color effect than shorter exposure times. Memory color effects disappear when an observer is allowed to make an exact color match, when the demand characteristics are such that an exact match is possible (Bolles, Hulicka, & Hanley, 1959).

The application of a signal detection analysis of the effect of memory color on form perception showed that memory color decreased the response bias of observers

when identifying forms or objects (Mial, Smith, Doherty, & Smith, 1974). Memory color of familiar objects (brick, grass, sky, etc.) tended to increase in saturation and lightness when the memory color was matched to a colored chip (Bartelson, 1960).

Recently, researchers found that indeed the Commission Internationale d'Eclairage (CIE) chromaticity coordinates of memory colors for familiar objects were different (however, showed not general pattern of becoming lighter or more saturated) than the actual color and that the differences were dependent on the nature of the familiar object (Pérez-Carpinell, de Fez, Baldoví, & Soriano, 1998).

In summary, memory color studies have indicated that memory is inaccurate, specifically tending to become more saturated and lighter, memory becomes more inaccurate with longer exposure times (300 ms) and memory is better under conditions of stimulus appropriateness. The next section addresses color memory investigations.

### Color Memory

Assessing the causal phenomena underlying color constancy, Jin & Shevell (1996) employed a color memory task with a delay of 10 minutes (thus a test of long-term memory) between presentation of the standard color and presentation of the comparison colors. The investigators used one of two types of backgrounds: a complex pattern of several color patches or a neutral gray field. Greater accuracy for color memory was demonstrated for long and medium wavelengths than short wavelengths (where there were shifts in both hue and saturation). Furthermore, these findings were similar, but more pronounced for complex than neutral gray backgrounds. No causal

interpretations were made with regard to the differential finding due to backgrounds.

Nilsson & Nelson (1981) investigated color memory shifts across delays from .1 to 24.3 seconds for 16 different wavelengths. They found no effect of delay on color memory shifts and concluded that memory for color is stable up to 24.3 seconds. They did find small shifts for certain wavelengths at certain delays. Blues became greener and reds became yellower. Greens became yellower for very short delays and bluer at longer delays. This finding was suspected to simply be the Bezold-Brücke shift where blue-greens and yellow oranges shift toward the outer edges of the visible spectrum with increases in intensity (Hurvich, 1981; Schiffman, 1996; Wasserman, 1978). However, they ruled this out because the shifts were in the wrong directions. Furthermore, they demonstrated that violets, green-blues (blue-greens) and yellow-oranges were more accurately remembered. Yellows and greens also showed color shifts which were only on the dimension of saturation. When they compared the results of the delay procedure to simultaneous presentation no differences were observed. This was interpreted as memory of the color closely resembling the sensory response activated by the original color (Nilsson & Nelson, 1981). The possible role of reverberating neural circuits as a memory mechanism was mentioned as a potential explanatory mechanism for this finding.

Hamwi and Landis (1955) conducted a study of memory for colored chips across delays of 15 minutes, 24 hours and 65 hours and found more errors for lightness (blackness and whiteness) than for hue; and that this finding was consistent regardless of

length of delay. Also, while studying successive and simultaneous color matching, it was found that successive color matches (with a 5s delay) had greater saturation (purity) and lightness, indicating an increase in both with memory (memory was poorer) (Newall, Burnham, & Clark, 1957).

Researchers studying the relationship between imagery abilities and visual memory for color (both short-term and long-term) found that individuals with vivid imagery (high imagers) scored reliably worse on color memory tasks (Heuer, Fischman, & Reisberg, 1986; Reisberg, Culver, Heuer, & Fischman, 1986). They proposed that the high-imagers experience an imagination-enhancing-plausibility effect in which the vividness of the high-imagers' imagery enhanced the plausibility of an incorrect answer. In other words, the high-imagers were able to imagine (vividly) a host of responses to the color memory task, thus widening the acceptable range of choices and increasing their chances of an incorrect choice (Heuer et al., 1986; Reisberg et al., 1986).

In an interesting study performed at a scientific exhibition where 1,216 individuals participated by stopping by a demonstration booth, it was found that the majority of errors in a color memory task were toward more saturated and lighter comparisons (Henderson, Morley, & Halstead, 1971). Significant effects on color memory for test hue (the worst remembered colors being yellow, light green, blue and pink; the best remembered being orange) and delay time (errors increasing with longer delay times) were observed by Pérez-Carpinell, Baldoví, de Fez, and Castro (1998).

Uchikawa and Shinoda (1996) demonstrated that color memory may be due to

color categories in that colors become more confused within the same or neighboring color categories (the categories being white, black, red, green, yellow, blue, brown, orange, purple, pink, and gray). They concluded that there may be a color category mechanism in visual color processing. Contrary to viewing the mechanism as a perception-based physiological one, others have considered it to be based in language; as a linguistic code for color categories which can then affect perception of those colors (Garro, 1987). Along these same lines, it was found that normal individuals (suffering no lateralized or global brain damage) showed a right visual field (hence left hemisphere) superiority for color memory tasks (Malone & Hannay, 1978). Yet, when demand characteristics for using color names were removed, the effect disappeared. Furthermore, Bornstein (1976) demonstrated that the label (color name) given to a color by an experimenter affects the memory for that color.

Another study assessed color memory for colors in isolation versus colors as part of an image (meaningful or not) (Francis & Irwin, 1998). It was found that memory for color is better when associated with meaningful or non-meaningful images as compared to isolated colors. Burnham and Clark (1955), in a study assessing the instrumentation for a color memory test, found no significant differences between individuals with training in color versus individuals with no training in color.

In summary, the general conclusions from the research on color memory are that memory becomes lighter and more saturated and memory is better for violet, blue-green, yellow-orange and orange test hues and worse for yellow, light green, blue and pink.

Also, there appears to be no effect of color experience and contradictory findings regarding delay times.

### Model of Color Memory

Sokolov (1993; 1998a) developed a model of color memory in which the long-term memory neurons for color were isomorphic to a four-dimensional (red-green, blue-yellow, brightness, and darkness) sensory color detection map. This sensory color detection map was envisioned as a hypersphere with coordinates for red-green, blue-yellow, lightness, and darkness. Hue, saturation, and lightness changes in color are represented by differing excitation vectors and angles within the hypersphere as per the coordinates within (Izmailov & Sokolov, 1991; Sokolov, 1998b).

Studies have indicated that this exists not only for humans, but monkeys and fish, as well (Latanov, Leonova, Evtikhin, & Sokolov, 1997). Furthermore, these neurons will discharge during a delay period for recall and are localized in the inferotemporal cortex (in primates). Additionally, a semantic map of color names is thought to be similarly isomorphic to the sensory color detection map and the long-term neurons (Sokolov, 1993). In conclusion, Sokolov suggested that the detector map of sensory neurons, the short-term map of color neurons, and the long-term map of color neurons act as three screens reflecting color signals. Also, symbolic semantic representation (i.e., words) of color is accomplished through the neurons of the long-term memory map each being associated with a semantic neuron. Memory is thought to be the reverberation of these neurons which make up the sensory color detection map.

## Signal Detection Theory

Signal detection theory offers the intriguing possibility of investigating the participants' actual sensitivity with regard to the subjective dimensions of test colors (hue, saturation and lightness) or whether it is a function of changes in the motivational state (willingness to respond) of the participants. The theory of signal detection assumes two separate states of the world (in this instance, methodological states): noise and signal-plus-noise. These two states can be considered as two separate distributions, that may or may not overlap. If these distributions overlap, there is much confusion and participants have a difficult time separating out signal from noise. In this case sensitivity to the signal (correct color identification, in this study) would be low. This is quantified by a measure denoted as  $d'$ . As the distributions of noise and signal-plus-noise become more separate, the participant becomes more sensitive to signal and  $d'$  increases. The measure of  $d'$  can be considered to be a measure of the distance between these two distributions (Green & Swets, 1966; Swets, 1996).

There is also a point above which a participant will always respond yes that a signal was present and below which a participant will always respond no a signal was not present. This point may be placed anywhere along the two overlapping (or not) distributions of noise and signal-plus-noise. This measure is called the response criterion and is denoted  $\beta$ . This response criterion changes due to the participants' motivational state (willingness to respond) such that a strict criterion is where a participant is less likely to respond yes, whether a signal is present or not, and a liberal

criterion exists when a participant is very willing to respond yes, whether or not a signal is present (Green & Swets, 1966; Swets, 1996).

Signal detection procedures allow a calculation of both d-prime and beta, and thus enables an investigator to determine if manipulations are affecting the sensitivity of participants or their response criteria. The typical signal detection experiment consists of a forced-choice procedure (usually yes-no) where a signal is either present or absent. A yes response when the signal is present is called a hit and when absent, a false alarm. A no response when the signal is present is called a miss and when absent, a correct rejection. Through calculating the differences between the percentage of hits and false alarms, investigators using these procedures can calculate measures for d-prime and beta.

#### Applications of Signal Detection Theory

Signal detection procedures have been applied in various different arenas of investigation. These include the areas of animal psychophysics (determining d-prime and beta for rats and other organisms to sensory stimuli), sensory physiology, reaction time, time discrimination, vigilance and recognition memory (Green & Swets, 1966; Marston, 1996; Swets, 1996). Also, the procedures have been successfully applied to assess medical imaging diagnoses, aptitude tests and survey research, sensitivity to warnings of danger, advertising, and decision making during combat training (Cradit, Taschian, & Hofacker, 1994; Eubanks & Killeen, 1983; Lehto & Papastavrou, 1998; Swets, 1996).

## High versus Low Vividness Imagers

In addition to the studies already discussed concerning the differences between high and low vividness imagers on color memory tasks (Heuer, et al., 1986; Reisberg, et al., 1986), other studies have assessed high and low vividness imagers on memory tasks. Cohen and Saslona (1990) found results consistent with those already discussed with regard to measures of imagery vividness (as measured by the Vividness of Visual Imagery Questionnaire [VVIQ]) and color recall tasks (high vividness imagers performed more poorly than low vividness imagers). However, they did find that another imagery questionnaire (measuring the frequency of imagery use) did correlate positively with the color recall task.

Other investigators have found a relationship between scores on the VVIQ and imagery accuracy (as assessed by answering questions concerning previously imaged objects) in that they are positively correlated (Walczyk & Hall, 1988). However, Markham and Hynes (1993) demonstrated an inverse relationship between scores on the VVIQ and accuracy of recalling previously imaged forms. It was also found that with regard to eyewitness testimony, high imagers (as per the VVIQ) performed worse on discriminating sources of previously viewed items (in a filmclip) from written descriptions (Dobson & Markham, 1993).

### Pilot Study

An exploratory pilot study was conducted to assess the relative contributions of hue, saturation and lightness dimensions to the memory for color across sensory memory,

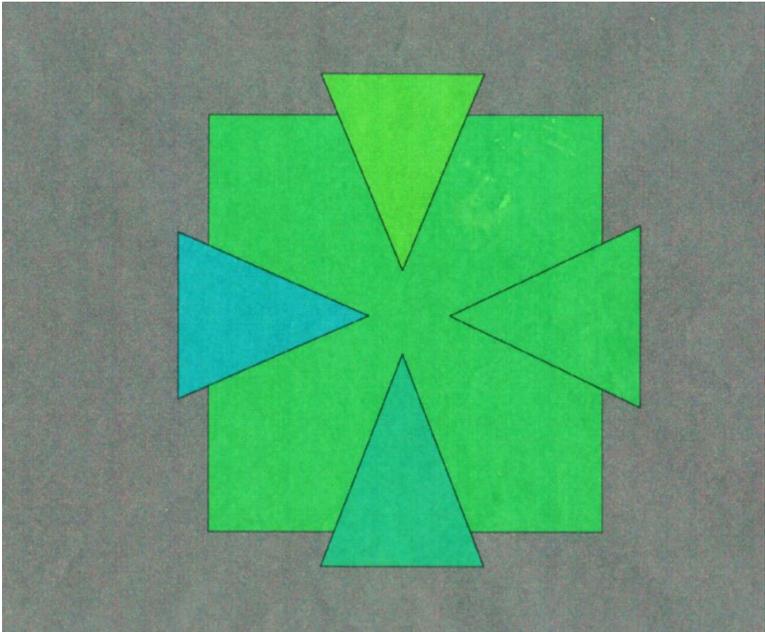
short-term memory and long-term memory. Also, the investigator wished to explore the use of a computer-facilitated display for the presentation of the standard and background colors.

### Method

Participants. Thirty-two (21 female, 11 male) 18-26 year old (mean age=20.66) healthy undergraduate students enrolled in psychology courses participated in the experiment for extra credit toward their grades. Participants were screened for normal or corrected-to-normal visual acuity and normal color vision.

Materials. The color memory task was written as a PowerPoint '97 (Microsoft Corp.) presentation. This presentation consisted of five test hues in the shape of a square subtending 16° visual angle, each of which had four comparison stimuli for each color dimension (hue, saturation and lightness) in smaller triangular shapes subtending 8.5° visual angle (see Figure 1). Although this Figure shows the comparisons overlaid upon the test hue for ease of presentation in this report, participants never saw an overlay but instead viewed the test hue first and then viewed the four comparisons simultaneously after some interval. Therefore, there was a total of 12 comparisons for each test hue (only four per trial). The test hues were blue, blue-green, green, yellow and orange. The hue comparisons differed from the background hue by 10 DAC (digital-analog conversion) units, the saturation comparisons by 60 DAC units, and the lightness comparisons by 15 DAC units (these are the changes made in terms of pixels in the PowerPoint '97 (Microsoft Corp.) software program. The program consisted of five

Figure 1. Excerpt From Program: Green Test Hue with Hue Comparisons



trial types: a 25 millisecond exposure-immediate comparison presentation with mask (a white square presented immediately after the background hue and before the comparisons) (type 1); a 25 millisecond exposure-immediate presentation of comparisons (type 2: same as type 1 but without the mask); a 25 millisecond exposure-5 second delay before comparisons (type 3); a 1 second exposure-5 second delay before comparisons (type 4); and a 1 second exposure-30 second delay before comparison (type 5). During the 30 second delay in trial type 5 a message was flashed for a 5 second duration which said, Please be patient.... The 25ms exposure trials were assumed to represent trials assessing sensory memory, while the 1s exposure, 5s delay of comparisons represented short-term memory trial and the 1s exposure, 30s delay of comparisons trial represented long-term memory. The Please be patient... message was included in an attempt to interfere with any maintenance rehearsal which may have been occurring during testing as that specific trial was supposed to be a test of long-term and not short-term memory. All test and comparison stimuli were presented against a neutral gray background. The order of trial type and placement of comparisons was determined with a random number table. The entire program took 35 minutes to complete. This program was performed by a Pentium computer (233 MHZ).

Participants far and near visual acuity and color vision were assessed with a Stereo Optical Optec 2000 Vision Tester (Industrial Model, Serial Number: 120-2093).

Design and procedure. Participants individually entered a dimly-lit room (2.50 cd/m<sup>2</sup>) where the experiment was conducted. Upon signing a copy of the informed

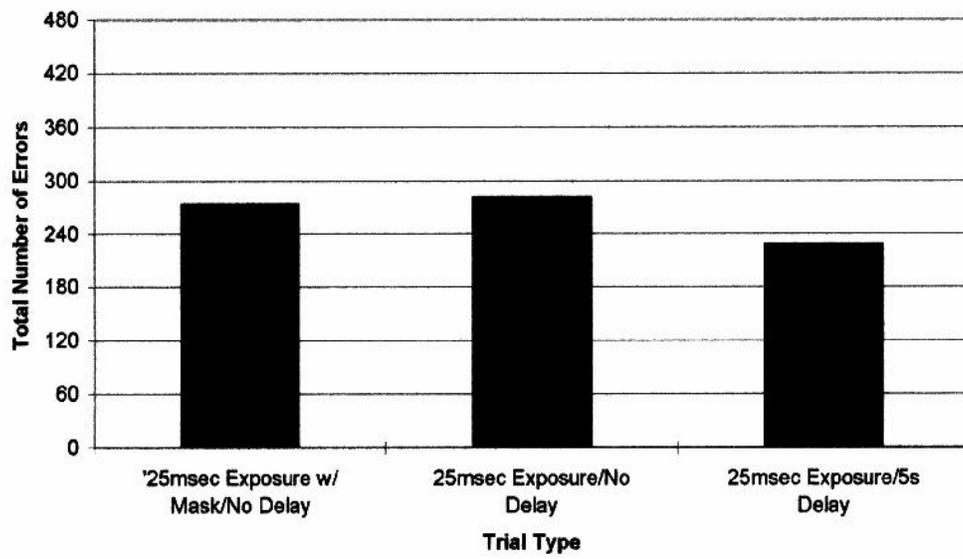
consent form, the participants were given the vision screening test (normal color vision and near and far acuity in both eyes was required) and asked to rank their artistic ability on a scale of 1 to 10 where 10 represented excellent artistic ability and 1 represented poor artistic ability. If the participants ranked their artistic ability a 5 or above, they were then asked the type of artistic activities in which they engaged.

Upon completion of the vision screening, participants were instructed as to the procedures and the self-running PowerPoint presentation was begun. The experimenter recorded the participants choice for the comparison which matched the test hue on a separate data sheet. The entire procedure took approximately 45 minutes to complete.

## Results

Manipulation check. Trial type 1 and trial type 3 were included as manipulation checks for the sensory memory trial (type 2) to assess whether or not sensory memory was actually being investigated at all even though the computer program indicated a 25 ms exposure time, it is questionable to the present investigator as to the refresh rate of the present computer system and its monitor). A repeated measures ANOVA performed for errors across trial types 1-3 was significant ( $F(2,958) = 8.83, p < .0001$ ). Post hoc comparisons (LSD,  $p < .05$ ) indicated that trial types 1 (273 errors) and 2 (281 errors) were significantly different from trial type 3 (228 errors) but not one another (see Figure 2). Since trial type 1 contained a mask, if sensory memory was being investigated the errors should have been much greater than without the mask (the appearance of the test hue would have been completely masked). Also, the trial with the 5s delay should have

**Figure 2. Total Number of Errors for Trial Types 1-3**

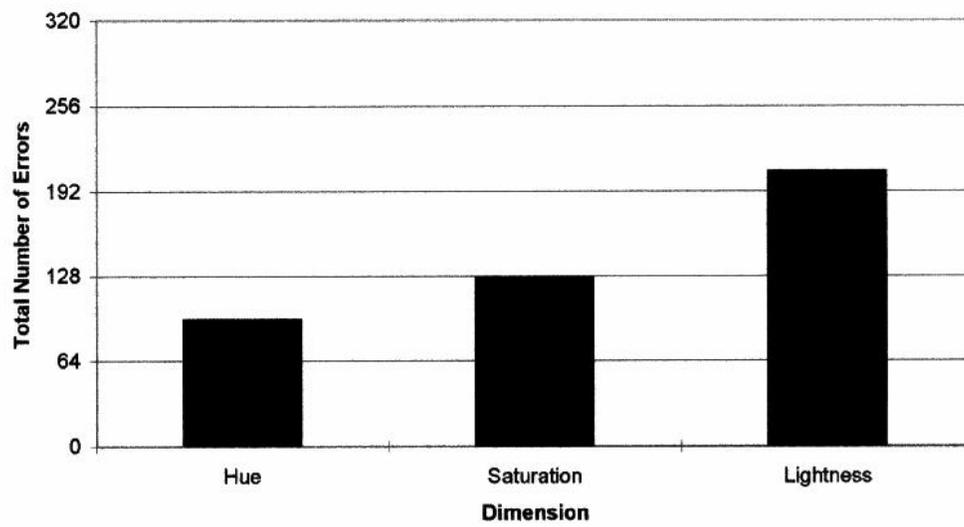


greater errors as well because sensory memory should have completely faded by 5 seconds (the errors were significantly lower for this trial probably because short-term memory, rather than sensory memory, was being assessed). Given these results, it was concluded that sensory memory was indeed not being assessed by these trials and these trials (types 1-3) were excluded from further analyses.

Analysis proper. A 3 (Dimension: hue, saturation, lightness) X 2 (Trial Type: types 4 and 5) X 5 (Test Hue: blue, blue-green, green, yellow, orange) repeated measures ANOVA was performed on the error data and revealed significant main effects for Dimension ( $F(2,62) = 34.06, p < .0001$ ) and Test Hue ( $F(4,124) = 3.708, p < .007$ ), and a significant Dimension X Test Hue interaction ( $F(8,248) = 8.151, p < .0001$ ). The main effect for Trial Type was non-significant consistent with previous investigations demonstrating that length of delay has no effect on color memory (trial type 4 and 5 differed only with respect to delay of comparison presentations). With regard to the Dimension main effect, pairwise comparisons (LSD procedure;  $p < .05$ ) showed hue (95 errors), saturation (127 errors) and lightness (207 errors) were significantly different from one another (see Figure 3). For Test Hue, orange (64 errors) was significantly different other test hues: blue (98 errors), blue-green (86 errors), green (92 errors), and yellow (89 errors) (see Figure 4).

The interaction revealed that for the hue dimension, test hue blue-green was significantly different from all others but orange, blue was significantly different from all other test hues (as was green), yellow was significantly different from all but orange, and

**Figure 3. Dimension Main Effect for Pilot Study**



**Figure 4. Test Hue Main Effect for Pilot Study**



orange was significantly different from blue and green only (see Table 1 for total errors and Figure 5). For the saturation dimension, test hue blue-green was significantly different from green and orange (all other differences being non-significant); and for the lightness dimension, test hues blue-green and yellow are significantly different from green and orange (all other differences being non-significant). Across dimensions, for blue and orange, hue and saturation were significantly different than lightness; for blue-green, saturation and lightness were significantly different than hue; for green, hue and lightness were significantly different than saturation; and for yellow, all dimensions are significantly different. Finally, the correlation between the participants self-reported artistic rank and their total number of errors was non-significant.

#### Discussion of Pilot Study

One of the purposes of the pilot study was to identify whether the present computer program could be useful as a tool for the investigation of color memory. It was determined in the analysis of the 25 ms exposure trials that the mask had no effect (contrary to a prediction based on masking effects in sensory memory) and the 5s delay enhanced memory for color rather than decreased memory ability (the decrease would be predicted from the duration of sensory memory). Therefore, it was concluded that the present computer system is incapable of the brief exposure times necessary to ensure an assessment of sensory (versus short-term) memory. However, the computer system and program appears sufficient for the investigation of color memory with longer exposure times (>1s).

Table 1.

Number of Errors for Dimension Across Test Hues for Pilot Study.

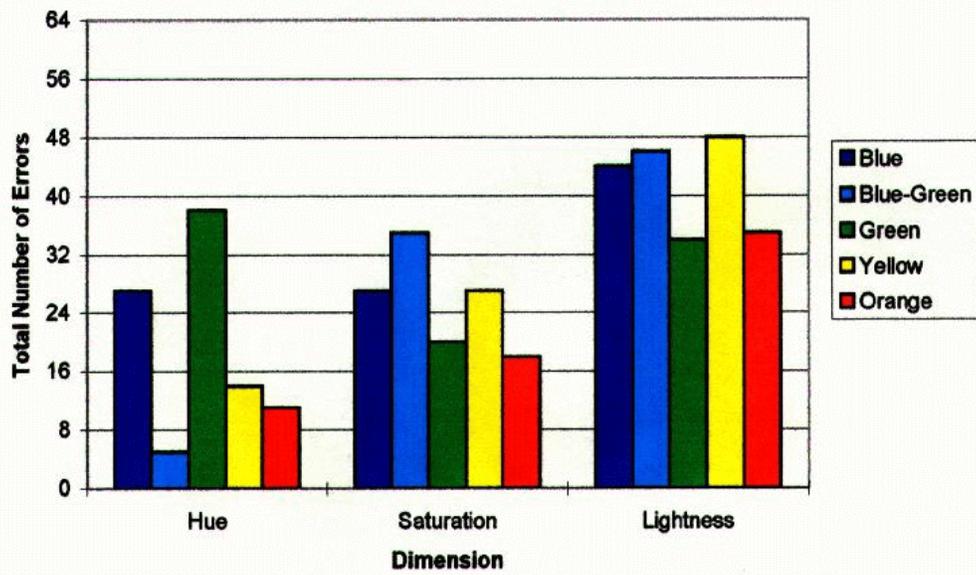
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Test Hue	Dimension			Total
	Hue	Saturation	Lightness	
Blue	27	27	44	98
Blue-Green	5	35	46	86
Green	38	20	34	92
Yellow	14	27	48	89
Orange	11	18	35	64
Total	95	127	207	

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Note: Total possible per cell (excluding total): 64.

**Figure 5. Dimension X Test Hue Interaction for Pilot Study**



Delay times up to 30s had no effect on color memory as evidenced by the non-significant main effect for Trial Type. Consistent with prior research (Hamwi & Landis, 1955; Nilsson & Nelson, 1981), this suggests that investigations of color memory need not manipulate a delay variable. Yet individual differences have yet to be investigated systematically.

Participants committed significantly fewer errors for the test hue orange than the others investigated. This may be an arbitrary finding or indicative of a greater sensitivity in memory to longer-wavelength light. Future investigations could delineate this finding further. It is interesting that in the pilot study, the main effect for orange was greatly moderated by the Dimension X Test Hue interaction.

The significant Dimension X Test Hue interaction in the pilot study indicated that the effect of dimension differentially affected color memory across test hues. However, all test hues other than green tend to follow the pattern of increasing errors for saturation and lightness as opposed to hue.

### The Present Study

The present study constituted an expansion of the pilot study with the inclusion of other variables. This study was a repeated measures 3 (Dimension: hue, saturation, lightness) X 3 (blue, green, orange test hues) factorial design. The present investigation was concerned with analyzing the differential effects of the dimensions of hue, saturation and lightness on color memory. Also, the findings discussed earlier concerning high vividness imagers poor performance on color memory tasks deserved further

investigation. Therefore, the d-prime, beta and error data were correlated with the scores obtained on the VVIQ. The test hues blue, green and orange were chosen for representativeness of short, medium and long wavelength hues of the visual spectrum<sup>1</sup>. Furthermore, this study used two different methodological procedures in order to analyze fully the effects of hue, saturation and lightness and high and low vividness imagers. The first procedure was similar to the pilot study in which the dependent variable was the total number of errors. The second procedure allowed a signal detection analysis in which d-prime (the measure of sensitivity) was calculated and analyzed. It was hypothesized that errors would be greater and d-prime would be lower (performance would decrease) for lightness, saturation and hue trials, respectively, as manifested by a main effect for dimension. Furthermore, based on previous findings that high imagers perform poorly on color memory tasks, it was hypothesized that scores on the VVIQ would be negatively correlated to d-prime and beta, and positively correlated with the number of errors committed by the observers. Although the pilot study indicated a significant effect of test hue, a specific hypothesis concerning the test hue main effect was not constructed. Previous research had indicated no general spectral bias in memory for color (with the possible exception of blue-green and yellow-orange, which are not significantly different in the pilot study). Lastly, this study further assessed the

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<sup>1</sup> The test hue red would be more representative of long-wavelength hue but was not chosen because all of the comparisons for the hue dimension would have had to have been decreasing (as increasing would be infra-red light and beyond the visible spectrum). However, the long wavelength mechanism is sensitive to wavelengths which appear more yellow-orange than red.

usefulness of a computer display for the investigation of color memory (a methodology currently not being used).

In summary, the hypotheses were as follows:

Hypothesis 1: Errors (from the total errors procedure) would be greatest for lightness, less so for saturation and least for hue comparisons, respectively, as manifested by a significant main effect for dimension.

Hypothesis 2:  $d'$  would be lowest for lightness, higher for saturation and highest for hue comparisons, respectively, as manifested by a significant main effect for dimension.

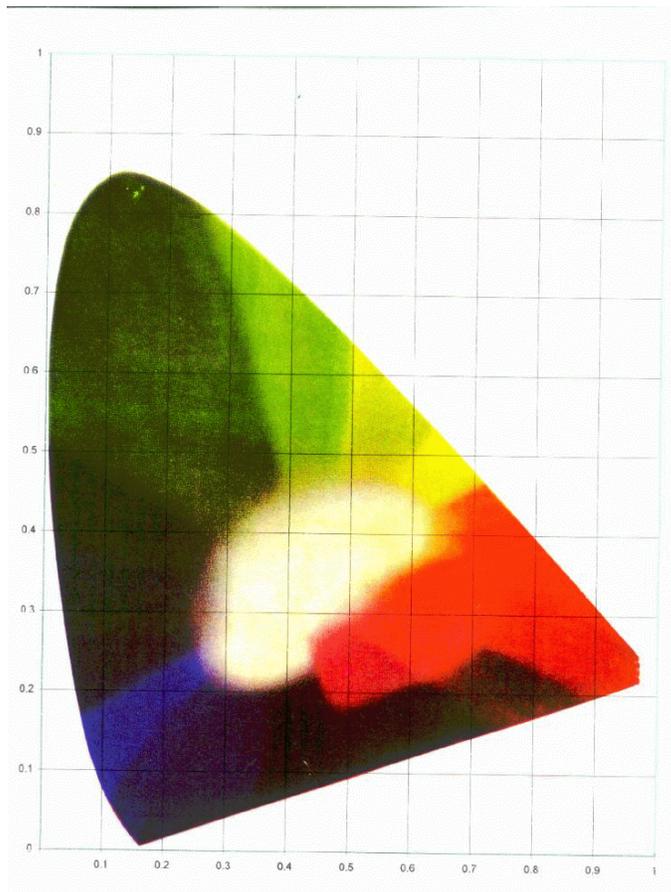
Hypothesis 3: Scores on the VVIQ would be negatively correlated with  $d'$  and beta.

Hypothesis 4: Scores on the VVIQ would be positively correlated with the number of errors committed in the total errors procedure.

#### Computer Stability and CIE Chromaticity Coordinates

Subsequent to collecting pilot data and prior to collecting data for the present study the DAC units were converted to CIE chromaticity coordinates and the computer was assessed for stability across time. CIE color space defines any color in terms of three chromaticity coordinates (see Figure 6). These coordinates are  $x$ ,  $y$ , and  $Y$ , where the  $x$  and  $y$  coordinates relate to both hue and saturation of a color (in arbitrary units ranging from 0 to 1) and  $Y$  is a measure of luminance in units of  $\text{cd}/\text{m}^2$ . Even though the

Figure 6. CIE Color Space (abscissa = x CIE coordinate; ordinate = y CIE coordinate).



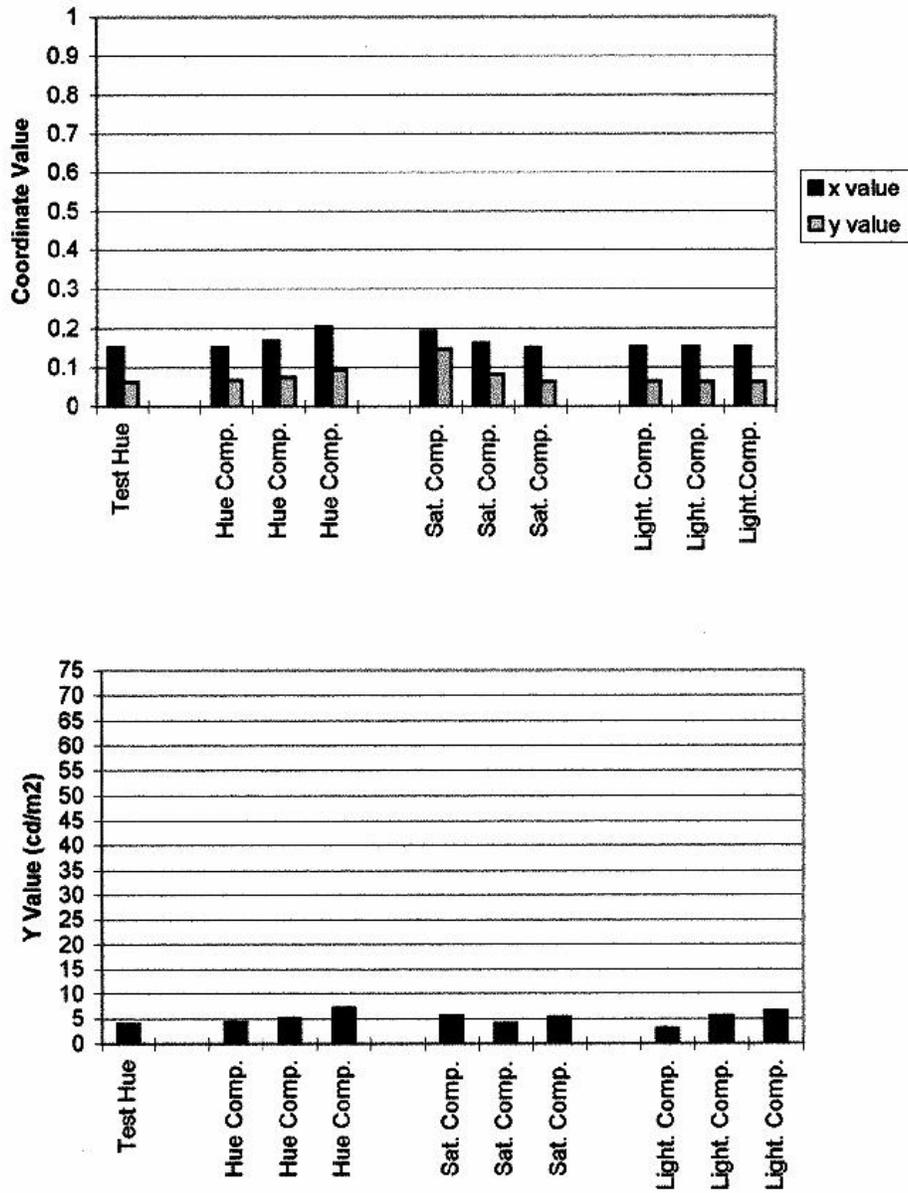
DAC units were held constant for two dimensions when a third was changed, objective assessment of the dimensions (hue, saturation, lightness) with a colorimeter (Graseby Optronics, SLS 9400 colorimeter, serial number: 8U007) showed this not to be the case (in terms of the CIE chromaticity coordinates). Primarily, the lightness dimension (as measured by the Y coordinate in CIE color space) changed considerably when only saturation was changed as per the DAC units (see Figures 7 - 9). Using the colorimeter, the stimuli (comparisons) were adjusted so that only one dimension was changed while the other two were indeed held constant (see Figures 10 - 12). Also, the stability of the computer monitor for displaying the test hues was assessed. This was accomplished by measuring CIE chromaticity coordinates for the three standard stimuli once an hour for eight hours (eight hours was considered a safe window of time as the experimenter was only collecting data across an eight hour period of time, at most). It was found that after an hour of warm-up time the monitor was indeed stable and identical CIE chromaticity coordinates were measured across the eight hour time period (see Figure 13). It was decided that in any investigation using computer monitors presenting color stimuli the computer and monitor will need to be turned on and warmed up for, at minimum, one hour.

## Design and Procedure

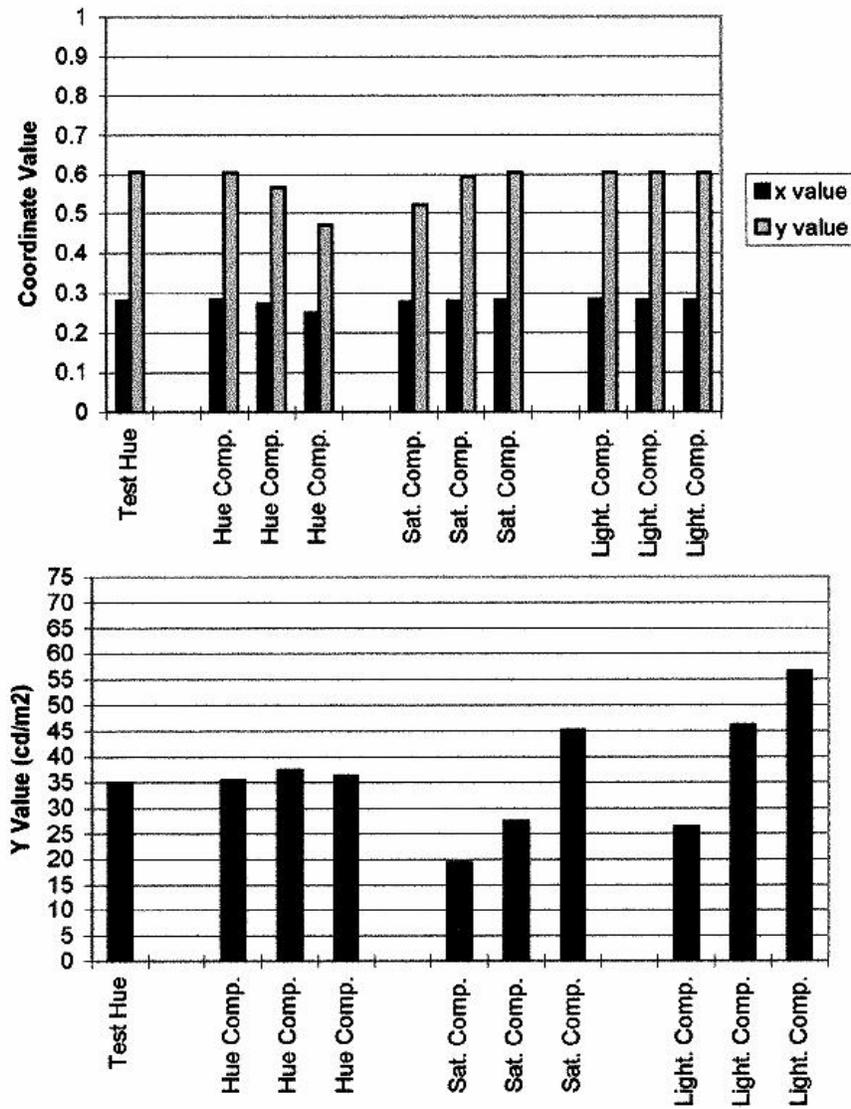
### Participants

Participants were 52 healthy 17 to 22 year old (mean age = 20) undergraduate students (26 female, 26 male) enrolled in psychology courses at Virginia Tech were

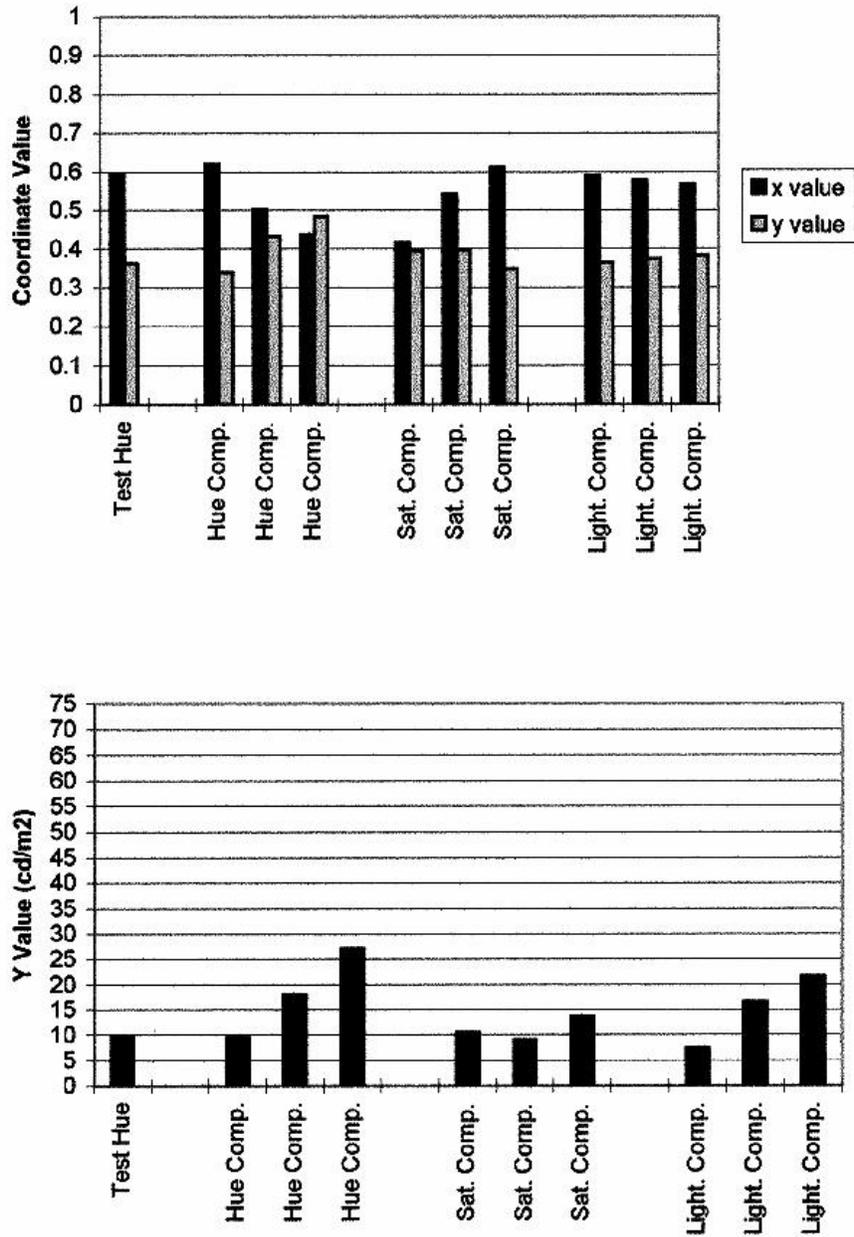
**Figure 7. x, y and Y CIE Values for Blue Test Hue Before Calibration with Colorimeter**



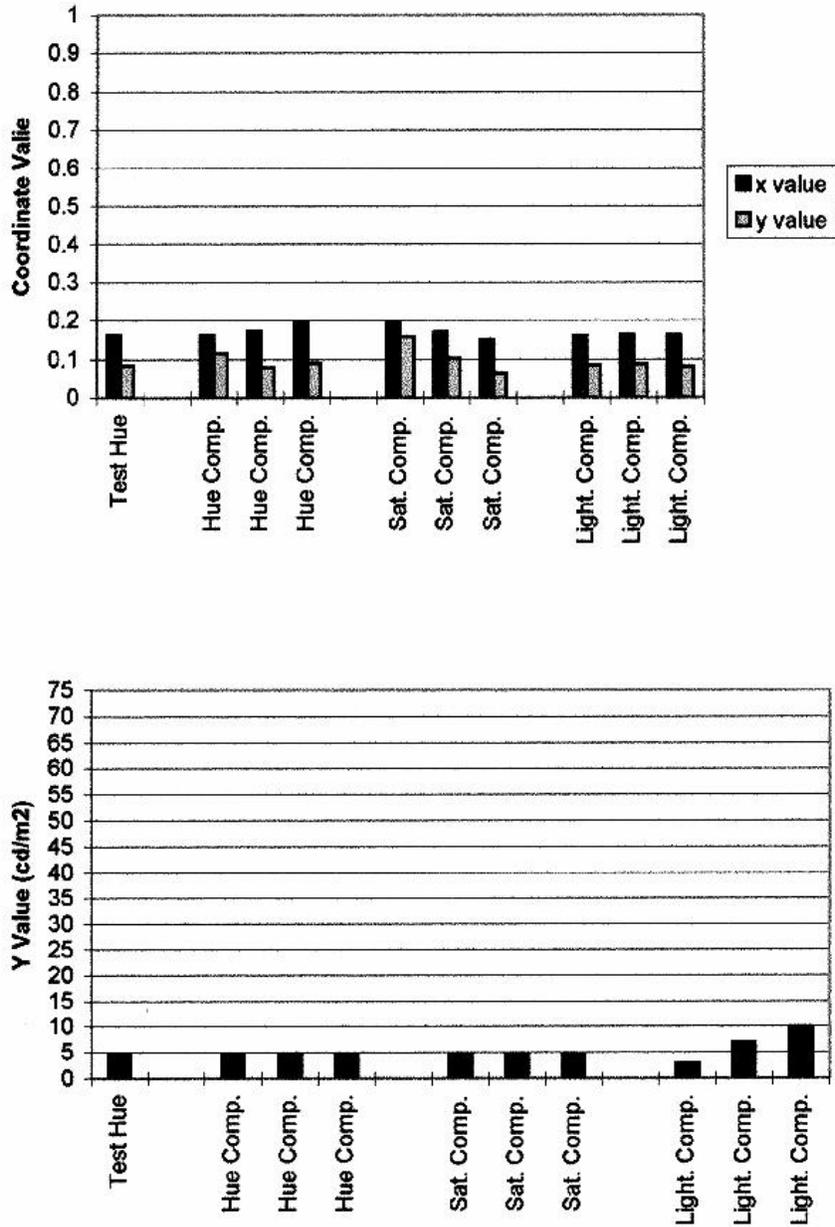
**Figure 8. x, y and Y CIE Values for Green Test Hue Before Calibration with Colorimeter**



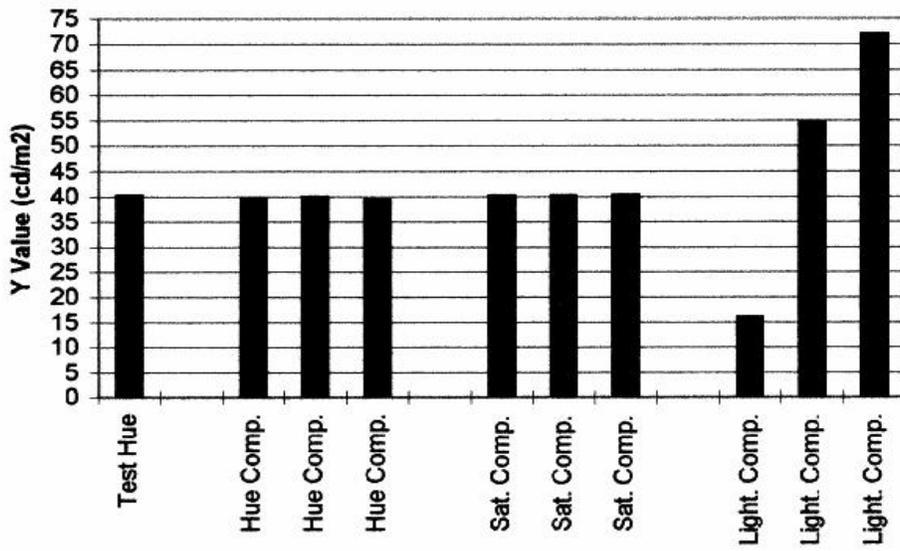
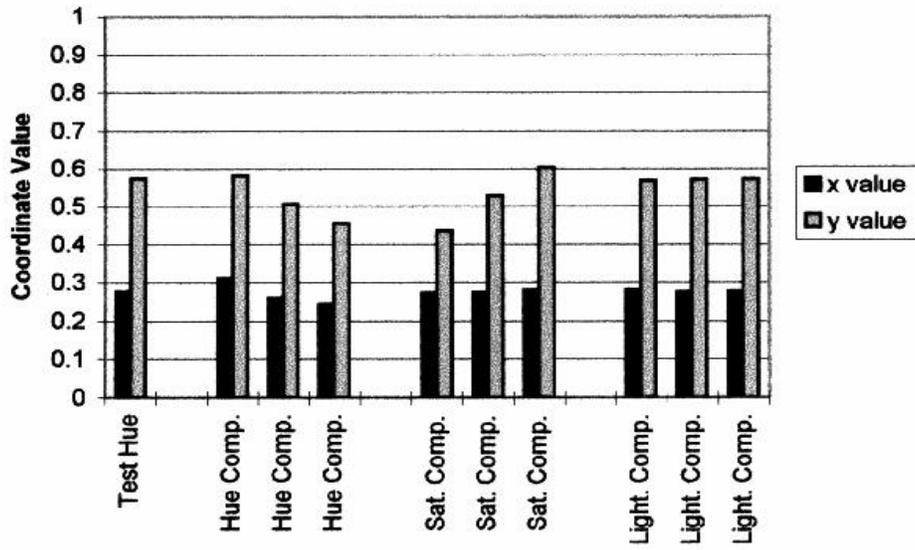
**Figure 9. x, y and Y CIE values for Orange Test Hue Before Calibration with Colorimeter**



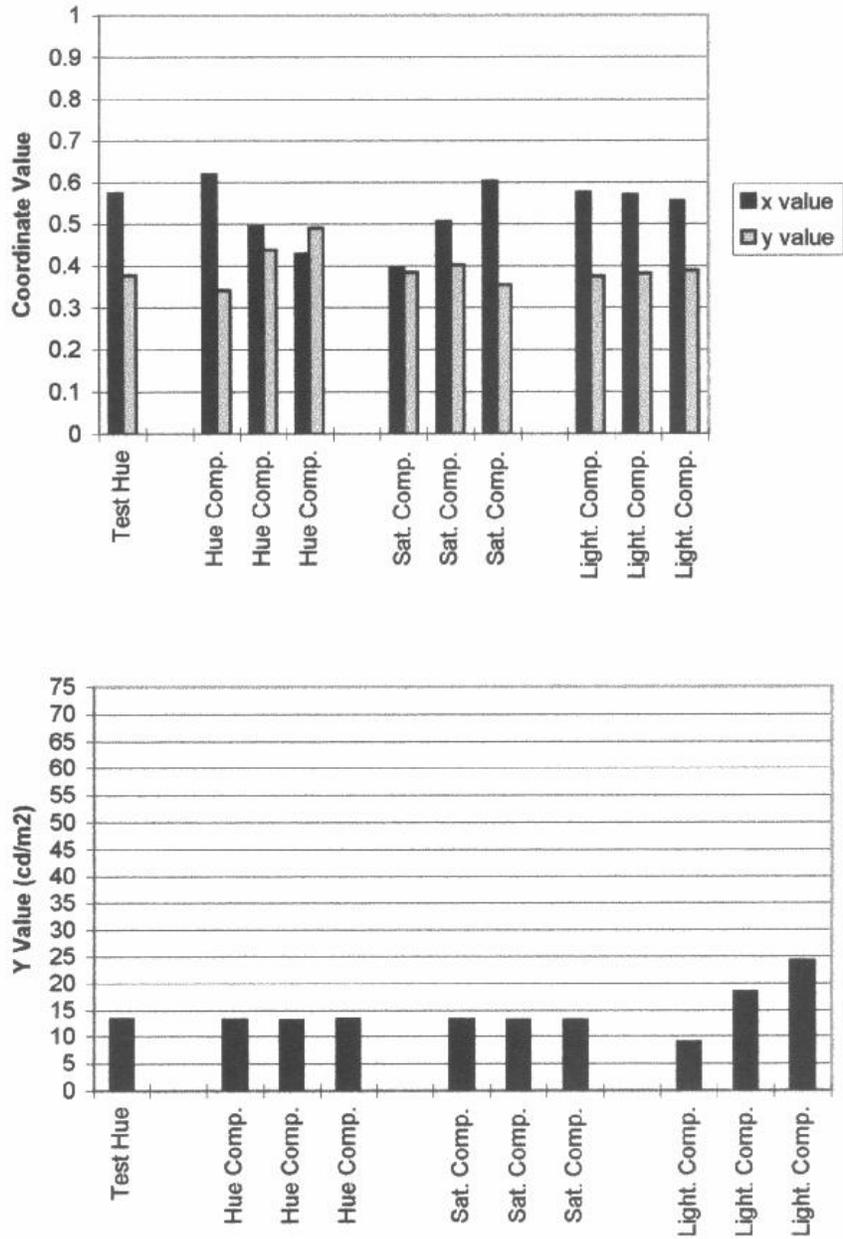
**Figure 10. x, y and Y CIE Values for Blue Test Hue after Calibration with Colorimeter**



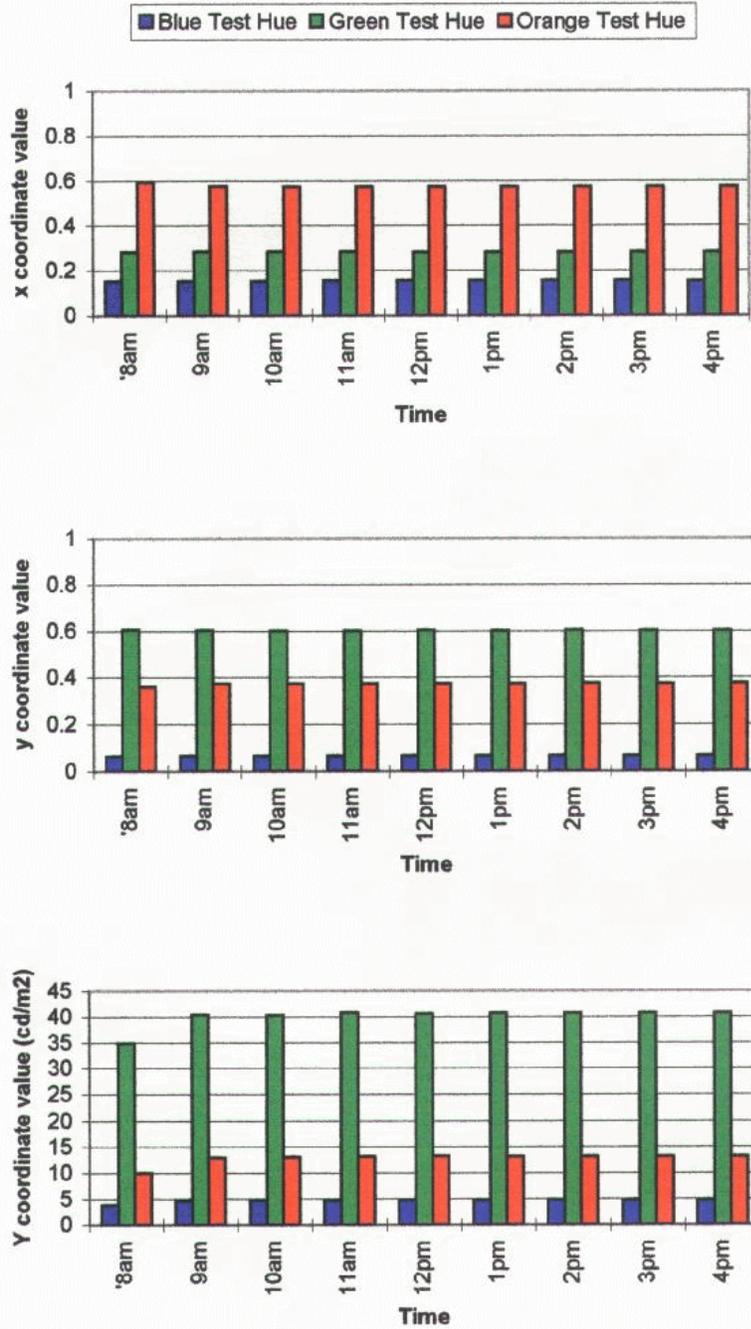
**Figure 11. x, y and Y CIE Values for Green Test Hue after Calibration with Colorimeter**



**Figure 12. x, y and Y CIE Values for Orange Test Hue after Calibration with Colorimeter**



**Figure 13. CRT Drift for x, y and Y CIE Values across 8-hour time span**



recruited to participate in this study for which they received extra credit points toward their grades in their respective courses. Participants were required to have normal color vision and 20/20 (corrected) visual acuity both near and far for both eyes (one participant was found to have a sub-lux lens and below normal acuity and color vision and was eliminated from further data analyses). A medical screening questionnaire (see Appendix A) was administered to all participants and none were rejected.

### Materials

The total errors program (PowerPoint '97 Microsoft Corp.) was identical to the pilot study procedure, but used only the 1s exposure, 5s delay of comparisons trial for blue, green and orange test hues (as the pilot study indicated no significant differences for delay; see Tables 2 and 3 for DAC units and CIE coordinate values of these stimuli). There was a total of 45 trials in this part of the procedure. For each test hue, there were trials in which the comparisons differed only with respect to one of the dimensions (hue, saturation or lightness). There were five trials of each giving a total of 5 (separate, identical trials) x 3 (test hue) x 3 (dimension) = 45 trials. The program analyzed through signal detection procedures consisted of all three test hues (blue, green and orange) at the beginning (for 5s each). Then, after a 5s delay, a series of 144 comparison colors (of the same size square shape) were presented (for 3s each with a 1s interval between each). Of the 144 comparisons, 36 were the same as the originally viewed test hues. These programs were performed by a Pentium computer (233 MHZ) with a 17 inch color monitor. Participants far and near visual acuity and color vision was assessed with a

Table 2

DAC (Digital to Analog Conversion) Units for Program Stimuli.

Test Hue	DAC Units		
	Hue	Saturation	Light.
Blue Test Hue	175	142	99
Hue Comparison 1	155	196	73
Hue Comparison 2	187	193	91
Hue Comparison 3	195	195	81
Sat. Comparison 1	175	75	82
Sat. Comparison 2	175	118	93
Sat. Comparison 3	175	255	92
Light. Comparison 1	174	134	80
Light. Comparison 2	175	146	117
Light. Comparison 3	175	191	140

Table 2, Cont d

DAC (Digital to Analog Conversion) Units for Program Stimuli.

Test Hue	DAC Units		
	Hue	Saturation	Light.
Green Test Hue	88	142	115
Hue Comparison 1	65	195	88
Hue Comparison 2	103	194	100
Hue Comparison 3	108	193	99
Sat. Comparison 1	88	73	137
Sat. Comparison 2	88	110	123
Sat. Comparison 3	88	255	89
Light. Comparison 1	88	113	87
Light. Comparison 2	88	163	133
Light. Comparison 3	86	227	155

Table 2, Cont d

DAC (Digital to Analog Conversion) Units for Program Stimuli.

Test Hue	DAC Units		
	Hue	Saturation	Light.
Orange Test Hue	10	195	102
Hue Comparison 1	0	195	114
Hue Comparison 2	20	196	82
Hue Comparison 3	30	195	68
Sat. Comparison 1	10	76	101
Sat. Comparison 2	10	135	102
Sat. Comparison 3	10	255	96
Light. Comparison 1	10	196	87
Light. Comparison 2	10	194	117
Light. Comparison 3	10	195	132

Table 3

CIE Coordinate Values for Program Stimuli.

Test Hue	CIE Values		
	x	y	Y (cd/m <sup>2</sup> )
Blue Test Hue	.163	.085	4.72
Hue Comparison 1	.163	.115	4.79
Hue Comparison 2	.173	.078	4.73
Hue Comparison 3	.196	.091	4.70
Sat. Comparison 1	.195	.158	4.66
Sat. Comparison 2	.172	.103	4.77
Sat. Comparison 3	.151	.064	4.74
Light. Comparison 1	.162	.085	2.92
Light. Comparison 2	.165	.087	6.94
Light. Comparison 3	.163	.082	9.88

Table 3, Cont d

CIE Coordinate Values for Program Stimuli.

Test Hue	CIE Values		
	x	y	Y (cd/m <sup>2</sup> )
Green Test Hue	.279	.575	40.10
Hue Comparison 1	.310	.583	39.60
Hue Comparison 2	.258	.507	40.00
Hue Comparison 3	.245	.456	39.40
Sat. Comparison 1	.273	.437	40.10
Sat. Comparison 2	.275	.530	40.10
Sat. Comparison 3	.282	.605	40.30
Light. Comparison 1	.281	.570	16.00
Light. Comparison 2	.277	.573	54.60
Light. Comparison 3	.278	.574	72.00

Table 3, Cont d

CIE Coordinate Values for Program Stimuli.

Test Hue	CIE Values		
	x	y	Y (cd/m <sup>2</sup> )
Orange Test Hue	.574	.376	13.20
Hue Comparison 1	.619	.341	13.10
Hue Comparison 2	.495	.438	13.00
Hue Comparison 3	.427	.491	13.30
Sat. Comparison 1	.397	.383	13.10
Sat. Comparison 2	.505	.402	13.00
Sat. Comparison 3	.603	.354	13.00
Light. Comparison 1	.576	.374	8.97
Light. Comparison 2	.570	.380	18.30
Light. Comparison 3	.556	.388	24.10

Stereo Optical Optec 2000 Vision Tester (Industrial Model, Serial Number: 120-2093).

As indicated before, participants completed a medical screening questionnaire (see Appendix A).

The VVIQ. The VVIQ is a sixteen-item self-report questionnaire (see Appendix B) which measures imagery vividness and allows for a differentiation between high and low imagers. It has been used extensively in previous research (see above discussion and Marks, 1973; 1989; McKelvie, 1995a; 1995b). Average split-half reliabilities ranged from .86 to .90 and Cronbach's alpha ranged from .87 to .89 across various studies (McKelvie, 1995a; 1995b). Test-retest reliability coefficients ranged from .94 (immediate retest) to .74 (delayed retest of 3 to 7 weeks) and alternate form reliability ranged from .54 to .64. In a review of literature using the VVIQ, McKelvie (1995a; 1995b) concluded that criterion validity was .27 (estimated across 71 studies) which was deemed acceptable.

Past researchers have either administered the VVIQ while participants have their eyes open or closed (or both [open then closed] and calculated the average score). McKelvie (1995a; 1995b) argues that eyes-open or eyes-closed administration of the VVIQ has no effect on scores. Other researchers have found that the eyes-open and eyes-closed administrations on the VVIQ were correlated (.56 to .72), but that the order (whether eyes-closed was administered first or second) did make a difference in that when eyes-closed administrations followed eyes-open, higher ratings of vividness were found (Campos, López, & González, 1999). Furthermore, these investigators

demonstrated no gender difference with regard to the eyes-open or eyes-closed procedures. This study incorporated the eyes-open procedure as the experimental tasks were also performed with eyes open, thus maintaining some ecological validity.

### Procedure

Participants reported to a dimly lit ( $2.50 \text{ cd/m}^2$ ) laboratory for the session. They were given the medical screening questionnaire and then the visual screening procedure as described in the pilot study. The VVIQ was then administered (eyes-open) and upon conclusion of the questionnaire, testing began. Participants were seated on a laboratory stool with their head positioned in a head and chin rest so that they viewed the computer screen from a distance of 45 cm. Instructions were given and the PowerPoint '97 (Microsoft Corp.) computer program was initiated.

The procedure analyzed through signal detection procedures consisted of participants viewing all three test hues (blue, green and orange) at the beginning. Then, after a 5s delay, a series of 144 comparison colors (of the same size square shape -  $16^\circ$  visual angle) was presented for a duration of 3s each (with a 1s interval between each). The participant noted verbally yes or no as to whether the comparison was the same as one of the original test hues viewed. From these data, the percentage of hits and false alarms were calculated allowing for further calculation of d-prime values. Of the 144 comparisons, 36 were the same as the originally viewed test hues.

The procedure for the measurement of total errors consisted of the participants viewing the test hue square for 1s, and then 5s later viewing the four triangular-shaped

comparisons (8.5° visual angle) simultaneously and indicating which was the same as the original test hue viewed. The comparisons were displayed for 3s followed by a recall screen (which was also displayed for 3s, after a delay of 1s the next trial commenced), allowing the participants enough time to indicate their response. The recall screen consisted of four triangular-shaped stimuli (of the same size and visual angle of the comparison stimuli) of a neutral gray hue, in which were the letters A, B, C or D. The participant indicated which of the triangular-shaped comparisons just seen was their choice by indicating the letter which corresponded to their choice. There was a total of 45 trials for this procedure.

The order of comparisons in the signal detection procedure and the order of trials in the total error procedure were random as determined by a random number table. All participants viewed the signal detection procedure first followed by the total errors procedure. This was decided based on the fact that participants viewed the original test hues only once at the beginning of the program for the signal detection procedure. All subsequent comparisons would be made regarding that one viewing. If the signal detection procedure followed the total errors procedure, then the participants would have viewed the comparisons 147 times (the 144 trials of the total errors procedure and the three at the beginning of the signal detection procedure). In the total errors procedure, participants viewed a test hue at the beginning of each of the 45 trials, which were in random order; therefore, the viewing of the test hue and comparisons from the signal detection procedure first had a minimal effect, if any.

## Results

### Total Errors Procedure

A 3 (Dimension: hue, saturation, lightness) X 3 (Test Hue: blue, green, orange) repeated measures ANOVA was performed on the number of errors committed (out of a total of five - as there were five trials per condition) from the total errors procedure. There was a significant main effect for both Dimension ( $F(2,102) = 39.48, p = .0001$ ) and Test Hue ( $F(2,102) = 41.62, p = .0001$ ), and a significant Dimension by Test Hue interaction ( $F(4,204) = 26.05, p = .0001$ ) (see Table 4 for ANOVA source table). Pairwise comparisons (least significant difference [LSD] procedure) revealed that for dimension, the lightness condition had significantly more errors committed (2.25) than saturation (1.54) or hue (.90) (see Figure 14; error bars on all figures represent standard deviations). Saturation and hue conditions were also significantly different from one another. For Test Hue, the green test hue had significantly more errors committed (2.21) than the blue test hue (1.56) or orange test hue (.93) (see Figure 15). The blue and orange test hues were also significantly different from one another.

Analyses of the Dimension by Test Hue interaction with paired  $t$ -tests (with Bonferroni correction; see Table 10) revealed that the effect of dimension was significant for green and orange tests hues (hue, saturation, and lightness conditions all significantly different) but not for the blue test hue (see Table 5 for means and Figure 16).

### Signal Detection Procedure - $d'$ -prime

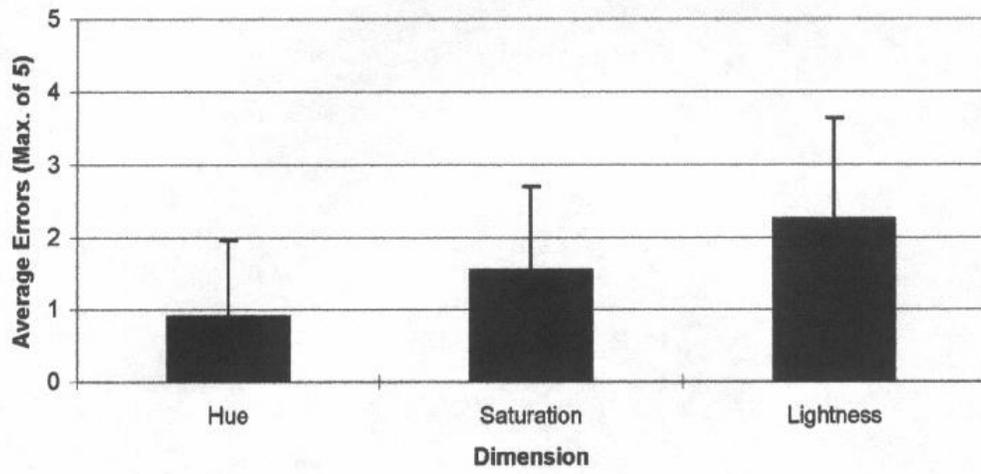
In order to investigate potential practice or fatigue effects, the 144 trials of the

Table 4

ANOVA Source Table for Errors Dependent Variable.

Source	df	SS	MS	F
Dimension	2	142.83	71.41	39.48
Test Hue	2	128.21	64.11	41.62
Dim.X Test Hue	4	124.42	31.11	26.05
ERROR(Dim.)	102	184.51	1.81	
ERROR(TestHue)	102	157.12	1.54	
ERROR(DimXTestHue)	204	243.58	1.19	

**Figure 14. Dimension Main Effect for Errors**



**Figure 15. Test Hue Main Effect for Errors**

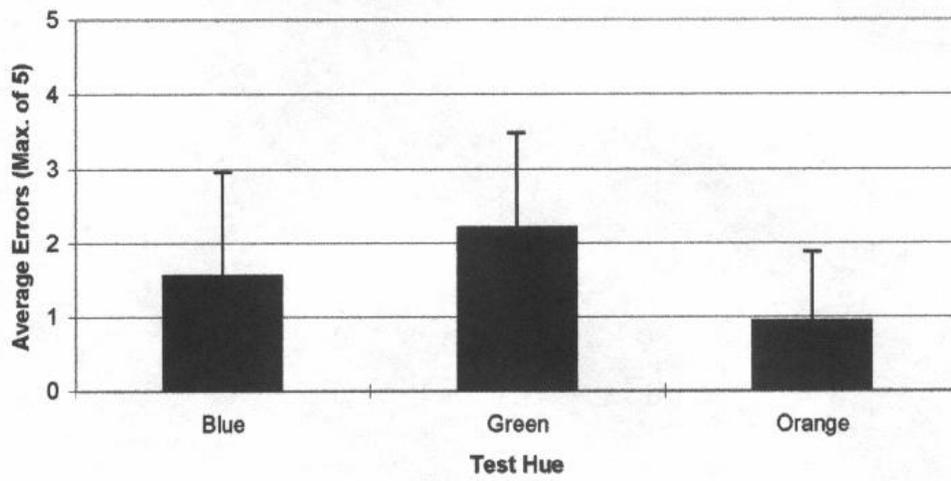


Table 5

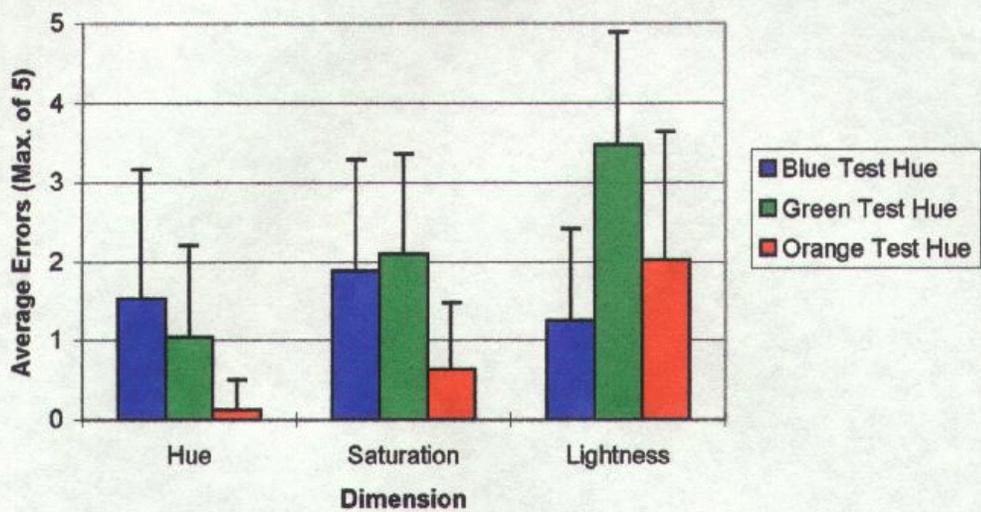
Average Errors (Maximum of 5) for Dimension by Test Hue Interaction.

---

Dimension			
Test Hue	Hue	Saturation	Lightness
Blue	1.54	1.89	1.25
Green	1.04	2.10	3.48
Orange	0.12	0.64	2.02

---

**Figure 16. Dimension X Test Hue Interaction for Errors**



signal detection procedure were blocked into units of 36 trials each and the errors for each block of 36 trials were graphed (see Figure 17). Errors (defined as a miss or false alarm) did not change across blocks of 36 trials indicating no practice or fatigue effects. The d-prime values (calculated from the signal detection procedure) were subjected to a 3 (Dimension: hue, saturation, lightness) X 3 (Test Hue: blue, green, orange) repeated measures ANOVA. This indicated a significant main effect for Dimension ( $F(1.23, 62.77 - \text{using Greenhouse-Geisser correction}) = 65.48, p = .0001$ ), Test Hue ( $F(2, 102) = 15.54, p = .0001$ ) and a significant Dimension by Test Hue interaction ( $F(2.91, 148.63 - \text{using Greenhouse-Geisser correction}) = 23.07, p = .0001$ ) (see Table 6 for ANOVA source table). Pairwise comparisons (LSD,  $p < .05$ ) on the main effect for Dimension specified that d-prime was significantly higher for the hue comparisons (1.59) than for saturation (1.31) or lightness comparisons (.91) (see Figure 18). Furthermore, the saturation and lightness comparisons were also significantly different from one another. Pairwise comparisons of the Test Hue main effect revealed that the green test hue had a significantly higher d-prime (1.78) than either the blue (.94) or orange (1.09) test hues which were not significantly different from one another (see Figure 19). Analyses of the Dimension by Test Hue interaction with paired  $t$ -tests (with Bonferroni correction; see Table 10) revealed that the effect of Test Hue was significant only for hue and lightness comparisons. For saturation comparisons, the green test hue was only significantly different from the blue test hue. Furthermore, hue and saturation conditions were significantly different from lightness conditions (but not one another) for the blue

**Figure 17. Number of Errors Across Trials for  
Signal Detection Procedure**

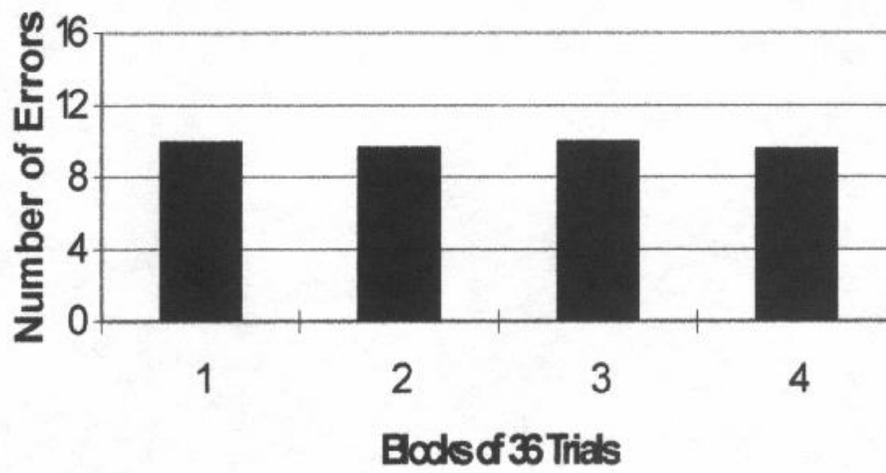
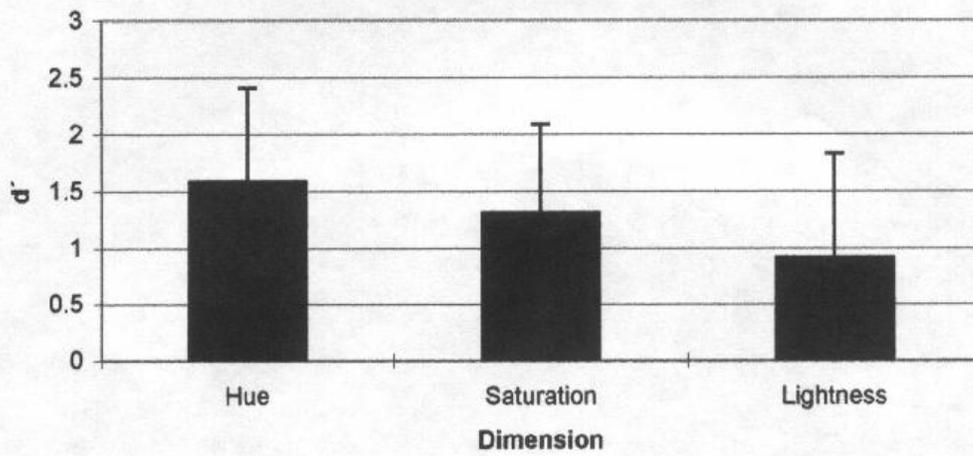


Table 6

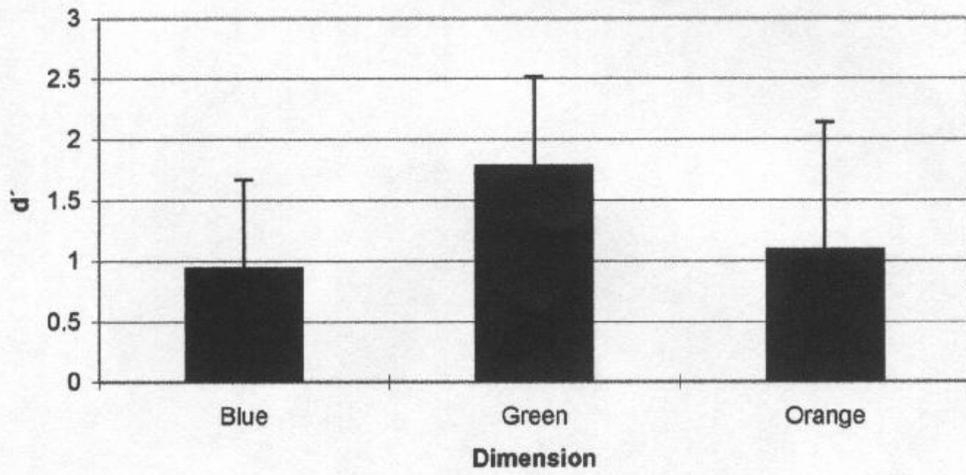
ANOVA Source Table for d-prime

Source	df	SS	MS	F
Dimension	1.23	36.58	29.72	65.48
Test Hue	2	61.50	30.75	15.54
Dim.XTestHue	2.9	17.20	5.90	23.07
ERROR(Dim.)	62.77	28.49	.454	
ERROR(TestHue)	102	201.86	1.979	
ERROR(Dim.XTestHue)	148.62	38.02	.256	

**Figure 18. Dimension Main Effect for  $d'$**



**Figure 19. Test Hue Main Effect for  $d'$**



and orange test hues; whereas, for the green test hue, the hue condition was significantly different from the saturation and lightness conditions (which were not significantly different from one another) (see Table 7 for means and Figure 20).

#### Signal Detection Procedure - beta

The beta values (calculated from the signal detection procedure) were subjected to a 3 (Dimension: hue, saturation, lightness) X 3 (Test Hue: blue, green, orange) repeated measures ANOVA. This showed a significant main effect for Dimension ( $F(1.71, 87.12 - \text{using Greenhouse-Geisser correction}) = 60.97, p = .0001$ ), Test Hue ( $F(2,102) = 19.10, p = .0001$ ) and a significant Dimension by Test Hue interaction ( $F(3.19, 162.51 - \text{using Greenhouse-Geisser correction}) = 26.85, p = .0001$ ) (see Table 8 for ANOVA source table). Pairwise comparisons (LSD procedure,  $p < .05$ ) of the Dimension main effect revealed that the hue comparisons (1.62), saturation comparisons (1.28) and lightness comparisons (.99) were all significantly different from one another (see Figure 21). For Test Hue, the orange test hue (1.69) was significantly different from both blue (.99) and green (1.18) test hues (see Figure 22). The blue and green test hues were not significantly different from one another.

Analyses of the Dimension by Test Hue interaction with paired  $t$ -tests (with Bonferroni correction; see Table 10) revealed that the only conditions that had significantly higher beta values were the orange hue, orange saturation, and green hue conditions, that were not significantly different from one another (additionally, the green hue condition was not significantly different from the blue hue condition) (see Table 9

Table 7

d-prime Values for Dimension by Test Hue Interaction.

---

Dimension			
Test Hue	Hue	Saturation	Lightness
Blue	1.13	0.98	0.72
Green	2.24	1.53	1.56
Orange	1.40	1.43	0.44

---

**Figure 20. Dimension X Test Hue Interaction for  $d'$**

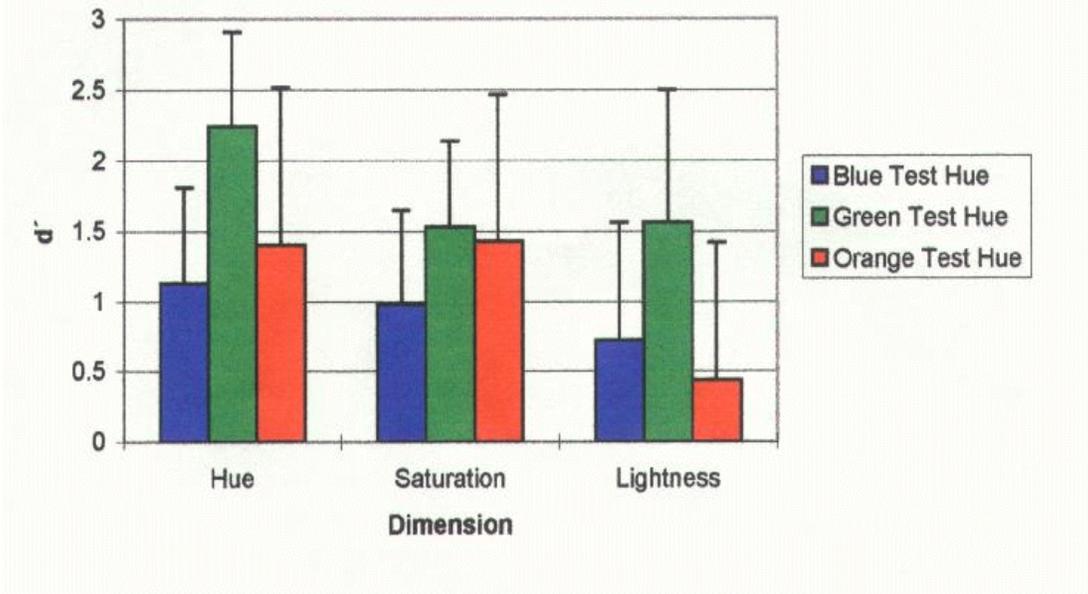
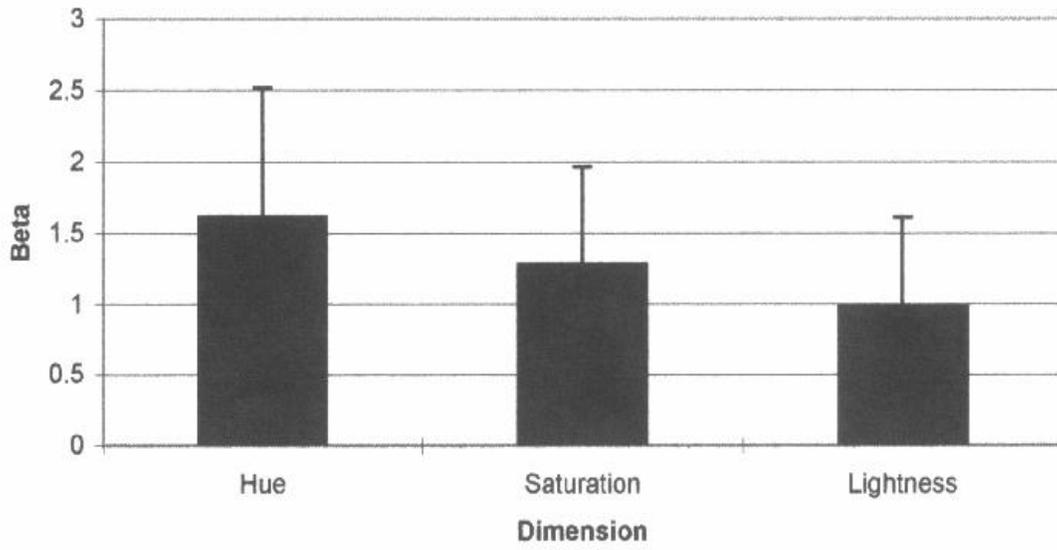


Table 8

ANOVA Source Table for beta.

Source	df	SS	MS	F
Dimension	1.71	33.38	17.78	60.97
Test Hue	2	37.42	18.71	19.10
Dim.X TestHue	3.2	26.23	8.23	26.85
ERROR(Dim.)	87.12	25.41	.292	
ERROR(TestHue)	102	99.94	.980	
ERROR(Dim.XTestHue)	162.51	49.82	.307	

**Figure 21. Dimension Main Effect for Beta**



**Figure 22. Test Hue Main Effect for Beta**

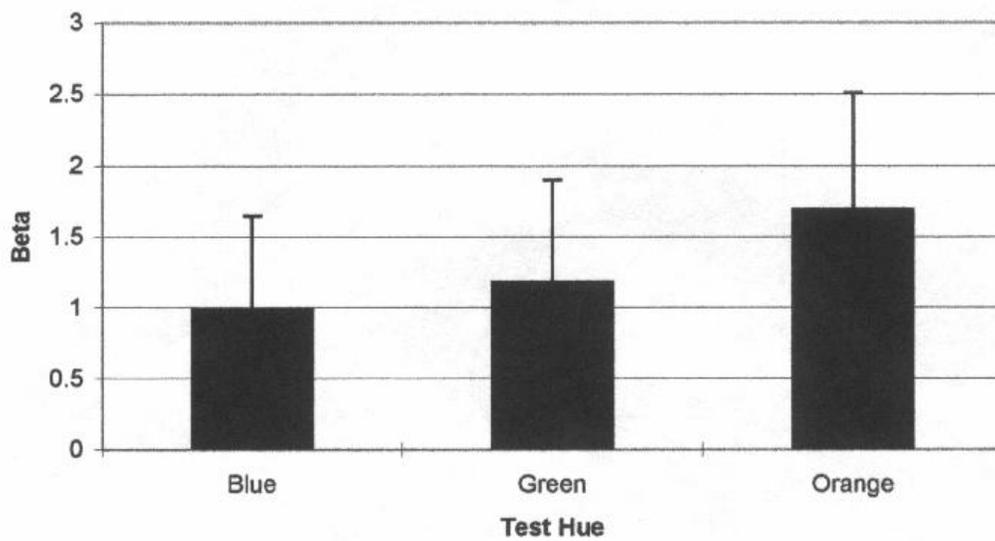


Table 9

beta Values for Dimension X Test Hue Interaction.

---

Test Hue	Dimension		
	Hue	Saturation	Lightness
Blue	1.21	0.97	0.89
Green	1.63	0.82	1.08
Orange	2.01	2.04	1.01

---

Figure 23. Dimension X Test Hue Interaction for Beta

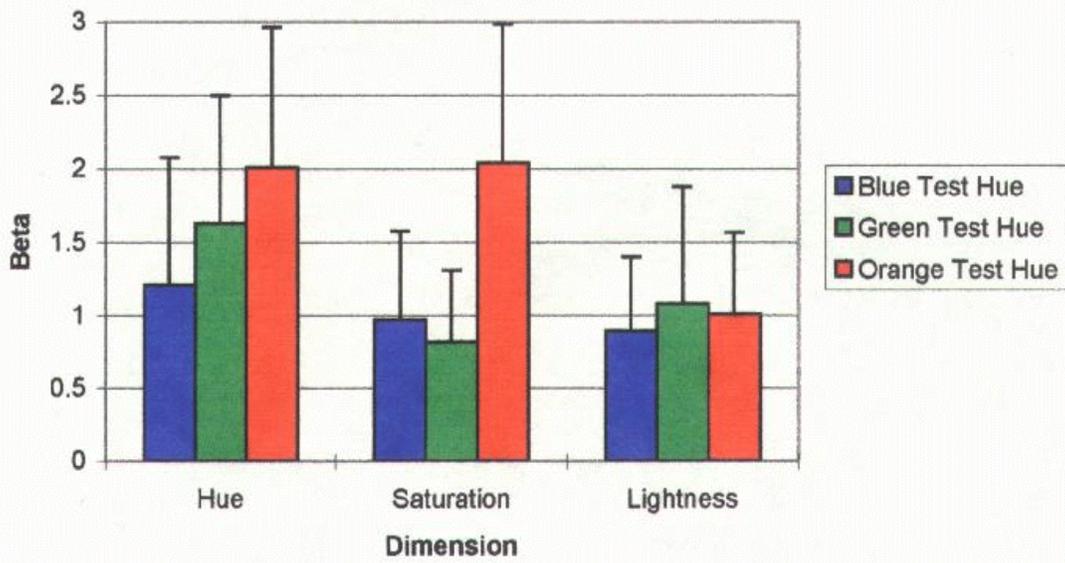


Table 10

t-Values for Comparisons of Dimension X Test Hue Interaction for d-prime, Beta and Errors Procedures.

Comparisons	Procedures		
	d-prime	beta	Errors
O/H - O/S	-.75	-.68	-4.80***
O/H - O/L	8.06***	7.89***	-8.21***
O/H - B/H	1.46	4.86***	-5.89***
O/H - B/S	2.25	6.48***	-8.97***
O/H - B/L	3.28*	7.20***	-6.61***
O/H - G/H	-4.61***	2.31	-5.69***
O/H - G/S	-.71	8.69***	-10.94***
O/H - G/L	-.72	5.76***	-16.09***
O/S - O/L	8.79***	8.30***	-5.63***
O/S - B/H	1.70	5.11***	-3.67**

Table 10, Cont d.

t-Values for Comparisons of Dimension X Test Hue Interaction for d-prime, Beta and Errors Procedures.

Comparisons	Procedures		
	d-prime	beta	Errors
O/S - B/S	2.52	6.79***	-6.15***
O/S - B/L	3.61**	7.80***	-3.37**
O/S - G/H	-4.72***	2.45	-2.41
O/S - G/S	-.61	8.99***	-7.73***
O/S - G/L	-.65	5.80***	-12.72***
O/L - B/H	-4.28***	-1.71	1.50
O/L - B/S	-3.30*	.46	.46
O/L - B/L	-1.55	1.18	3.12
O/L - G/H	-10.32***	-4.98***	3.60**
O/L - G/S	-6.27***	1.93	-.30

Table 10, Cont d.

t-Values for Comparisons of Dimension X Test Hue Interaction for d-prime, Beta and Errors Procedures.

Comparisons	Procedures		
	d-prime	Beta	Errors
O/L - G/L	-5.52***	-.67	-5.79***
B/H - B/S	2.13	2.91	-1.30
B/H - B/L	4.42***	3.32*	1.03
B/H - G/H	-7.42***	-2.70	1.97
B/H - G/S	-2.85	3.17	-1.85
B/H - G/L	-2.50	.88	-6.45***
B/S - B/L	2.81	.89	2.55
B/S - G/H	-9.18***	-4.79***	3.30*
B/S - G/S	-4.15***	1.42	-.93
B/S - G/L	-3.56**	-.93	-6.08***

Table 10, Cont d.

t-Values for Comparisons of Dimension X Test Hue Interaction for d-prime, Beta and Errors Procedures.

Comparisons	Procedures		
	d-prime	Beta	Errors
B/L - G/H	-9.19***	-5.79***	1.08
B/L - G/S	-5.04***	.92	-3.93***
B/L - G/L	-4.74***	-1.49	-9.95***
G/H - G/S	14.03***	9.47***	-5.32***
G/H - G/L	6.42***	5.24***	-11.26***
G/S - G/L	-.32	.261	-5.63***

Note: O = Orange Test Hue; B = Blue Test Hue; G = Green Test Hue; H = Hue Dimension; S = Saturation Dimension; L = Lightness Dimension; \* =  $p < .002$ ; \*\* =  $p < .001$ ; \*\*\* =  $p < .0001$ .

for means and Figure 23).

### Reliability of Color Memory Tasks

A one-week test-retest reliability session was performed on 39 of the 52 original participants (all were asked to return in one week, 39 actually did). Pearson correlation coefficients were calculated between performance at week one and performance at week two (see Table 11). For the signal detection procedure, only eight of the eighteen conditions had significant reliability coefficients ranging from .33 to .64 (average reliability coefficient for signal detection procedure = .31). These included the orange hue, green hue and green lightness conditions for the d-prime data, and the blue hue, saturation and lightness and green saturation and lightness conditions for the Beta data. For the total errors procedure, eight of the nine conditions (all but the orange hue condition) had significant reliability coefficients ranging from .33 to .73 (average = .49).

### VVIQ

The average VVIQ score across the 52 participants was 59.64 (SD = 8.42; range: 34 - 76). The frequency distribution of VVIQ scores is shown in Figure 24. The 39 test-retest participants also took the VVIQ at week two and the reliability coefficient was  $r = .76$ ,  $p = .0001$ . This reliability is within the range found for the VVIQ at 3 to 7 week retest (McKelvie, 1995a; 1995b). The only condition which was correlated with scores on the VVIQ was the blue hue condition for the d-prime data ( $r = .35$ ,  $p = .012$ ). All other correlations failed to reach significance (see Table 12).

Table 11

One-week Test-retest Reliability Coefficients (Pearsons r) for Performance on the d-prime, Beta and Errors Procedures.

Test Hue/Dimension	Procedure		
	d-prime	Beta	Errors
Blue/Hue	.002	.57****	.73****
Blue/Saturation	.03	.41**	.54****
Blue/Lightness	.12	.64****	.49***
Green/Hue	.44**	.29	.33*
Green/Saturation	.22	.41**	.52***
Green/Lightness	.45**	.36*	.55****
Orange/Hue	.25	.27	.15
Orange/Saturation	.19	.31	.46**
Orange/Lightness	.33*	.24	.67*

\* =  $p < .05$ ; \*\* =  $p < .01$ ; \*\*\* =  $p < .001$ ; \*\*\*\* =  $p < .0001$ .

**Figure 24. Frequency Distribution of VVIQ Scores**

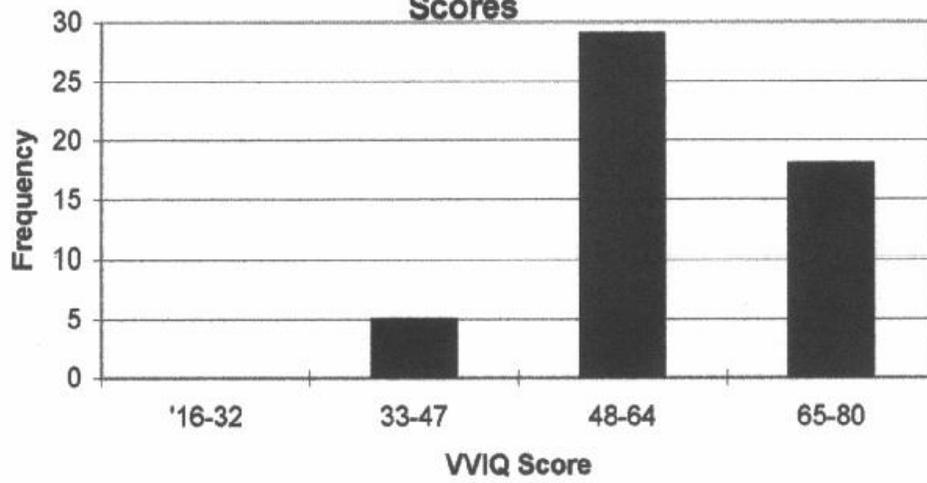


Table 12

Pearsons r Correlation Coefficients Between Scores on the VVIQ and Performance on d-prime, Beta and Errors Procedures.

Test Hue/Dimension	Procedure		
	d-prime	Beta	Errors
Blue/Hue	.35*	.10	-.06
Blue/Saturation	.16	-.12	-.04
Blue/Lightness	.05	-.05	-.11
Green/Hue	-.05	.18	-.06
Green/Saturation	-.14	.10	.11
Green/Lightness	-.11	.15	-.03
Orange/Hue	.17	.13	-.07
Orange/Saturation	.22	.15	.15
Orange/Lightness	.17	-.13	-.02

\* =  $p < .01$ .

### Estimates of Effect Magnitude

One way of estimating the magnitude of an effect is a measure of strength of association which can be thought of as a metric of the proportion of variance accounted for in the sample. A common descriptive measure of this is eta squared (Hays, 1981). The effect of Dimension on d-prime, beta and errors showed an eta squared of .56, .55 and .44, respectively. The effect of Test Hue on d-prime, beta and errors showed an eta squared of .23, .27 and .45, respectively. Finally, eta squareds for the Dimension by Test Hue interaction effect on d-prime, beta and errors are .31, .35 and .34, respectively.

Another estimate of strength of association is omega squared. This is an estimate of the population variance accounted for by the treatments of the ANOVA test statistic (Kirk, 1999). Cohen (1988) put forth guidelines for the interpretation of omega squared in which a omega squared of .01 indicates a small association, .06 indicates a medium or moderate association, and .14 indicates a large association. The effect of dimension on d-prime, beta and errors showed a omega squared of .54, .53 and .42, respectively. The effect of test hue on d-prime, beta and errors indicated a omega squared of .22, .26 and .44, respectively. Finally, omega squareds for the dimension by test hue interaction effect on d-prime, beta and errors were .29, .32 and .32, respectively. According to the guidelines described just above, all of these are considered quite large associations.

Another estimate of effect magnitude is the use of Cohen's (1988) concept of effect size. Cohen's estimate of effect size,  $d$ , categorizes effect sizes into small (0.2),

moderate (0.5) and large (0.8) effects. Other estimates of effect sizes exist which are comparable to Cohen's  $d$ . One of these  $d$ -like statistics appropriate for use with the ANOVA is Hedges'  $g$  statistic. The results of this statistic can be interpreted using Cohen's guidelines for  $d$  described above (Kirk, 1999). Hedges'  $g$  was calculated for the contrasts within the main effects of dimension and test hue and the dimension by test hue interaction. For  $d$ -prime, the average effect size (Hedges'  $g$  statistic) was .67 (.41, 1.01 and .60 for the individual significant comparisons) for the dimension main effect, and .54 for the test hue main effect (effect sizes were .59 and .49 for the two significant comparisons). For the dimension by test hue interaction as per the  $d$ -prime values, the average effect size was 1.13 (ranging from .53 to 2.25 across the 21 significant comparisons; see Table 13). These effect sizes are, on average, moderate to large.

For beta, the average effect size for the dimension main effect was .77 (.63, 1.15 and .52 for the individual comparisons) and .59 for the test hue main effect (.67 and .51 for the two significant comparisons). The dimension by test hue interaction for the beta values revealed an average effect size of 1.14 (ranging from .45 to 1.62 across the 18 significant comparisons; see Table 13). These effect sizes are also, on average, moderate to large effects.

For the error data, the dimension main effect revealed an average effect size of .67 (.48, 1.01 and .53 for the individual comparisons), and the test hue main effect indicated an average effect size of .69 (.52, .51 and 1.03 for the individual comparisons). The average effect size for the dimension by test hue interaction with regard to the error

Table 13

Effect Sizes (Hedges g) for Significant Comparisons of Dimension X Test Hue Interaction for d-prime, Beta and Errors Procedures.

Comparisons	Procedures		
	d-prime	Beta	Errors
O/H - O/S	ns	ns	0.80
O/H - O/L	0.92	1.28	1.61
O/H - B/H	ns	0.88	1.21
O/H - B/S	ns	1.31	1.72
O/H - B/L	0.68	1.46	1.31
O/H - G/H	0.94	ns	0.88
O/H - G/S	ns	1.57	2.13
O/H - G/L	ns	1.06	3.27
O/S - O/L	0.97	1.33	1.07
O/S - B/H	ns	0.92	0.70

Table 13, Cont d.

Effect Sizes (Hedges g) for Significant Comparisons of Dimension X Test Hue Interaction for d-prime, Beta and Errors Procedures.

Comparisons	Procedures		
	d-prime	Beta	Errors
O/S - B/S	ns	1.35	1.08
O/S - B/L	0.73	1.51	0.61
O/S - G/H	0.95	ns	ns
O/S - G/S	ns	1.62	ns
O/S - G/L	ns	1.10	2.46
O/L - B/H	0.83	ns	ns
O/L - B/S	0.66	ns	ns
O/L - B/L	ns	ns	ns
O/L - G/H	2.25	0.86	0.64
O/L - G/S	1.41	ns	ns

Table 13, Cont d.

Effect Sizes (Hedges g) for Significant Comparisons of Dimension X Test Hue Interaction for d-prime, Beta and Errors Procedures.

Comparisons	Procedures		
	d-prime	Beta	Errors
O/L - G/L	1.19	ns	0.96
B/H - B/S	ns	ns	ns
B/H - B/L	0.53	0.45	ns
B/H - G/H	1.74	ns	ns
B/H - G/S	ns	ns	ns
B/H - G/L	ns	ns	1.28
B/S - B/L	ns	ns	ns
B/S - G/H	1.98	0.89	0.59
B/S - G/S	0.91	ns	ns
B/S - G/L	0.72	ns	1.13

Table 13, Cont d.

Effect Sizes (Hedges g) for Significant Comparisons of Dimension X Test Hue Interaction for d-prime, Beta and Errors Procedures.

Comparisons	Procedures		
	d-prime	Beta	Errors
B/L - G/H	2.06	1.04	ns
B/L - G/S	1.13	ns	0.70
B/L - G/L	0.95	ns	1.73
G/H - G/S	1.28	1.15	0.78
G/H - G/L	0.88	0.66	1.72
G/S - G/L	ns	ns	1.04

Note: O = Orange Test Hue; B = Blue Test Hue; G = Green Test Hue; H = Hue Dimension; S = Saturation Dimension; L = Lightness Dimension.

data was 1.28 (ranging from .59 to 3.27 across the 23 significant comparisons; see Table 13). Again, these effects are, on average, moderate to large in size.

## Discussion

### Dimension

The main effect of dimension is consistent with the first hypothesis and previous literature. Errors were greatest for lightness comparisons, then saturation, and least for hue comparisons. Likewise, d-prime values (representing sensitivity) were least for lightness comparisons, then saturation, and greatest for hue comparisons (consistent with hypothesis 2).

However, this finding is tempered by the significant dimension by test hue interaction which indicates that, for errors, the effect was not present for the blue test trials and, for d-prime values, the effect of dimension was somewhat moderated in that all the dimensions were not different from one another across test trials. Specifically, for the orange test hue, d-prime was lowest for lightness, but hue and saturation conditions were not different from one another (although they were higher than lightness - as expected). Conversely, for the green test hue, hue conditions had the highest d-prime, but saturation and lightness trials were not different from one another (although they were lower than hue - as expected). For the blue test hue, d-primes for hue conditions were greater than lightness (as expected), however, saturation was not different from either hue or lightness conditions.

There were no manipulations of benefits and costs, so there were no hypotheses

made with regard to beta. The differences in beta, then, were due to whatever internal process(es) in the participants allowed for the adoption of a conservative or liberal response bias. There was a significant main effect for beta for dimension in that participants adopted a more conservative response bias for the hue conditions, less so for saturation (significantly), and also less so for lightness conditions.

Again, this main effect was moderated by the dimension by test hue interaction which indicates that the main effect of dimension on beta was due to the test hues green and orange which showed a substantial differentiation across dimension. Indeed, for the blue test hue, beta was not significantly different across test hues. Participants adopted a more conservative response bias for the green hue, orange hue and orange saturation conditions. Interestingly, these are the conditions with the fewest errors from the total errors procedure (which is expected with the adoption of a conservative criterion). It may be that these conditions were more easily accomplished and, therefore, participants adopted a more conservative response bias.

### Test Hue

Although no differences across test hue were hypothesized, they were found. For errors, the test hues were all significantly different from one another with errors being greatest for the green test hue, followed by blue and then the orange test hue. This is consistent with at least one other study that found that memory was worse for green than orange (Pérez-Carpinell, Baldovi, de Fez & Castro, 1998).

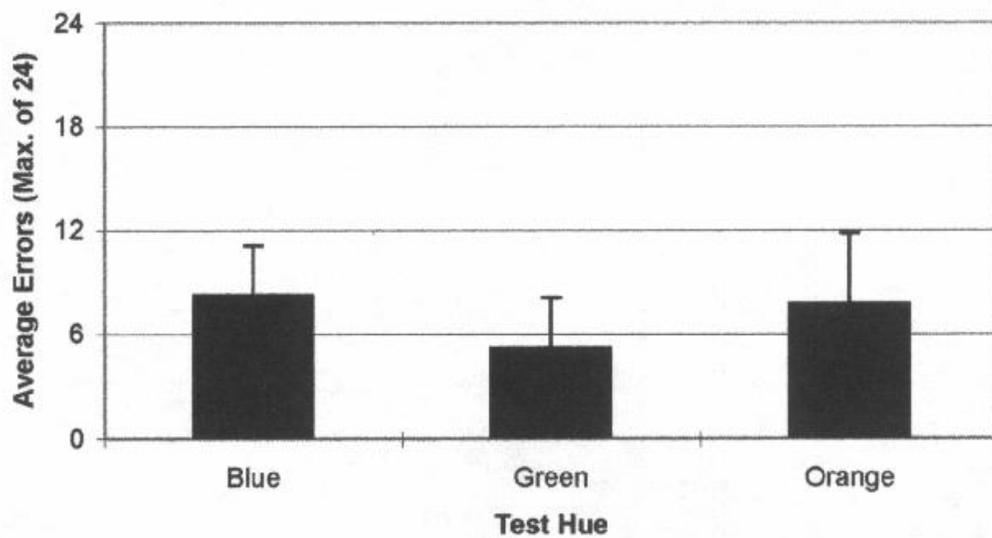
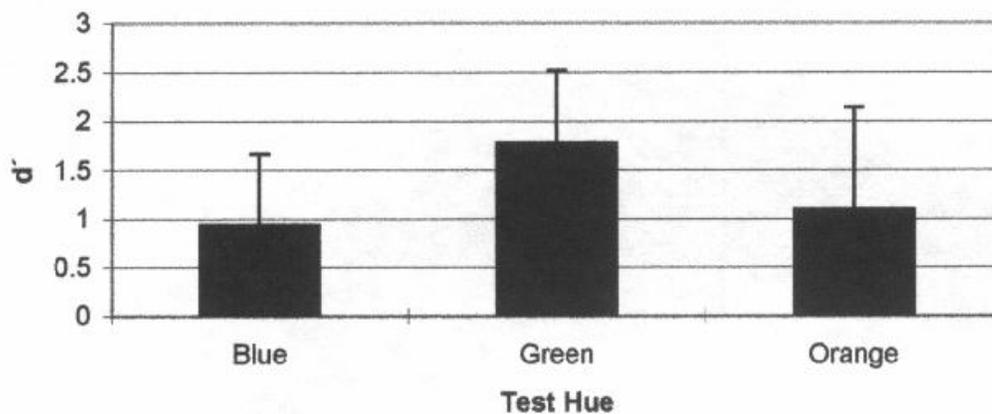
It is not unusual for studies of color memory to find differences due to hue, but

there is little to no consistency as to which hues are different. However, this main effect was also tempered by the dimension by test hue interaction which revealed that the preponderance of errors for the green test hue occurred under the lightness conditions, the lack of errors for orange is more pronounced under hue and saturation conditions, and for the blue test hue, errors were not significantly different across dimension. For  $d'$ , the green test hue had a significantly higher  $d'$  than blue or orange test hues. This was particularly true for the hue and lightness conditions as manifested by the dimension by test hue interaction.

It seems contradictory that the same green test hue which had the highest error rate would also have the highest  $d'$ . However, the total error procedure was different than the signal detection procedure and it would be interesting to know whether the contradiction of the green test hue is due to perceptual or procedural effects. To this end, errors were calculated from the signal detection procedure itself by defining an error as a false alarm or a miss. As can be seen in Figure 25, a comparison of the  $d'$  values and the errors calculated from the signal detection procedure alleviates the contradiction and leads to the conclusion that the source of the original contradiction is most likely procedural in nature. Test hue also had a significant effect on beta in that the orange test hue displayed a significantly higher beta than either blue or green test hues. This effect was more pronounced for hue and saturation trials as revealed by the dimension by test hue interaction.

### Reliability

**Figure 25. Comparison of  $d'$  Values and Errors Calculated From Signal Detection Procedure**



It can be concluded from the majority of non-significant reliability coefficients as per the signal detection procedure that either color memory is not reliable or that performance on the color memory task is not reliable. However, most of the reliability coefficients for the total errors procedure were significant (albeit moderate, at best) leading one to conclude that it is probably the procedure which is demonstrating the reliability rather than color memory skill itself (with the total errors procedure being more reliable than the signal detection procedure). If it were indeed the color memory skill itself displaying the reliability (or lack thereof), one would expect to see it regardless of task type.

### VVIQ

Overall, scores on the VVIQ were not correlated with performance on the color memory tasks (only the d-prime value for the blue hue task was moderately correlated [ $r = .35, p = .012$ ]). This is inconsistent with the two studies discussed which did find significant correlations with scores on the VVIQ (Heuer, et al., 1986; Reisberg, et al., 1986) and does not support hypotheses 3 or 4. This may be due to the differences in the nature of the color memory tasks or to the very lack of a relationship to begin with. There have only been two studies which have found relationships correlations between the VVIQ and performance on color memory tasks; and in those studies, the color memory tasks were embedded within a host of other tasks. Also, as seen in Figure 24, it appears that all participants in this study scored high on the VVIQ. Therefore, no low vividness imagers were assessed in this study. A general conclusion with regard to

imagery vividness and color memory cannot be made; however, within the confines of this study, no relationship was found.

### Interpretations and Implications

The hypothesis that d-prime would be less and more errors would be committed for lightness then saturation then hue was supported in this study, particularly for the test hues orange and green. This is consistent with previous research (Hamwi & Landis, 1955; Henderson, et al., 1971; Newall, et al., 1957). The neuroanatomical data suggest that lightness comparisons occur in the earlier visual processing stages of V1 and V2 (Zeki & Marini, 1998), and are probably performed by a separate mechanism than hue or saturation comparisons (Burns & Shepp, 1988; Mullen & Losada, 1994). Lightness judgements may also be due to Land's retinex algorithm which may be performed at area V4 with regard to color constancy (Zeki & Marini, 1998). Hue and saturation, however, are thought to be processed in terms of the types of spectrally opponent cells active (for hue) and the ratio of spectrally opponent cells to nonopponent cells active (for saturation) (DeValois & Jacobs, 1984). If such is the case, then memory for hue, saturation or lightness would entail the activation of these areas (along with the hippocampus, inferior temporal and inferior frontal lobes) in a reverberating circuit (Sokolov, 1993). In the case of hue, this circuit would be relatively simple involving the type of spectrally opponent cell (as per opponent process theory). For saturation, the circuit becomes slightly more complex considering not only the type of spectrally opponent cell, but the ratio of spectrally opponent to nonopponent cells also (including both opponent-process

and trichromatic theories). Finally, for lightness, the circuit would need to include the type of opponent cell, the ratio to nonopponent cells and the processing of lightness which, again, may be accomplished in V1 and V2 or due to the retinex algorithm, thought to possibly occur in V4. Given the potential differentiation of complexity of these neural circuits, it is no wonder that less sensitivity and more errors occur for lightness than saturation, than hue.

This study has implications for color vision theory, the use of computer displays in the investigation of color phenomena and environmental perception. It has been interpreted that memory is worse for lightness than saturation, then hue because of the complexity of neural circuits involved. This complexity also corresponds to various theories purported to describe color vision. The basis for memory for hue is a neural circuit involving the type of spectrally opponent cell which is consistent with opponent process theory. Perception and, thus memory, for saturation involves a ratio of opponent versus nonopponent cells which corresponds to both opponent process and trichromatic theories. Finally, memory for lightness involves the type of spectrally opponent cell, the ratio of opponent to nonopponent cells, and an even further analysis of lightness accomplished through the retinex algorithm of Land. Therefore, opponent-process, trichromatic and retinex theories are supported by these results. The basis for hue discrimination and memory is opponent-process theory (in terms of the type of spectrally opponent cell activated). The basis of saturation discrimination and memory is the both opponent-process and trichromatic theories (in terms of the ratio of opponent versus

nonopponent cells). Finally, the basis for lightness discrimination and memory is opponent-process, trichromatic and retinex theories (incorporating Land's [1964] retinex algorithm). The Ladd-Franklin theory is not applicable to these results and finds no support from them. However, this study was not designed to test the veracity of any of these theories of color vision. They are only being used as an effective mechanism for explanation and interpretation of these results. The opponent-process, trichromatic and retinex theories together provide the explanatory mechanism for these results without the inclusion of the Ladd-Franklin theory of color vision.

These results are also consistent with Sokolov's (1993;1998a) model of color memory. The excitation vectors and angles for hue memory are less complex (considering only two of the axes of the hypersphere [red-green and yellow-blue]). For lightness discrimination and memory, all four axes of the hypersphere must be considered (the above-mentioned axes plus the darkness and lightness axes). Finally, according to the Sokolov model, saturation discrimination and memory would rely on the computation of excitation vectors and angles lying along the surface of the hypersphere, thus, should be most difficult. These results indicate that, indeed, lightness and saturation are more difficult to remember accurately, but lightness is even more difficult than saturation which is inconsistent with Sokolov's model.

This study also leads to the recommendation of the use of a colorimeter to establish the CIE color coordinates for stimuli used in color research with computer displays. It was found that the DAC units displayed by programs designed to alter hue,

saturation and lightness dimensions are inaccurate. Individual computer monitors vary, but the recommendation is for at least one hour of warm-up time before displaying stimuli to participants for data collection purposes (as the monitor used in this study was determined to be stable after one hour).

Finally, the results of this study can be applied to environmental perception of color. The results of the one-week reliability of the color memory tasks suggests that studies assessing the perception of the color contained within environmental scenes need to make use of on-site or photosimulation procedures rather than having participants in such a study rely on biased memory. Furthermore, these procedures should be repeated with both the same and different observers.

Future research needs to make more use of fMRI technology during a color perception and color memory task to assess the similarities or differences in the brain regions activated during either the perception or memory task. It is anticipated that these areas will be similar across tasks (with the addition of areas associated with memory). Furthermore, the fMRI technology could assess different areas of brain activation for memory for hue versus saturation versus lightness to discriminate between the areas differentially activated by these various tasks. It would also be interesting to perform studies with regard to apparatus (computer displays versus Munsell chips), exposure time and delay, experience with color (artists versus non-artists), color preferences and practice. A study simply assessing the memory for colors in natural scenes would be instructive as to the implications for environmental perception, as well.

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Appendix A

Medical Screening Questionnaire

Medical Screening Questionnaire

Subject # \_\_\_\_\_

The following information is needed to screen for participation in the color memory study. We must know if you have had any medical problems which might interact with the study. It is important that you be as honest as you can.

1. Since birth have ever had any serious medical problems requiring hospitalization?

Circle one:    yes                      no                      if yes, please explain.

2. Have you ever hit your head and experienced a concussion?

Circle one:    yes                      no                      if yes, please explain.

3. Have you ever had any visual problems?

Circle one:    yes                      no                      if yes, what were/are they?

4. Do you currently have or have you ever had any of the following? Circle yes or no.

yes                      no                      diabetes

yes                      no                      neurological problems

yes                      no                      epilepsy or seizures

yes                      no                      brain disorder

yes                      no                      stroke

If you circled yes to any of the above conditions, please explain.

5. Have you ever been diagnosed formally to have had...

yes	no	learning deficiency or disorder
yes	no	reading deficiency or disorder
yes	no	attention deficit disorder
yes	no	hyperactivity

6. List any of the over-the-counter or prescription medications you are presently taking:

## Appendix B

### Vividness of Visual Imagery Questionnaire (VVIQ)

Vividness of Visual Imagery Questionnaire  
Form 1

For each of the following suggested images, please rate its vividness in your mind's eye as follows:

1. No image at all, you only know that you are thinking of the object
2. Vague and dim
3. Moderately clear and vivid
4. Clear and reasonably vivid
5. Perfectly clear and as vivid as normal vision

For items 1 - 4, think of some relative or friend who you frequently see (but who is not with you at present) and consider carefully the picture that comes before your mind's eye.

Item

- |    |   |   |   |   |   |   |
|----|---|---|---|---|---|---|
| 1. | The exact contour of face, head, shoulders and body.    | 1 | 2 | 3 | 4 | 5 |
| 2. | Characteristic poses of head, attitudes of body, etc.   | 1 | 2 | 3 | 4 | 5 |
| 3. | The precise carriage, length of step, etc., in walking. | 1 | 2 | 3 | 4 | 5 |
| 4. | The different colors worn in some familiar clothes.     | 1 | 2 | 3 | 4 | 5 |

Visualize a rising sun. Consider carefully the picture that comes before your mind's eye.

Item

- |    |  |   |   |   |   |   |
|----|--|---|---|---|---|---|
| 5. | The sun is rising above the horizon into a hazy sky. | 1 | 2 | 3 | 4 | 5 |
| 6. | The sky clears and surrounds the sun with blueness.  | 1 | 2 | 3 | 4 | 5 |
| 7. | Clouds. A storm blows up, with flashes of lightning. | 1 | 2 | 3 | 4 | 5 |
| 8. | A rainbow appears.                                   | 1 | 2 | 3 | 4 | 5 |

Think of the front of a shop which you often go to. Consider the picture that comes before you mind s eye.

Item

- |     |  |   |   |   |   |   |
|-----|--|---|---|---|---|---|
| 9.  | The overall appearance of the shop from the opposite side of the road.                           | 1 | 2 | 3 | 4 | 5 |
| 10. | A window display including colors, shapes and details of individual items for sale.              | 1 | 2 | 3 | 4 | 5 |
| 11. | You are near the entrance. The color, shape and details of the door.                             | 1 | 2 | 3 | 4 | 5 |
| 12. | You enter the shop and go to the counter. The counter assistant serves you. Money changes hands. | 1 | 2 | 3 | 4 | 5 |

Finally, think of a country scene which involves trees, mountains and a lake. Consider the picture that comes before your mind s eye.

Item

- |     |   |   |   |   |   |   |
|-----|---|---|---|---|---|---|
| 13. | The contours of the landscape.                                  | 1 | 2 | 3 | 4 | 5 |
| 14. | The color and shape of the trees.                               | 1 | 2 | 3 | 4 | 5 |
| 15. | The color and shape of the lake.                                | 1 | 2 | 3 | 4 | 5 |
| 16. | A strong wind blows on the trees and on the lake causing waves. | 1 | 2 | 3 | 4 | 5 |

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Ph.D.- Psychological Sciences, *Defended* January 2000  
Virginia Polytechnic Institute and State University  
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M.S. - Applied Experimental Psychology, 1990  
Virginia Polytechnic Institute and State University  
Blacksburg, VA

B.S. - Psychology, 1987  
Christopher Newport College  
Newport News, VA

**Positions Held**

**Adjunct Instructor** (January 1999 - May 1999)  
- Concord College, Athens, West Virginia:  
**Courses Taught:**  
-Introductory/General Psychology

**Graduate Instructor** (January 1999 - May 1999)  
- Virginia Polytechnic Institute and State University,  
Blacksburg, VA.  
**Courses Taught:**  
-Animal Behavior

**Adjunct Instructor** (August 1998 - December 1998)  
- Concord College, Athens, West Virginia:  
**Courses Taught:**  
-Introductory/General Psychology (2 sections)

**Full-time, Restricted, Faculty Instructor** (January 1998 - May 1998)  
- Concord College, Athens, West Virginia:  
**Courses Taught:**  
-Learning and Behavior (2 sections with laboratory)  
-Introductory/General Psychology (2 sections)

**Adjunct Instructor** (August 1997 - December 1997)

- Concord College, Athens, West Virginia:

**Courses Taught:**

- Animal Behavior
- Introductory/General Psychology (2 sections)

**Full-time, Restricted, Faculty Instructor** (September 1996 - July 1997)

- Christopher Newport University, Newport News, VA:

**Courses Taught:**

- Introductory/General Psychology (3 sections)
- Experimental Psychology I (2 sections with laboratory)
- Experimental Psychology II (Advanced-with laboratory)
- Senior Seminar in Environmental Psychology
- Sensation and Perception (with laboratory)
- Coordinator for the Directed Research Program  
Coordinated undergraduate research for credit. Included mentoring, assisting with organization, and overseeing process. Also, coordinated with other departmental faculty members who were mentoring students.
- Other duties included academic advising of students, establishment and implementation of the undergraduate research participation for extra credit system (along with another faculty member). Attended faculty meetings and functions.

**Adjunct Instructor** (January 1996 - August 1996)

- Christopher Newport University, Newport News, VA:

**Courses Taught:**

- Introductory/General Psychology
- Experimental Psychology (with laboratory)

**Full-time, One Semester, Faculty Instructor** (January 1991 - May 1991)

- Mary Washington College, Fredericksburg, VA.

**Courses Taught:**

- History and Systems of Psychology (2 sections)
- Sensation and Perception (with laboratory)
- Other duties included the assistance of other professors in the supervision of independent studies, assistance with upper-level students

in the preparation of senior research projects, attending (on a limited basis) faculty meetings and functions.

**Adjunct Instructor** (August 1990 - December 1990)

- Thomas Nelson Community College, Hampton, VA.

**Courses Taught:**

- General Psychology (2 sections)
- Applied Psychology

**Adjunct Instructor** (May 1990 - August 1990)

- Virginia Polytechnic Institute and State University, Blacksburg, VA.

**Courses Taught:**

- Sensation and Perception (with laboratory)

**Adjunct Instructor** (January 1990 - May 1990)

- New River Community College, Dublin, VA.

**Courses Taught:**

- General Psychology (2 sections)

**Teaching Assistant** (September 1987 - January 1990)

- Virginia Polytechnic Institute and State University, Blacksburg, VA.

Assisted professors with various courses including Introductory Psychology, Sensation and Perception, and History and Systems. Duties included teaching the laboratory sections of Introductory Psychology and Sensation and Perception, assisting the professor with the construction of tests, and substituting as lecturer when needed.

**Advanced Graduate Coursework**

- |  |                               |
|--|-------------------------------|
| -Research Methods                          | -Biological Bases of Behavior |
| -Learning                                  | -Advanced Statistics (I & II) |
| -Community Psychology                      | -Developmental Psychology     |
| -Information Processing                    | -Hypnosis                     |
| -Social/Personality Psyc                   | -Behavioral Management of     |
| -Advanced Sensory Processes                | Large Scale Systems           |
| -Psychophysiology                          | -Basic Neurochemistry (AUD)   |
| -Neurocognition (AUD)                      |                               |
| -30 hours of Research/Thesis credits       |                               |
| -45 hours of Research/Dissertation credits |                               |

### **Research Activities (Consulting)**

- Completed environmental perception study in Calhoun, TN for Bowater Southern Paper Co., 1990
- Completed environmental perception study in NC and TN for Champion Paper Co., 1998
- In the process of submitting environmental perception research for publication.

### **Publications and Presentations**

Prestrude, A. M., & Laws, E. L. (1988, September 2). Photosimulation study of the scenic impact of treated papermill effluent on the appearance of a riverscape. Paper presented to the 11th European Conference on Visual Perception, Bristol, England.

Prestrude, A. M., & Laws, E. L. (1989, January 20). Bowater Hiwassee River Project. Bowater Southern Paper Co., Calhoun, TN.

Laws, E. L., & Prestrude, A. M. (1989, March 22-25). Magnitude estimation and the evaluation of scenic beauty impact of industry on riverscapes. Paper presented at the Southeastern Psychological Association, Washington, DC.

Laws, E. L. (1990, April). The effect of instructions on scenic beauty ratings of riverscapes and the prediction of those ratings by environmental questionnaires. Unpublished Masters Thesis, Virginia Polytechnic Institute and State University.

Prestrude, A. M., Laws, E. L., & McMurry, D. K. (1991, April 9). Hiwassee River Color Perception Study. Paper presented at the 1991 TAPPI Environmental Conference, San Antonio, TX.

Prestrude, A. M., Laws, E. L., & Cherry, D. (1999). Pigeon River Color Study: Technical Report.

**Other Skills**

- Computer literate for word processing and statistical analyses (SPSS, SAS, etc.)
- Excellent scientific writing skills
- Trained in the analysis and data acquisition of MRI, fMRI, EEG and ERP methods
- Powerpoint projection classroom technology.

**References Available on Request**