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Identification of category boundaries and intergroup discrepancies in color perception

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Identification of category boundaries and

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Abstract

Past research has suggested that language plays a role in the perception of color. To address this claim, two studies were conducted intended to achieve two primary goals: First, to develop a test capable of identifying categorical boundaries in color perception without the use of linguistic references, and second, to demonstrate that the test is capable of identifying differences in subjective perceptions of color between groups, should subjective perceptual differences exist. Two studies compared participants with normal, and with color deficient vision. Results indicated that the newly developed research method is capable of identifying significant perceptual differences in categorical color perception between groups with different subjective impressions of color.

Color perception presents an intriguing puzzle for researchers in cognitive psychology. Generally speaking, the hardware enabling color perception in human beings is essentially identical for everyone with normally functioning visual systems. Humans are equipped with photoreceptors adapted to respond to the color spectrum, and portions of the brain higher in the sequence of visual processing provide the subjective experience of actually perceiving color. Despite this fact, the question of exactly what the subjective experience of color is for each individual remains a mystery. Further, at the present time, there are no investigative processes available with which to solve this mystery. Most individuals with normally functioning color vision systems can agree that grass is green, the sky is blue, and tomatoes are red, but this still says nothing about the actual experience of seeing "green", "blue", or "red".

Inquiry into the subjective qualities of color perception provided the impetus for Young and Helmholtz's trichromatic theory of color vision as well as for Hering's opponent-process theory, both developed well before physiological evidence was available to validate the theories (Helmholtz, 1852; Hering, 1878, 1905, 1964; Young, 1802). However, despite technological advances for studying the physiological components of the visual system, many questions involving color vision remain unanswered. Included in these questions are issues of the universality of color vision, how much agreement exists between wavelengths and hues, and how exactly colors are categorized.

Past research on color perception found that individuals in most cultures perceive colors in a similar fashion (Berlin & Kay, 1969). For example, despite variations in the terminology used to identify colors, individuals from most cultures agree on which hues represent the "best" green, "best" red, "best" blue, etc. (Berlin & Kay, 1969). If however, differences in color perception between various groups or cultures are identified, the question of interest is how these differences have come about. Factors spanning the entire spectrum of possibilities, from genetic makeup to linguistic evolution, potentially underlie the observed differences. In order to properly address these differences, the exact nature of the differences must be identified. It is in this respect that the research proposed here aims to aid in understanding color perception. By properly identifying the areas of the visible color spectrum where various groups differ in their perceptual experiences, detailed attention can be directed to the structures and processes potentially responsible for the differences.

Theories of Color Vision

Color vision has intrigued philosophers and scientists for thousands of years and has been a formal subject of interest in the scientific world since the 1800's. Three early vision researchers, Thomas Young (1773-1829), Hermann von Helmholtz (1821-1894), and Ewald Hering (1834-1918), proposed the first formal theories of color vision based on psychophysical data nearly a century before physiological methods were developed to provide evidence for the theories.

The first of the theories, the trichromatic theory of color vision, suggested that color vision is dependent upon three different receptor mechanisms, each highly sensitive to different portions of the visible color spectrum (Young, 1802; Helmholtz, 1852). The theory states that because each receptor is stimulated differently at any given intensity and wavelength of light, unique patterns of firing in the nervous system result in perception of particular colors that correspond to particular wavelengths. To test the theory, Helmholtz used a color-matching task in which participants were required to adjust the amounts of three different wavelengths of light, such that the resulting color matched the color of a preset test field of light. Helmholtz concluded that because this matching task could be completed with no less than three separate wavelengths, human color perception must be achieved through the use of no less or more than three different types of color receptor. Not until the 1960's were researchers able to verify the claims of Young and Helmholtz, when the absorption spectra of three separate pigments in the cones were identified (Brown & Wald, 1964). The three pigments displayed maximum absorption of electromagnetic waves at 419nm, 531nm, and 558nm, corresponding to short, medium, and long wavelength regions of the visible light spectrum. Some time later, researchers working at Stanford University identified the gene sequences coding for the proteins of the three different cone pigments (Nathans, Thomas, & Hogness, 1986). The identification of these gene sequences provided the researchers with evidence that the different cone pigments contained opsin molecules comprised of disparate amino acid chains, causing the pigments to have differing absorption spectra.

Another early theory attempting to explain color vision was Hering's opponent-process theory (Hering, 1878, 1905, 1964). Hering argued that the Young-Helmholtz theory was an inadequate model of color perception because of its internal inconsistency. His arguments were based on phenomenological observations, positing that the subjective impression one has of yellow cannot be reduced to a mixture of red and green, as was implied by the Young-Helmholtz theory. According to Hering's opponent-process theory, the visual system contains three opposing mechanisms for identifying color. Each of the mechanisms corresponds to one set of the following pairs: black/white, red/green, and blue/yellow. According to the theory, the opponent-process mechanisms are excited by light from one member of the pair and inhibited by light from the other. Hering's ideas were also prompted, in part, by the phenomenological observation of opposing afterimages. For example, if the color red is presented to an area of the visual field for a short period of time, when removed, the area previously occupied by red appears green. Conversely, when the initial image is green, the afterimage appears red. The same relationship holds for the pairs of blue/yellow and black/white.

Although intuitively accurate, Hering's theory was not widely accepted until the middle of the 20th century, when researchers began identifying opponent neurons in the lateral geniculate nucleus (LGN) that responded differentially to wavelengths from opposite ends of the visible light spectrum (DeValois, 1960; Svaetichin, 1956). Through an increased understanding of the visual system at the cellular level, researchers were able to explain the opponent-processes of color vision by means of lateral inhibition. Through lateral inhibition, neurons at later stages of the visual pathway are able to excite or inhibit the activity of neighboring neurons, and do so based on the input being received at the retinal level. The resulting effect of this opponent process is an increased ability to discriminate between wavelengths that might otherwise appear relatively similar when using only cone vision.

For nearly half a century, Young and Helmholtz's trichromatic theory and Hering's opponent-process theory were regarded as competing theories. It seemed improbable that the two theories, albeit both very plausible, could both be correct. It was only after significant advancements in the area of physiological research that the issue was resolved. As tends to be the case when two competing theories have substantial amounts of supporting evidence, the best explanation for the phenomenon typically results from a synthesis of the two theories. It is now generally accepted that both theories are in fact correct. The Young-Helmholtz trichromatic theory accurately describes the necessary components of color vision at the retinal level—the earliest stage of the visual system. The Hering opponent-process theory describes activity occurring at a later stage in visual processing, after the visual signals have reached the LGN.

Deficiencies in Color Vision

Once the components of a correctly working visual system were known, the causes of observed color deficiencies in the human visual system were easier to isolate. The most common forms of deficiency in color vision are a result of improperly functioning cone receptors. More precisely, individuals with deficient color vision typically have one or more cone receptor types absent, or have one or more cone receptor types with an abnormal visual pigment (Goldstein, 2002).

Among the earliest methods for diagnosing deficiencies in color perception was the same color-matching task Helmholtz had used to support the trichromatic theory of color vision. If an individual was capable of providing what he or she perceived as a match to a test field of light using only two wavelengths of light rather than three, this provided a strong indication that the individual was missing at least one type of photopigment. Based on this procedure, three types of color deficiency were identified. Monochromatism, the most severe form, is the result of an absence of two, or more often, all three types of functioning cone receptors. Monochromats with no functioning cone cells are the only color deficient group that can truly be considered "color-blind". Because monochromats with no functioning cone types use exclusively rod vision, they are very sensitive to light, and have very poor visual acuity, even in foveal vision. Dichromatism, the most commonly diagnosed form of color deficiency, results from the absence of one of the three types of visual pigments (Jacobs, 1993). Depending on which pigment and corresponding cone is impaired, dichromatism can be classified into one of the three following categories: Protanopia, a deficiency representing missing pigment in the long-wavelength cones; Deuteranopia, a deficiency representing missing pigment in the medium-wavelength cones; and Tritanopia, a deficiency believed to represent missing pigment in the short-wavelength cones (Goldstein, 2002; Nathans et al., 1986). The final form of color deficiency is termed anomalous trichromatism and results not from a missing cone pigment, but rather from a shift in the peak absorption spectra of the medium and long wavelength cones (Neitz, Neitz, & Jacobs, 1991). In anomalous trichromatism, the maximum absorption spectra of the long wavelength cones is shifted towards that of the medium wavelength cones, or the maximum absorption spectra of the medium wavelength cones is shifted towards that of the long wavelength cones.

Attempting to imagine the visual environment as it appears to individuals possessing deficiencies in color vision is a difficult task. Many perception textbooks display what the authors believe to be the subjective experience of color for individuals with color vision deficiencies, but it is difficult to gauge the accuracy of the demonstrations. Authors with normal color vision can speculate based on the known absorption spectra of color deficient systems, but because individuals with color vision deficiencies have no referent for comparison, there is no objective way to determine if the illustrations accurately reflect the subjective experience of deficient color vision.

Prevalence of Color Vision Deficiencies

From an evolutionary perspective, color vision is important for acquiring food, selecting mates, avoiding predators, identifying environmental indicators of danger, as well as a myriad of other tasks (Zegura, 1997). Because of the importance of color vision, it might be expected that few individuals in the population would exhibit deficiencies in color vision. In fact, only approximately 6-8% of the population experience deficiencies in color vision, and because the gene sequence coding for the most common forms of color deficiency, anomalous trichromatism and dichromatism, are carried on the X chromosome, the vast majority of those with deficiencies are male (Boynton, 1979; Goldstein, 2002; Nathans et al., 1986).

Identification of the exact areas of the color spectrum where the subjective perception of color differs between individuals with deficient color vision and individuals with normal color vision holds practical applicability in a number of ways. If a test can accurately identify differences in the subjective perception of color between groups with known physiological differences in visual systems—individuals with normal or deficient color vision in this case—the same test should theoretically be capable of identifying differences in subjective color perception between groups with no known physiological differences, should subjective differences in perception between those groups exist. The identification of differences in the subjective perception of color between individuals with normal and color deficient vision is one of the primary goals of the present research. The method by which this difference will be examined, as well as the implications of the findings, will be discussed in greater detail later in the manuscript.

Color Perception Research

In the past 40 years, color perception has been investigated from the perspectives of psychology, physiology, and anthropology. Among the most enduring and influential of the research is Brent Berlin and Paul Kay's widely cited anthropological study entitled, *Basic Color Terms: Their Universality and Evolution* (1969). Berlin and Kay developed interest in the universality of color terms because of the apparent ease with which basic color terms were translated between many different languages. At the time that they were developing their study, the prevailing thought among professionals in the field was that language divided color space in an arbitrary fashion and that language affected the way in which those who spoke the language perceived colors (Hardin & Maffi, 1997). Berlin and Kay (1969) proposed a method by which they would identify basic color terms as separate from the non-basic or secondary color terms, followed by a task designed to locate the "best" examples of colors within the basic color categories. Basic color terms, According to the Berlin and Kay (1969), were those terms that were general and salient. General referred to the idea that the term for a particular color could not be described as a subset of any other color, and salient referred to the availability and usage of the color term in the vernacular of a wide cross-section of languages. To identify the "best" examples of the basic colors, participants were instructed to choose from a display of color tiles the most representative example of a color that had been identified as a "basic" color. Finally, participants were instructed to indicate the regions of the Munsell space that could be accurately classified as containing each of the "basic" colors. If a high level of consensus between cultures was observed, the researchers felt that they would then be able to argue that color categorization was not based on linguistic constraints. The original Berlin and Kay study included participants representing 20 different languages who were from loci as diverse as Tahiti and Mesoamerica.

Berlin and Kay (1969) reached two major conclusions regarding cross-cultural perception of color. First, among the languages studied, and presumably among all languages, there can be as few as two, and as many as 11 basic color terms. However, for all humans, regardless of the number of available color terms, there exist 11 basic perceptual color categories. Second, across all languages, there is a fixed pattern of color term acquisition that can be considered an evolutionary pattern. The 11 color terms enter a language as perceptual categories in the following order: black and white; red; green, blue, and yellow; brown; purple, pink, orange, and gray.

Since the publication of *Basic Color Terms*, it has been determined that the color term “gray” may appear in the languages of many cultures at an earlier stage (Kay, Berlin, Maffi, & Merrifield, 1997). Cultures with relatively few basic color terms tend to be less technologically advanced, whereas cultures with all 11 basic color terms are nearly always technologically and culturally advanced (Berlin & Kay, 1969). Based on their findings, Berlin and Kay presented a strong case for the idea that color perception was not shaped by language as had been previously believed. In fact, they argued that the inverse was true, that language for describing color followed a predictable pattern of acquisition based on inherent properties of the visual system, and that this pattern was essentially ubiquitous among all human cultures.

Since the publication of *Basic Color Terms*, a substantial amount of criticism has been leveled at Berlin and Kay regarding the methods by which they collected their data. Among the most serious of the criticisms of Berlin and Kay are the following: a) participants from only 20 languages is not enough to warrant universal generalizability; b) the data for the original study were collected at the University of California Berkeley rather than in the cultures from which the participants had originated; c) many of the participants spoke English in addition to their native language; d) for many of the languages, only three or fewer participants were used; and e) the researchers conducting the interviews were rarely fluent in the native languages of the participants (Kay et al., 1997).

In response to these criticisms, and in an attempt to develop a broader empirical basis for the conclusions of Berlin and Kay, the World Color Survey (WCS) was launched in 1976. In addition to addressing criticisms of the Berlin and Kay study, the intent of the WCS was to clarify issues of universality in color categorization and acquisition of basic color naming (Kay et al., 1997). Because the WCS was modeled after the original work of Berlin and Kay, the methodology only deviated in the areas that had been heavily criticized. The WCS collected data from participants of 110 different languages, at the actual locations where the languages were spoken. At least 25 people from each language participated, and individuals who spoke only the native language were used as often as possible. A final deviation from the original Berlin and Kay work involved presenting only one Munsell color chip at a time while determining the "best" example of a basic color category.

The conclusions of the WCS are in many ways analogous to the conclusions of the original Berlin and Kay study. The differences in the conclusions of the two studies lie primarily in the classification of the evolutionary stages of the basic color naming systems. As mentioned earlier, data from the WCS indicated that the original evolutionary naming sequence outlined by Berlin and Kay (1969), which had the six primary colors identified by Hering (red/green, blue/yellow, white/black) appearing before any secondary colors, required a provision allowing for the early appearance of gray (Kay, Berlin, & Merrifield, 1991). Aside from changes in the sequence of basic color term acquisition, the WCS did little to alter the conclusions of Berlin and Kay's original study. Most importantly, the WCS applied more sound methodology and the findings of Berlin and Kay (1969) were replicated.

More recently, due to significant advancements in physiological science, a number of researchers have begun questioning the conclusions of Berlin and Kay and the WCS. In a series of studies published in *Nature*, researchers building off of the work of Neitz et al. (1991) concluded that the genetic components underlying normal color vision are not truly universal, as was suggested by Berlin and Kay (Merbs & Nathans, 1992; Winderickx, Lindsey, Sanocki, Teller, Motulsky, & Deeb, 1992). The studies claim to have identified an amino acid responsible for the development of cone pigments that appeared in one form in roughly 60% of their sample and another form in the remaining 40%. As a result of the polymorphism, the majority of their sample had long-wavelength cones with maximum absorption spectra of 557nm, whereas the remaining participants displayed maximum absorption in the long-wavelength cones at 552nm (Merbs & Nathans, 1992). The discrepancy in the maximum absorption spectra was sufficient to account for a noticeable difference in the color matching results between the groups. Given these findings, it seems plausible to suggest that this particular polymorphism may contribute to the relatively high prevalence of anomalous trichromatism. However, it is possible that individuals with shifted peak absorption spectra resulting from the polymorphism are not identified as anomalous trichromats. If the prevalence of this genetic variation is as high as Merbs and Nathans (1992) suggested, it is likely that some of the variance in color term agreement among individuals with "normal" color vision can be explained via physiological differences.

Perceptual Categorization Research

Following the publication of *Basic Color Terms,* a number of researchers attempted to replicate the identification of the "basic" colors, as defined by Berlin and Kay. Corbett and Davies (1997) suggested that new tests developed to identify the "basic" color terms are predicated upon three goals. The first goal is the development of a test capable of distinguishing between basic and non-basic colors. Second, the test must be capable of distinguishing among the basic colors after they have been separated from the non-basic colors. Finally, the test must be capable of identifying regular patterns in the ordering of the appearance of the basic terms. Interestingly, the standard by which many researchers judge new methods of determining the "basic" colors is the degree to which data collected via the new test matches data collected via the methods of Berlin and Kay (1969).

Some of the more recent methods for identifying color categories across cultures employ behavioral as well as linguistic measures. Behavioral measures for determining basic color categories include reaction time measures for naming colors, measures of how frequently a color word is used in a naming experiment or in an experiment asking participants to list as many different colors as possible, and measures of how consistently color terms are used in everyday speech. Traditional linguistic measures, such as those used by Berlin and Kay (1969), include frequency of occurrence of color terms in texts and the number of derived forms of color terms available in the language (Corbett & Davies, 1997). Because one of the goals of the present study is to identify categorical boundaries in the color spectrum, possibly providing a corresponding measure of basic color terms, a review of some of the basic literature on categorization research is necessary.

In addition to the research attempting to identify basic color terms, there is an abundance of research investigating the more general task of categorizing stimuli that are naturally represented by a continuum, rather than as discrete parts.

Consider, for example, the fact that humans with normal color vision see light of particular wavelengths as particular colors. There is nothing “red” about electromagnetic waves 630 nm in length or “blue” about waves 460 nm in length. The phenomenological experience of seeing the color “red” is merely the mechanism by which the perceptual system indicates that light of a particular wavelength is present in the visual environment. The visual system interprets a continuous variable—the visible light spectrum—as comprised of individual categories, namely red, orange, yellow, green, blue, and violet. Color represents just one continuous variable perceived as being composed of individual categories by the perceptual system. Other examples include phonemic sounds, spatial relations used in structural descriptions of objects, and even positions of parts of the face used to identify facial expressions.

Theories of how the human perceptual system divides continuous variables into phenomenological categories typically fall into three categories: naturalistic theories, perceptual change theories, and labeling theories (Pilling, Wiggett, Özgen, & Davies, 2003). Naturalistic theories view categorical perception as a hard-wired perceptual phenomenon mediated by the perceptual systems whereby a uniform physical continuum is broken into distinct components representing separate categories (Bornstein, 1987; Snowden, 1987). The apparent ability of animals and infants to identify categorical boundaries within continuous variables supports the naturalistic contention that categorical perception is hard-wired (Bornstein, Kessen, & Weiskopf, 1976; Davies & Franklin, 2002; Franklin & Davies, 2002; Gerhardstein, Renner, & Rovee-Collier, 1999). Perceptual change theories suggest that categorical perception effects are acquired rather than inherent in the nervous system (Pilling et al., 2003). Finally, labeling theories posit that when discriminating among stimuli that naturally fall on a continuum, it is verbal labels rather than perceptual systems that mediate the task (Pilling et al., 2003). Labeling theories, in general, suggest that because stimuli within a category share a label, and stimuli crossing category boundaries have different labels, that the verbal system is responsible for categorization effects.

Although there is an abundance of support for a naturalistic explanation of categorical perception, including the results of Berlin and Kay (1969), Roberson and Davidoff (2000) found evidence for the labeling theory of categorical perception. In their study, participants were briefly presented with a color swatch of varying shades of blue or green, followed by an interference task that could be either verbal or visual in nature. Following the interference task, participants were presented with two additional color swatches and were instructed to choose from the two alternatives the color that most closely matched the initially presented swatch. The colors of the two alternatives were blue and green, blue and blue, or green and green. The authors argued that, because performance was hindered more by the verbal interference task than by the visual interference task, categorical perception was mediated by the verbal labeling of the colors. In a near replication of Roberson and Davidoff (2000), Pilling et al. (2003) obtained similar results, but they were careful to state in the discussion that a pure labeling theory of categorical perception was not supported by the results of either study. Their reasoning was that in both studies participants were required to keep the initially presented color in memory during the interference task, before deciding which of two later presented alternative choices most closely matched the initially presented color. Thus, the categorical comparison was between a perceptual stimulus and a stimulus held in working memory, rather than between two perceptual stimuli. In other words, the design of the experiment was inadequate for providing support to a pure labeling theory of categorical perception. It comes as no surprise, given the experimental design of Roberson and Davidoff (2000) and Pilling et al. (2003), that the label of the color played an important role in participants' ability to discriminate between similar color categories.

In an effort to demonstrate the existence of categorical perception for color with no need for linguistic mediation, the proposed study will not require participants to store colors in working memory before making category judgments. If categorical perception for colors is observed with no utilization of memory or the labels needed for storage in memory, the results will support a naturalistic view of categorical perception. The conclusions of Berlin and Kay (1969) and the WCS have not been replicated using a purely perceptual test—that is, a test free of linguistic constraints—and thus the possibility that language exerts an influence on color perception remains. It is in this regard that the research presented here aims to supplement the current literature on categorical perception of color.

Present Study

The goals of the presented research were twofold: First, to demonstrate that categorical boundaries in color perception could be identified with no reference to verbal labels, and second, to provide a method for determining whether groups varying on dimensions affecting subjective perception of color actually perceive colors in subjectively different ways. Experiment 1 was designed to test both of these goals, whereas Experiment 2 was designed to replicate the results of Experiment 1 with the inclusion of verbal labels, as well as to control for variable categorization strategies.

Experiment 1

The first experiment was designed to identify the categorical boundaries between the basic colors on the visible color spectrum: red, orange, yellow, green, blue, and purple. Participants with both normal and deficient color vision were included to determine whether the test was capable of identifying areas of the color spectrum where groups with differing perceptual abilities perceive subjectively different colors. The task for the participants was to choose which of two alternative color squares most closely matched a referent color square in terms of hue. The referent color square was a color located between the two alternative colors on the color spectrum. The two alternative colors were always adjacent to one another on the color spectrum. For example, if the two alternative colors were green and blue, the referent color was some shade of green or blue located between the two on the color spectrum. For an example, see Figure 1.

Figure 1

Figure 1. Sample stimulus from Experiment 1. Participants' task was to choose which of the two side alternative colors most closely matched the center (referent) color in terms of hue.

The logic of the experiment suggests that the point at which participants choose either alternative 50% of the time (the transition point) represents the categorical boundary between the two alternative colors. Supposing that this boundary exists as a perceptual category independent of the purely physical aspects of the stimuli (i.e. the literal amount of blue or green in the referent color), the transition point will not necessarily correspond to the literal center point between the two colors. In other words, if perceptual categorization of the referent color in this experiment is based only on the relative contributions of the hues in the referent color rather than on perceptual categories inherent in the visual system, the point at which an observer should say that the referent matched either of the two alternatives is the point at which the referent is composed of 50% of each of the colors. For example, in Experiment 1, the hue values (in Adobe Photoshop) for the basic colors green and blue were 120° and 240° respectively. If no perceptual category exists separating green and blue, the expected transition point where participants switch from choosing the green alternative as more similar to the referent than the blue alternative, should be at 180°. A transition point at any position other than the physical center between the two alternative colors supports a naturalistic explanation of color categorization due to the fact that the categorization is based not on physical distance from the alternative colors, but on some perceptual category inherent in the visual system.

The inclusion of participants with deficient color vision provides a method for determining whether the experimental design is capable of identifying differences in subjective color perception between groups with known differences in color perception. Differences in the mean color category transition points between participants with normal color vision and participants with deficient color vision will provide support for the capability of the proposed design to identify differences in subjective color perception between any two groups with potentially dissimilar subjective impressions of color.

Method

Participants

Participants were undergraduate students Iowa State University. Of the 22 participants, 15 had normal color vision (5 males, 10 females), and 7 had deficient color vision (6 males, 1 female). Participants with normal vision (hereafter referred to as normal) were given class credit in return for their participation, and participants with deficient vision (hereafter referred to as deficient) were paid $20 for their participation. The color vision abilities of all participants were tested using software for detecting color vision deficiencies purchased from *Visual Mill™.* All participants' were first tested using a Pseudo-Isochromatic color palate (similar to an Ishihara palate) presented via computer. If deficiencies in color vision were identified, participants then completed the Munsell-Farnsworth 100-Hue color vision test for a more complete diagnosis. Participants were classified as having normal color vision if they made no mistakes on the Pseudo-Isochromatic color palate test. All participants classified as having deficient color vision displayed weak to very poor red-green color discrimination along a deuteran (red-green) axis.

Apparatus

Experimental stimuli were presented on a Macintosh 17-inch LCD display, powered by a Macintosh G4 desktop computer. Responses were recorded via two keys on a standard Macintosh keyboard. Programming, stimuli presentation, and data collection were executed via Superlab v. 1.77. Stimuli were created using Adobe Photoshop 7.0. Each stimulus occupied a visual angle 26.3° horizontally and 5.7° vertically, and consisted of three colored squares, each occupying 5.7° x 5.7° of visual angle, evenly spaced and vertically centered on the monitor (see Figure 1). The colors of the referent (center) squares were created by holding both the brightness and saturation constant at a maximum value of 100 while systematically increasing the hue by three degrees, beginning with zero, on the Photoshop color wheel. The referent square was presented in 120 different hues. The comparison colors were the exemplars of the referent colors that best represented the "basic" colors of red, orange, yellow, green, blue, and purple. The Photoshop hue values of the "basic" referent colors were 0° for red, 27° for orange, 63° for yellow, 120° for green, 240° for blue, and 279° for purple. The values for red, green, and blue represented the levels at which neither of the other two primary colors contributed to the hue. The values for orange, yellow, and purple were chosen based on a pilot study in which participants were presented with 12 equally spaced examples of each of the three colors, and were instructed to select the "best" example of the respective color. This method is similar to the method employed by Berlin and Kay (1969) for determining the "best" examples of the 11 basic colors identified in their study.

Procedure

Prior to beginning the experiment, each participant's color vision was tested. Following color vision testing, participants were seated at the computer and given instructions on the experimental task. Instructions indicated that upon being presented with three blocks of color, the participants' task was to choose which of the two alternative colors presented on the sides of the screen was "most similar in terms of hue" to the color block presented in the center of the screen. If the color block on the right was perceived as most similar to the center color block, participants were instructed to press the "/" key, which is on the right side of the keyboard. If the color block on the left was perceived as most similar to the center color block, participants were instructed to press the "z" key, which is on the left side of the keyboard. Participants pressed the same key to go on to the next trial. Trials were self-paced.

Each block consisted of 756 trials, made from six presentations of each of the 126 possible trial combinations (120 referent colors with 6 colors repeated so that the "best" instance of a color, green for example, served as an alternative color choice for comparisons between yellow and green, and green and blue). Each referent color was presented three times with the larger (in terms of Photoshop color wheel degrees) color alternative choice on the right, and three times with the larger color alternative choice on the left. All 756 trials within each block were completely randomized. Participants each completed four blocks. One block took approximately 20 minutes to complete.

Results

Due to the large number of data points collected, the design of the experiment was quite powerful. To avoid the possibility of making a Type I error in the analyses, all hypotheses were tested at $\alpha = .01$ with two tails. The points at which participants' mean responses crossed 50% were interpreted as the perceptual boundary between two adjacent colors. This boundary indicated the point at which participants' perception of the referent color "switched" from the belonging to the category of the smaller color of the comparison pair to belonging to the category of the larger color of the pair (e.g. green to blue, or blue to purple). To determine the perceptual transition points for each participant, the mean responses to the color angles surrounding the point at which response tendencies equaled 50% were used to linearly interpolate the exact angle at which each participants' responses crossed the 50% mark. The perceptual transition points for all participants in each group, normal and deficient, were then pooled to determine the mean perceptual transition point between each color pair for each group. The mean values were then compared using a between subjects t-test to determine if the perceptual transition points varied reliably between the two groups. The results are summarized in Table 1 and presented graphically in Figure 2.

Table 1.

50% Perceptual Transition Points Between Colors (in terms of Photoshop Degrees) for Experiment 1

Color Comparison	Normal Vision Means (Standard Error)	Deficient Vision Means (Standard Error)
Red-Orange	16.3 (0.58)	17.1 (0.89)
Orange-Yellow	46.8 (0.8)	48.6 (0.81)
Yellow-Green	77.7 (0.57)	78.5 (1.6)
Green-Blue**	163.6 (1.45)	177.9 (3.77)
Blue-Purple**	265.3 (0.8)	270.6 (1.51)
Purple-Red	322.8 (1.66)	330.3 (1.37)

Table 1. Mean transition points between colors for participants with normal color vision (center column), and for participants with deficient color vision (right column). Significant differences between means are indicated by asterisks (**=p<.01).

Figure 2.

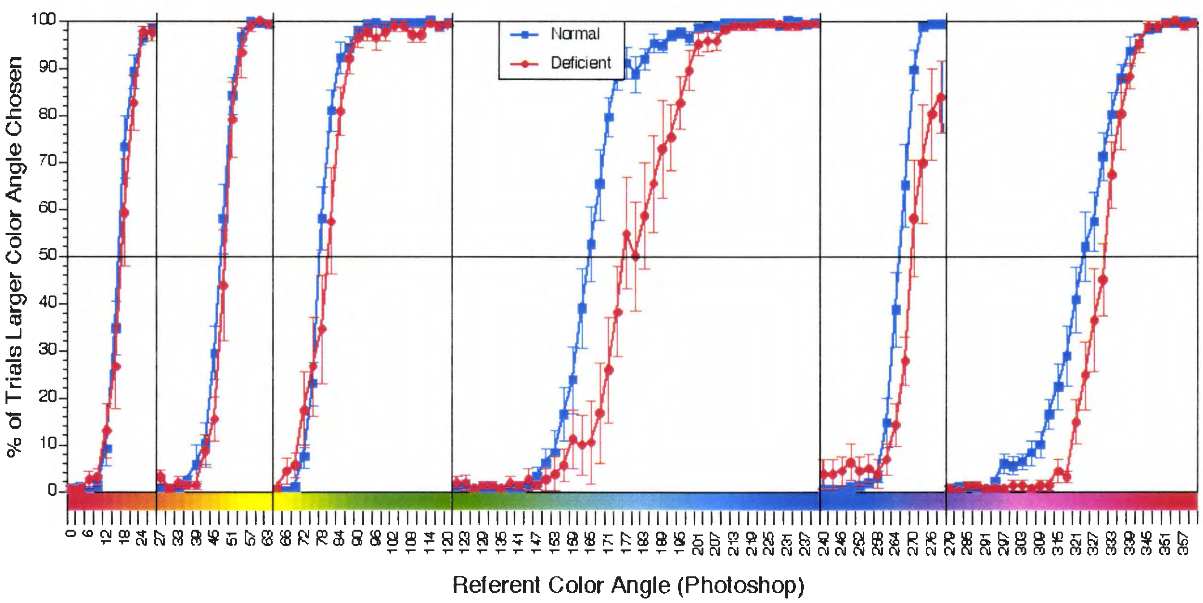

Figure 2. Results from Experiment 1. Curved lines represent response patterns of normal and deficient participants for each color comparison (R-O, O-Y, Y-G, G-B, B-P, and P-R). Perceptual transition points between colors (from Table 1) are represented by the points at which the horizontal 50% line intersects curved lines.

Comparisons between normal and deficient participants for the perceptual transition points between red-orange, orange-yellow, yellow-green, and purple-red yielded no significant differences. However, the mean perceptual transition point between green-blue was significantly different between the normal participants (M = 163.62, SD = 5.62) and deficient participants (M = 177.89, SD = 9.98), $t(20) = 4.322$, $p<.01$, as was the perceptual transition point between blue-purple for normal participants (M = 265.29, SD = 3.10) and deficient participants (M = 270.64, SD = 3.99), $t(20) = 3.44$, $p<.01$.

Discussion

The first goal of Experiment 1 was to identify perceptual boundaries between adjacent colors on the color spectrum with no reference to verbal labels. The second goal of Experiment 1 was to demonstrate that the method by which the boundaries were identified was capable of indicating where on the color spectrum two groups with differing color abilities perceived subjectively different impressions of color. Based on the results of the first experiment, both goals appear to have been achieved.

No color labels were used in generating the data, and the response patterns of the participants clearly indicate the areas of the color spectrum where perceptual boundaries are perceived between adjacent colors. Responses were simply choices reflecting comparisons among three stimuli that differed in hue. As predicted, the boundaries between colors often do not correspond with the center of the physical hue distance between the two basic comparison colors. Because of this, the argument can be made that the perceptual system is not using a simple rule by which colors are categorized by the relative level of basic hues comprising the color, but rather they are categorized by a shift in the perceptual quality of the color that does not correspond to the point at which a color consists of 50% of two adjacent colors.

Further, the data from the deficient participants demonstrate that the method used in Experiment 1 is capable of identifying differences in the subjective impression of color between groups with different perceptual abilities. The implications of this finding will be expanded in the General Discussion.

Although the procedure did not require the use of verbal labels, the results of Experiment 1 do not rule out the possibility that participants were using verbal labels to categorize the referent colors. Participants may have adopted a strategy by which they first silently named the referent color, and then decided to which of the two basic color alternatives the referent color belonged. While this naming strategy would not have affected identification of differences in subjective impressions of color between groups, it may have indicated inaccurate transition points between color categories. It is possible that the colors chosen as the basic color alternatives in Experiment 1 did not match participants' conceptions of red, orange, yellow, green, blue, or purple. If this were the case, some participants may have been comparing the referent color to a stored representation of the colors "blue", or "green" for instance, before making a response, whereas others may have been comparing the referent color to the physical stimuli presented on the screen before making a response. To test this possibility, a second experiment was conducted utilizing the same paradigm, with the exception of replacement of the two basic color alternatives with the actual names of the basic colors, printed in black. If no reliable differences were identified between the results of Experiment 1 and Experiment 2, the possibility of the results having been influenced by a silent naming strategy or incorrect selection of basic color alternatives would be ruled out.

Experiment 2

The purpose of Experiment 2 was to determine whether the use of the actual color names (labels) in place of the two side alternative color squares would yield results significantly different from those of Experiment 1. The design of Experiment 2 was identical to that of Experiment 1 except for the replacement of the alternative color choices with *names* of colors rather than examples of the actual colors. (See Figure 3 for an example.)

Figure 3.

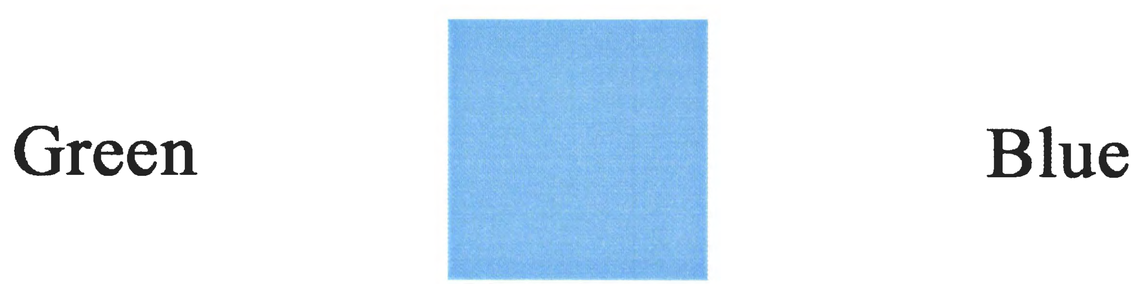

Figure 3. Sample stimulus from Experiment 2. As in Experiment 1, the task was to choose which of the two side alternative choices that the center (referent) color square most closely matched.

Method

Participants

All participants from Experiment 1 participated in Experiment 2. No new participants were included. Participants with normal vision were given class credit in return for their participation, and participants with deficient vision were paid $20 for their participation.

Apparatus

The apparatus used in Experiment 2 was identical to those of Experiment 1, with the exception of the altered stimuli previously discussed (see Figure 3).

Procedure

Because the participants' color vision was tested during Experiment 1, it was not tested again during Experiment 2. Aside from this difference, the procedure and number of trials in Experiment 2 were identical to that of Experiment 1.

Results

All hypotheses were tested at α = .01 with two tails. To assess the perceptual transition points for each participant (the points at which participants' mean responses crossed 50%), the mean responses to the color angles surrounding the point at which response tendencies equaled 50% were used to interpolate the exact angle at which each participant perceived the referent color as belonging to either surrounding category color 50% of the time. The perceptual transition points for all participants in each group, normal and deficient, were then pooled to determine the mean perceptual transition point between each color pair for each group. The mean values were then compared using a between subjects t-test to determine if the perceptual transition points varied reliably between the two groups. The results are summarized in Table 2 and presented graphically in Figure 4.

Table 2.

50% Perceptual Transition Points Between Colors (in terms of Photoshop Degrees) for Experiment 2

Color Comparison	Normal Vision Means (Standard Error)	Deficient Vision Means (Standard Error)
Red-Orange	12.1 (1.16)	15.6 (1.6)
Orange-Yellow	46.8 (1.49)	52.2 (1.26)
Yellow-Green	75.0 (0.98)	79.0 (1.57)
Green-Blue**	164.6 (1.28)	181.5 (4.65)
Blue-Purple	263.1 (1.09)	267.5 (2.51)
Purple-Red**	325.3 (2.02)	340.7 (2.54)

Table 2. Mean transition points between colors for participants with normal color vision (center column), and for participants with deficient color vision (right column). Significant differences between means are indicated by asterisks (**=p<.01).

Figure 4.

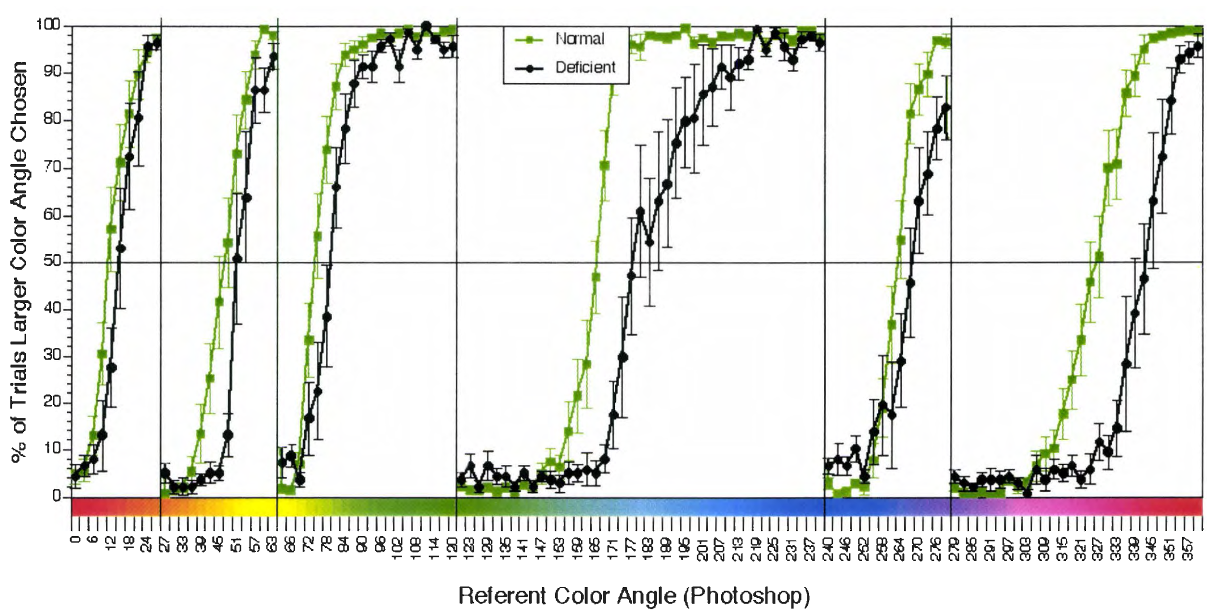

Figure 4. Results from Experiment 2. Curved lines represent response patterns of normal and deficient participants for each color comparison (R-O, O-Y, Y-G, G-B, B-P, and P-R). Perceptual transition points between colors (from Table 2) are represented by the points at which the horizontal 50% line intersects curved lines.

Comparisons between normal and deficient participants for the perceptual transition points between red and orange, orange and yellow, yellow and green, and blue and purple yielded no reliable differences. Significant differences were obtained however for the green-blue transition between normal participants ($M = 164.56$, $SD = 4.95$), and deficient participants ($M = 181.54$, $SD = 12.31$), $t(20) = 3.52$, $p<.01$, and for the purple-red transition between normal participants ($M = 325.30$, $SD = 7.83$) and deficient participants ($M = 340.74$, $SD = 6.71$), $t(20) = 4.492$, $p<.01$.

Because the objective of Experiment 2 was to determine whether the use of color labels altered the between-color categorical boundaries identified in Experiment 1, the results from the normal vision participants from Experiments 1 and 2 were also compared to one another. Because the normal vision participants were the same for both Experiments 1 and 2, a within subjects t-test was used to identify any significant differences in response patterns. For the within subjects t-test, $\alpha = .01$ with two tails. The results are summarized in Table 3 and are presented graphically in Figure 5.

Table 3.

50% Perceptual Transition Points for Normal Vision Participants in Experiments 1 & 2

Color Comparison	Experiment 1 Means (Standard Error)	Experiment 2 Means (Standard Error)
Red-Orange**	16.3 (0.58)	12.1 (1.16)
Orange-Yellow	46.8 (0.8)	46.8 (1.49)
Yellow-Green	77.7 (0.57)	75.0 (0.98)
Green-Blue	163.6 (1.45)	164.6 (1.28)
Blue-Purple	265.3 (0.8)	263.1 (1.09)
Purple-Red	322.8 (1.66)	325.3 (2.02)

Table 3. Mean transition points between colors for participants with normal color vision in Experiment 1 (center column), and for participants with normal color vision in Experiment 2 (right column). Significant differences between means are indicated by asterisks (**=p<.01).

Figure 5.

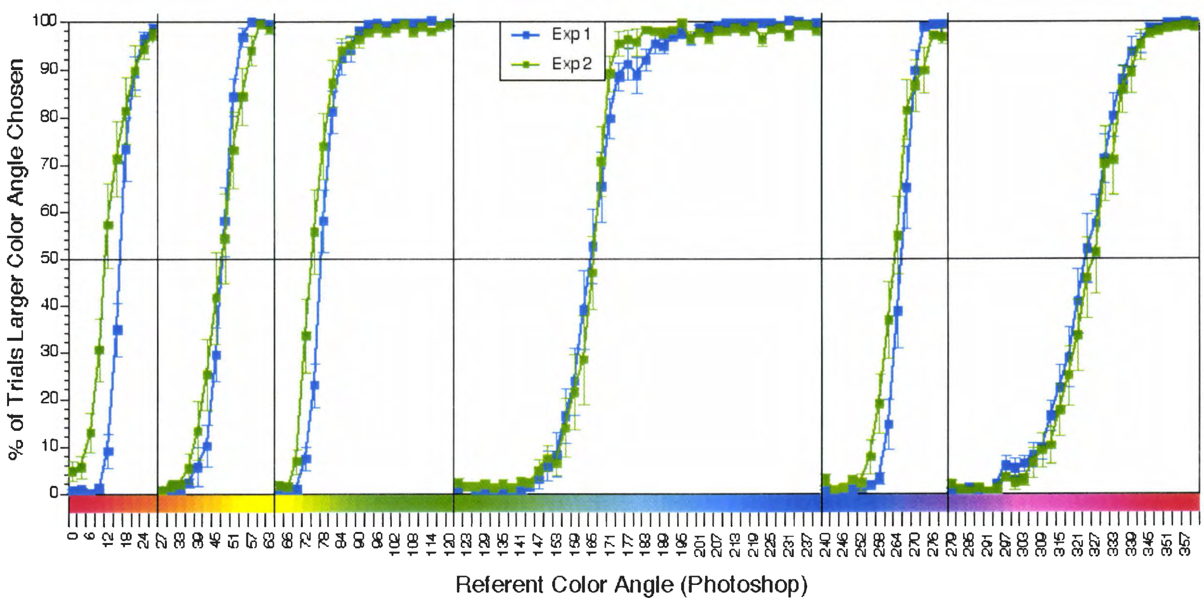

Figure 5. Comparison of results for normal vision participants in Experiments 1 (blue) and 2 (green). Despite differing tasks, the response patterns and perceptual transition points between colors for both experiments are very similar.

A within-subjects t-test conducted on the normal vision participants' data in both experiments revealed no reliable differences between the perceptual transition points of orange-yellow, yellow-green, green-blue, blue-purple, or purple-red between the two experiments. However, for the normal vision participants, a significant difference was revealed in the 50% transition point of red-orange between Experiment 1 ($M = 16.26$, $SD = 2.23$) and Experiment 2 ($M = 12.10$, $SD = 4.51$), $t(14) = 4.00$, $p<.01$.

Discussion

The objective of Experiment 2 was to determine whether substituting color names for actual colors would alter participants' color categorization strategies. In regards to the normal versus deficient participants, the data indicate that replacing actual colors with color labels does little, if anything, to improve the ability of deficient participants to categorize colors in a manner consistent with that of normal participants. Because of the fact that color labels do not reduce the intergroup discrimination capabilities of the experimental design, the original goal for Experiment 1 of developing a test for identifying intergroup differences in subjective color perception is further supported by the results of Experiment 2.

In addition, it appears that substituting color names for actual colors did little to alter participants' perception of categorical boundaries between colors. Aside from the red-orange boundary, there are no significant differences in normal participants' perceptual transition points between Experiments 1 and 2. The discrepancy in the location of the red-orange boundary between Experiments 1 and 2 is likely due to poor selection of the basic orange used as a comparison color in

Experiment 1. Based on the data, it appears that the particular hue of orange selected for use as a comparison color in Experiment 1 was too yellow, and needs to be shifted towards red for a more accurate representation of the color orange. Additional testing will be required to determine the exact cause for the discrepant red-orange boundary among normal participants between Experiments 1 and 2.

General Discussion

The goals of the present research were twofold. One goal was to provide a method for determining categorical boundaries between adjacent colors on the color spectrum with no reference to color labels. Insofar as the method represents a measure that can be administered to any individual regardless of language abilities, meaning that there is no need to know the name of a single color to properly complete the test, it would seem that the first goal has been achieved. In essence, the method used in Experiment 1 provides a way of determining where an individual, or a group of individuals, perceive the boundaries between colors to exist, regardless of whether those boundaries have been influenced by linguistic constraints. In fact, this versatility ties directly into the second goal of the current research, namely the goal of providing a quantitative measure of whether different groups perceive colors in qualitatively different ways.

The method of Experiment 1 provides a way to test whether or not different groups (cultures, genders, races, ages) experience subjectively different impressions of color. The results of both Experiments 1 and 2 demonstrate the ability of the research design to identify areas of the color spectrum where groups with different subjective perceptions of color differ from one another. The results of both experiments indicate that individuals with deficient color vision have subjectively different impressions of some colors than do individuals with normal color vision. For example, the color that appears to individuals with normal vision to be composed of equal parts of green and blue (the green-blue perceptual transition point) appears to individuals with deficient color vision to be composed almost entirely of green.

Because the method presented here has proven capable of identifying differences in color perception between groups known to differ in color perception, it holds the promise of identifying any intergroup differences in color perception, whether they are based on physiological factors, cultural factors, or any other factor that may potentially influence color perception. For example, the individuals described by Merbs and Nathans (1992) with genetically shifted maximum absorption spectra of the long wavelength cones could easily be tested using the current method to determine whether the polymorphism underlying the absorption shift creates a subjective impression of color different from that of normal vision individuals.

Because this test can be administered quickly, easily, and without reference to color names, it provides an ideal method for testing color perception across cultures and language barriers. By administering Experiment 1 via any laptop containing an Adobe Photoshop program that has been calibrated to match the colors of the screen used to collect the reference data, cross-cultural color analyses can be conducted with great efficiency and great ease. Further, the method of Experiment 1, because it does not require reference to or knowledge of color labels, could even be used to test color perception differences across species. With relative ease, researchers working with lab animals capable of being trained to discriminate between two alternatives could implement a design of this type into a study aimed at identifying differences in color perception across species.

The future of color perception research holds the promise of determining exactly how much influence, if any, factors other than physiology play in the subjective perception of color. Although the results of the current study cannot completely rule out the influence of language on the perception of categorical boundaries in color, they do provide a valuable new tool for providing support to naturalistic theories proposed by researchers such as Berlin and Kay (1969). For example, if language does influence color perception, cultures at different points in the evolution of basic color terms should display disparate results on the task of Experiment 1 presented in the current study. If, on the other hand, language has very little or no influence on color perception, cultures at all stages of color term evolution should theoretically display nearly identical results on a replication of Experiment 1.

Perhaps there are many factors influencing the subjective perception of color of which we are not yet aware. However, we are now equipped with a test for determining whether there are in fact perceptual differences to be studied, and if so, at which areas of the color spectrum perceptual systems are most susceptible to altering influences.

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