Perceived Lightness/Darkness and Warmth/Coolness in Chromatic Experience

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Abstract

There are widespread beliefs that red, orange, and yellow are warm colors while blue, green, and purple are cool. In addition, some colors, like yellow, are said to be lighter than others, such as blue. The present study investigated how the psychological dimensions of hue, saturation and lightness contribute to these distinctions, and attempted to relate ratings of these attributes to the Opponent Process Theory. Subjects rated colored chips from the Natural Color System atlas for their warmth/coolness or lightness/darkness. Increases in the percentage of saturation in a color produced warmer ratings with the specific amount of increase depending on the hue. Changes in lightness did not significantly affect warmth/coolness ratings. Increases in saturation and in blackness both produced darker ratings, but the size of the increase in ratings depended on the hue. In addition, hues associated with longer wavelengths were rated as warmer than those associated with shorter wavelengths, while hue had no significant effects on ratings of lightness/darkness. Furthermore, higher ratings of warmth were found to correspond with opponent channel activation in one direction, while lower ratings corresponded with activation in the opposite direction. This suggests that warmth ratings may be associated with the low-level physiological processes involved in color perception, rather than with the psychological dimension of hue, and that the attribution of thermal properties to colors may be more than simply a cognitive process.

Introduction

Since the time of the early Greeks, philosophers, artists, and scientists have been fascinated with color. While the earliest writings on color assume a philosophical view as to color's origin, subsequent research examined the physical properties of light and, eventually, the physiological mechanisms responsible for the sensation of color. Although much is now known about the quantitative dimensions of color and its perception, little is known about the qualitative aspects, specifically the emotional and evaluative responses that color evokes. This study addresses two of these reactions: the attribution of thermal properties to color and the categorization of colors as light or dark.

Wavelengths of light between approximately 400 and 700 nm comprise the visible spectrum, with wavelengths near 400 nm appearing purple and those around 700 nm appearing primarily red. The color that is associated most closely with variations in wavelength is the hue. Together with the other psychological components of color; saturation, brightness, and lightness; hue is used to describe the variations seen in different colors. Saturation refers to the percentage of hue in a color, or how pure the color is.

A red color with increasing amounts of white light added to it becomes more and more desaturated, resulting in a pinkish color. Brightness is the psychological correlate of the intensity of a light and refers to how bright or dim the color appears to be. The fourth variable, lightness, refers to the reflectance ratio of the apparent amount of light a surface reflects relative to surrounding surfaces. A colored surface that reflects more light than the surrounding surfaces will appear lighter than the other surfaces. Each of these four psychological attributes, hue, saturation, lightness, and brightness, are used in the description of color. However, color appears to be more than simply a psychological translation of light rays, often affecting human perception of the environment. Yet its exact effects are not known. Although results from studies of the effects of color on physiological variables such as heart rate, galvanic skin response, and body temperature are inconsistent (Fanger, Breum & Jerking, 1977; Jacobs & Hustmeyer, 1974; Ruggieri & Petruzziello, 1988; Wilson, 1966), data from studies of the evaluative effects are much more consistent. Although we now have a much greater understanding of how the perception of color occurs physiologically, we do not know how the affective results of that perception arise.

Warmth/Coolness

The attribution of warmth or coolness to a particular color is very common. Evans (1948) notes, “To the average observer it is reasonable to describe all colors from pure yellow through orange and red to and including the red magentas as warm colors, whereas all colors from greenish yellow through green cyan, and blue to bluish magentas as ‘cold’” (pp. 180-181). The warm-cool distinction has been extensively followed by artists who use specific color combinations to convey the thermal effect they desire. Denman Waldo Ross (1919, cited in Sloane, 1991), an American painter who wrote about color and drawing, explained, “Considering the different colors produced by pigments and pigment-mixtures we feel that some of them are relatively Hot (H) and others relatively Cold (C)...” (p. 89). He felt that red-orange is the hottest color, while green-blue is the coldest. Before discussing the warm/cool distinction further it is necessary to clarify what is meant when a color is described as warm or cool. Newhall (1941) explains that there are two kinds of warmth and coolness in relation to colors: emotional warmth and thermal warmth. A color can merely appear emotionally warm or cool, or it can actually evoke an affective response. Alternatively, it can actually change the perceived temperature of a surface or the surroundings, or it can merely appear to contain thermal properties. While various studies have addressed these different aspects of the warmth or coolness of colors, the present study examines whether colors appear to contain thermal properties. Empirical evidence has supported the philosophical distinction between warm and cool colors. Newhall (1941) presented his subjects with a chart on which was mounted a series of colored samples in the shape of a ring and asked them to select the warmest and coolest hues. Although the range of hues ranked as coolest was very large, red was clearly ranked as the warmest color.

Additional support for the distinction between warm and cool hues was given by Berry (1961) who investigated whether a subject's judgment of the ambient temperature in a room is affected by the hue of the environment. Subjects were placed in a room illuminated by a green, blue, yellow, amber, or white light and were instructed to tell the experimenter when the room temperature became uncomfortably warm. Whereas no significant differences in tolerated temperature as a function of color were found, when subjects were later asked to rate samples of these colors according to the amount of heat they transmitted, green and blue were ranked significantly cooler than yellow and amber. Similar results were obtained by Lewinski (1938), who placed subjects in a room illuminated with red, yellow, purple, orange, blue, or green lights and asked them to rate the warmth or coolness of the color. Red was rated the warmest, followed by orange, yellow, purple, green, and blue. However, these results are difficult to interpret since saturation, brightness, and lightness were not controlled in either experiment. Although Berry (1961) attempted to equate the colors for brightness, he apparently equated only their luminances. Since the luminance efficiency curves for brightness and luminance are not equivalent (if green and violet are equated for luminance than placed side by side, the violet will appear brighter) we cannot assume that brightness was properly controlled and, therefore, cannot discard the possibility that saturation, brightness, and lightness may have an effect on judgments of warmth. This concern is validated by Ross (1938) who projected lights of different wavelengths on a screen and asked subjects to rate the saturation, brightness, and temperature, among other characteristics, of the colors they saw. While his subjects tended to rate lights of long wavelengths as warm and those of short wavelengths as cool, his results also indicated that subjects associated lights of high brightness and saturation with heat. However, he argued that although brightness and saturation were related to temperature ratings, hue is the most important factor.

This conclusion was supported by Wright (1962), who emphasized that a major shortcoming of previous studies of the warmth and coolness of colors was the failure to address the perceptual dimensions of color other than hue. He asked subjects to rate one of 45 Munsell chips varying in hue, lightness, and saturation for its warmth or coolness, then examined the independent effects of these three variables using a partial regression analysis. He concluded that while lightness and saturation each exerted minor effects on warmth/coolness ratings, there was a well-defined effect of hue on these ratings. He claimed that his results suggest that as hue progresses from red to blue, ratings should become progressively cooler. Additionally, he claimed that the effects of lightness and saturation in his study "correspond in direction with the implications of previous work" (p. 238), which indicate that ratings of warmth correspond with higher levels of saturation and darkness. While he makes these conclusions regarding hue, saturation, and lightness, Wright presents no data or other results which allow this interpretation. Furthermore, while he recognizes the need to control for differences in lightness and saturation when evaluating warmth/coolness responses, he failed to conduct his study under controlled conditions; his stimuli were presented in daylight, an illumination other than that under which the Munsell system was calibrated. Thus, while he may have assumed that his samples were equated for saturation and lightness, by using the wrong illuminant he could not guarantee that this was so. As a result, their independent effects are not so easily analyzed.

While several studies have shown that we do separate colors into warm and cool, it is not yet fully understood how this distinction arose. One possible explanation for the attribution of warmth and coolness to colors is the association of these colors with sources of physical warmth (Optical Society of America [OSA], 1963), such as sunlight and fire for the warm colors and water for the cool colors (De Grandis, 1984). Another association was presented by Von Bezold (1876) who suggested that the coolness of blue arises from the association with the bluish reflected light from the sky on cold and cloudy days. The association hypothesis was supported by Newhall (1941) who asked his subjects to also explain their choice of warmest and coolest hues. Most of his subjects reported that the colors reminded them of objects and conditions which have thermal properties. On the other hand, Tatibana (1937) attempted to reduce the effects of these associations on warmth/coolness ratings by asking subjects to name the colors that best typified the adjectives of warm and cool using intuitional judgments rather than associations. He found that even with this restriction, the warm colors ranged from red to yellow, and that blue was most frequently named as cold. However, judgments of warmth or coolness also varied with the tint or shade of the color, indicating that lightness and saturation also affect these evaluations. While his results supported the differences between warm and cool colors observed in other studies, Tatibana (1937) concluded that his results did not support association as the explanation of this effect. Of course, despite the fact that Tatibana asked subjects not to use associations, he could not control whether or not they obeyed. The mere mention of associations as a way of rating colors' warmth may have induced subjects to use them, or at least to be unable to inhibit them. Thus, whether or not association is responsible for warmth/coolness judgments is still unclear.

Although studies such as those discussed have shown that we do ascribe thermal properties to colors, Evans (1948) noted that, as of 1948, to the best of his knowledge, no studies had addressed the extent to which the associations of different colors with different temperatures are "true perceptions" (p. 181). In other words, to what degree is color the effect, rather than the cause, of the emotional or physiological reactions associated with a color. Four and a half decades later, it appears that no work has yet been done.

Lightness/Darkness

Another aspect of color that is often alluded to is the separation of hues into light and dark. In much of the early literature the terms lightness and brightness are used interchangeably; only recently has emphasis been placed on their distinction since they are, in fact, two separate qualities. Therefore, in this paper, when citing a source that used one term when the other was intended the correct term is included in brackets.

While some argue that lightness is a relative term and applies only when comparing colors, others have suggested that it is an intrinsic characteristic of color. In the late 1870's Hering (1874/1964) wrote in his Outline of a Theory of the Light Sense: "Just as white is intrinsically a light visual quality and black in itself a dark one, I also think yellow is intrinsically a light visual quality and blue in itself is a dark one." (p. 63). Hering (1905/1964) felt that the colors yellow and red had an "intrinsic [lightness]" while blue and green had "intrinsic darkness". He claimed that if the blueness aspect of a blue color were to be removed, the color would become lighter, while if the yellowness of a yellow disappeared, it would become darker. According to Hering (1905/1964) every color has its own level of [lightness] or darkness, and that whichever predominates determines whether we call it a dark or a light color. Unfortunately Hering passed away before he was able to do more than make these initial observations.

Von Bezold (1876), too, made reference to the distinction between light and dark colors. "[Light and dark] are sometimes applied to differences noticeable between different hues. Thus we speak of blue as a dark color, of yellow as a light color." (p. 100).

In an attempt to systematize the relations between colors Hay (1845, cited in Sloane, 1991), a nineteenth-century color theorist, assigned to colors numerical values representing the proportion in which light and dark are found in each color. His lightness to darkness ratio for yellow is 3 to 1, while in blue it is 1 to 3, suggesting that blue is darker than yellow. Despite these theoretical references concerning the difference between light and dark colors, it appears that there are no data supporting these perceptual distinctions. De Grandis (1984) explains that yellow appears to be the [lightest] color because the spectral structure of the light it reflects is the closest to white, while violet, the nearest to black, is the least [light], but he does not cite any research supporting this statement. It is possible that these distinctions apply only for colors of particular saturations or intensities, but these variables are not mentioned in any of the statements concerning light and dark colors. Would a bright desaturated blue become lighter than a dim saturated yellow, or is the light-dark distinction based solely on the difference in hue?

Hering's Opponent Process Theory

The Opponent Process Theory, put forth by Hering (1905/1964), is based on the phenomenological aspects of color. Hering (1905/1964) noted that in addition to the four primary chromatic colors of the color circle, red, yellow, green, and blue, we also distinguish the intermediate hues of red-yellow, yellow-green, green-blue, and blue-red. However, there is no series of red-green or yellow-blue intermediate hues. That is, red and green are never seen together in a color, nor are blue and yellow. Hering (1905/1964) noted that "... redness and greenness as well as yellowness and blueness are mutually exclusive" (p. 49). This observation led him to postulate that the four primaries were opposed in two neural processes, one which signaled the presence of red or green and the other the presence of blue or yellow. A third process, an achromatic channel of black-white, was also suggested. With the support of physiological studies showing that different wavelengths can cause both excitatory and inhibitory responses in cells in the retina and the lateral geniculate nucleus (e.g., De Valois et al., 1964), Hering's theory has been widely accepted as the model for color appearance.

Although the Opponent Process Theory is generally complete in accounting for hue sensations, there is nothing inherent in the model that addresses the contrasting light-dark and warm-cool dimensions, Hering's earlier statement concerning light and dark colors notwithstanding. The purpose of the present study is twofold: firstly, to determine whether the judgments of lightness/darkness and warmth/coolness are reliable. That is, will a hue with a specific lightness, and saturation be given the same value of lightness/darkness or warmth/coolness by all observers? While Newhall's (1941) results concerning the attribution of warmth and coolness to colors appear to be the most reliable, no controls were made for differences in saturation and lightness, and their effects cannot be discounted. Furthermore, he presented his subjects with all stimuli at once, allowing comparison between colors before choosing the warmest and coolest ones. The present study investigates whether different hues convey warmth or coolness in the absence of other hues to which they could be compared. That is, is warmth or coolness an intrinsic characteristic of color, or do these qualities apply only in particular conditions? The second purpose of this experiment is to examine the basic attributes of chromatic experience, hue, saturation, and lightness, in an attempt to discover which are responsible for the perceptual judgments of lightness/darkness and warmth/coolness, and to relate these assessments to the underlying physiology of the Opponent Process Theory.

The Natural Color System

In addition to his formulation of the Opponent Process Theory, Hering (1905/1964) also postulated a systematic ordering of colors based on their phenomenological aspects, which he termed the natural color system. Hering recognized that the physical attributes of color are not translated linearly into psychological attributes. For example, a given increase in a light's intensity will not necessarily result in a similar increase in its brightness. In addition, the same physical stimuli can produce different color sensations depending on the surrounding conditions while quite different physical stimuli often produce identical color sensations. Thus, Hering formulated an ordering system based not on the physical properties of light, but rather on the resulting sensations of color. His system relies on the premise that any color can be described as resembling the six elementary colors: red, yellow, green, blue, black, and white. These colors are elementary because they cannot be described as a combination of any other colors. That is, unlike a color such as orange which can be said to possess red and yellow components, the elementary colors cannot be broken down any further.

Hering's ideas eventually gave rise to the Swedish Natural Color System (NCS) in which color space is established phenomenologically by defining each color according to its resemblance to the elementary hues. The NCS color space can be described as a combination of a color circle and a color triangle for each hue (See Figure 1). The four chromatic elementary hues (R=red, Y=yellow, G=green, B=blue) are placed at equidistant points around the color circle. The arc between each pair of elementary colors is divided into 100 equal steps representing a sample of all

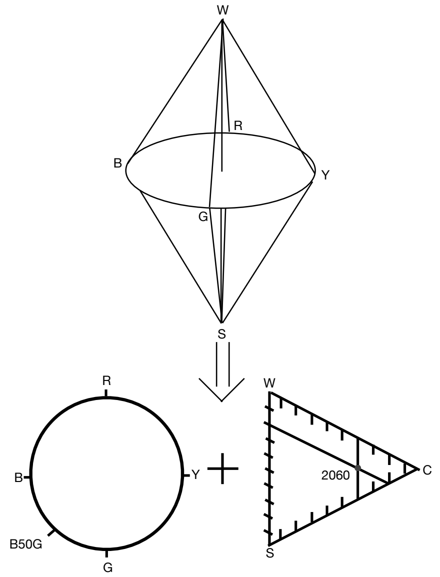

Figure 1: The NCS color solid and its two components: the color circle and the color triangle. Each hue around the color circle has a color triangle containing all of its possible nuances, or relationships between the percentage of black in the color and the saturation of the color.

the hues resembling the two elementary colors. Thus, each color may be expressed as a percentage according to its resemblance to the elementary hues. For instance, a color that appears to have equal amounts of blue and green falls halfway between unique blue and unique green and may be expressed as B50G (blue with 50 percent green). Similarly, a color with more blue than green would be, for example, B20G (blue with 20 percent green) whereas a color with more green than blue could be 880G (blue with 80 percent green).

Each hue on the color circle is also described by a color triangle in which one corner of the triangle represents maximum chromaticness (100 percent saturation) while the other two corners represent the achromatic elementary colors, white (W) and black (S). The scale between white and black is divided into 100 equal steps such that a color's resemblance to black is expressed as a percentage. In addition, the chromatic scale is also divided into 100 equal steps with the side of the triangle connecting white and black representing zero percent chromaticness. Hence, the color triangle yields a color's nuance, or its relationship to the achromatic elementary colors and its degree of saturation. For example, a 50 percent saturated color with 40 percent blackness has a nuance of 4050. Therefore, the complete NCS notation of a color that appears to be halfway between red and yellow, 60 percent of maximal saturation, and 20 percent black is 2060-Y50R.

Following the complete formulation of the NCS system an atlas of colored chips sampling the NCS color space was produced. The atlas contains 40 pages, each page representing one hue every tenth step around the color circle. Each page represents that hue's color triangle and contains color chips from every tenth step of chromaticness and every tenth step of blackness. In order to ascertain what variables determine whether a color is seen as light or dark and whether it is classified as a warm or a cool color, one dimension may be varied while the others are held constant. Thus, in the present experiment a series of chromatic chips taken from the NCS atlas and varying along the dimensions of saturation, hue, and lightness were used. The percentage of black in a color was determined to be representative of a color's lightness. Due to limitations of the NCS chips, brightness could not be varied and was therefore not investigated in this experiment.

If colored chips are equated for saturation and lightness, thereby differing only in hue, we can investigate whether hue is the dimension responsible for producing differences in lightness/darkness and warmth/coolness judgments. If hue is the determining factor we would expect differences between hues in these judgments when all other dimensions are controlled. If hue is not the crucial factor and lightness or saturation is responsible, the light/dark and warm/cool judgments should not vary. To examine the role of lightness in light/dark and warm/cool judgments responses to stimuli at four levels of lightness were compared. Variations in judgments across levels of lightness would indicate that this dimension has a large effect on warm/cool and light/dark judgments.

Another possible influence of light/dark judgments is the saturation of colors. In nature, yellow is the least saturated hue, which may result in its attribution of lightness, while blue and purple, often called dark colors, are generally very saturated. To investigate the correlation between lightness/darkness and saturation, ratings of stimuli equated for lightness were compared at four levels of saturation. The same method was used to investigate the effects of saturation on warm/cool ratings. Again, variations in judgments across saturation levels would indicate that saturation affects light/dark or warm/cool responses.

Method

Subjects

Subjects were 19 undergraduate students of Introductory Psychology, aged 18–21 with normal color vision, who received course credit for their participation. They were randomly assigned to either the warmth/coolness or lightness/darkness group, with 10 subjects in the warmth/coolness group and nine in the lightness/darkness group.

Materials

Ishihara color plates 10 and 22 were used to determine whether subjects had normal color vision.

Stimuli were rectangular colored chips of paper measuring 3.65 x 5 cm taken from the NCS atlas. Stimuli were chosen such that hue was sampled at eight equal intervals around the color circle, including the four primary colors of red, yellow, green and blue. Thus, the other four hues were orange (Y50R), yellow-green (G50Y), green-blue (B50G), and purple (R50B), In addition, the maximum saturation available that was common to all hues, 50 percent, was used for the constant saturation condition, with blackness ranging from 10 to 40 percent. For the constant lightness condition blackness was held at 10 percent, while saturation varied from the maximum saturation (50 percent) to 20 percent. Due to limitations in producing certain pigments, some chips were not available. Thus, 1050-RSOB was omitted from the range of chips, while 1020-G10Y and 1030-G10Y were substituted for the missing chips 1020-G and 1030-G. Because G and G10Y are so similar in appearance, it was assumed that any effects of this substitution would be minimal. Seven chips varying in saturation or lightness were used for each hue except R50B, for a total of 55 stimuli. A complete list of all chips used is in Appendix A. Stimuli were mounted on white rectangular pieces of paper measuring 10.2 x 14 cm and closely matching a luminance reflectance factor of 51.9 for an NCS nuance of 2500.

Procedure

All lights in the experimental room except the lamp used for testing were extinguished. Each subject was first tested for normal color vision, then informed of the experiment's procedure. Subjects were instructed to give a verbal rating of 1 to 10 of the lightness/darkness or warmth/coolness of each colored chip. For the lightness/darkness group 1 was specified as very light while 10 was very dark. For the warmth/coolness group 1 was specified as very cool while 10 was very warm. In order to minimize association with actual objects as well as mental comparison with previous responses to a given chip, subjects were instructed to respond as quickly as possible without compromising their best judgment of the specified attribute. Each stimulus was shown for two seconds, with the option of one additional presentation if requested. This option was taken, on average, less than once per subject. The series of 55 colored chips was shown four times with the order of presentation randomized within each series. After the second time the series was presented the subject was informed that the session was halfway over.

Results and Discussion

Experiment 1

Data for each subject were averaged to produce an individual's mean response for each stimulus in either the warmth/coolness condition or the lightness/darkness condition. The mean warmth/coolness ratings for each chip, by subject, are in Appendix A while those for the light/dark ratings are in Appendix B.

Table 1: Individual subjects' mean ratings and standard deviations for each hue, averaged over all saturations and lightnesses.

	Subject								
Hue	S1	S2	S3	S4	S5	S6	S7	S8	S9
B	2.83 ± 0.58	6.63 ± 1.16	4.17 ± 1.00	6.79 ± 0.19	5.54 ± 1.38	2.63 ± 0.49	4.92 ± 0.80	3.88 ± 1.05	6.00 ± 1.87
B50G	1.86 ± 0.43	8.71 ± 0.49	4.25 ± 0.82	1.86 ± 0.56	4.93 ± 1.06	2.79 ± 0.49	4.29 ± 1.06	2.64 ± 1.10	5.29 ± 1.45
G	2.21 ± 0.39	8.86 ± 0.28	3.29 ± 0.64	3.46 ± 0.34	4.29 ± 1.07	3.14 ± 0.32	4.29 ± 1.32	4.04 ± 1.21	5.93 ± 1.87
G50Y	2.75 ± 0.50	7.29 ± 1.02	4.39 ± 0.99	4.14 ± 0.38	4.82 ± 1.13	4.43 ± 0.80	5.21 ± 0.85	5.11 ± 1.22	5.71 ± 0.88
R	4.07 ± 0.49	4.86 ± 1.31	5.75 ± 1.65	4.50 ± 0.46	4.54 ± 0.42	5.57 ± 1.04	4.46 ± 0.55	4.54 ± 1.90	4.29 ± 1.09
R50B	6.32 ± 1.08	4.21 ± 2.03	7.64 ± 0.93	4.96 ± 0.53	6.25 ± 1.03	7.36 ± 1.21	5.54 ± 0.77	5.54 ± 2.55	4.96 ± 1.69
Y	7.75 ± 0.80	5.96 ± 2.00	7.18 ± 0.73	6.36 ± 0.38	7.14 ± 0.85	8.00 ± 1.02	6.11 ± 0.64	6.43 ± 2.43	6.07 ± 1.26
Y50R	8.25 ± 1.20	7.61 ± 0.85	5.14 ± 1.21	8.25 ± 1.21	6.61 ± 0.66	7.50 ± 1.01	5.71 ± 0.64	5.71 ± 1.44	6.43 ± 1.81

Warmth/Coolness

One subject in this condition elected to end the experiment early, so those data were discarded. Table 1 and Figure 2 show the average response to each hue given by all other subjects in the warmth/coolness condition. Because the response curve for subject 2 showed a trend opposite to that for the other subjects, it was assumed that the subject had reversed the scales, giving a 10 to very cool colors and a 1 to very warm colors. Hence, this subject's data were omitted from further analysis, resulting in a total of 8 subjects whose data were used. As the graph shows, all subjects' response curves approximately followed an S-shaped curve indicating a large effect of hue. Absolute values cannot be compared since subjects had their own internal rating scale, but relative values indicate similar trends in judgments of color temperature.

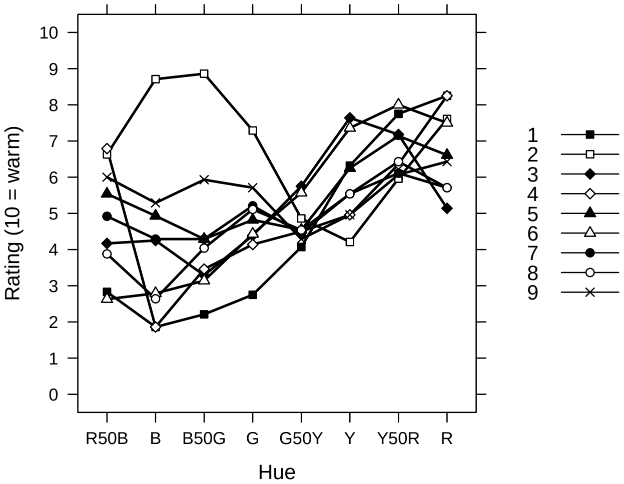

Figure 2: Individual warmth/coolness response curves for each hue, averaged over all levels of saturation and lightness in Experiment 1.

Data were subsequently averaged across subjects to obtain overall mean ratings for each chip. Results are depicted in Tables 2 and 3 and in Figures 3 and 4. Table 2 and Figure 3 show the mean ratings as they vary with saturation at a constant level of lightness. With each ten percent increase in saturation the rating of warmth increased as well. MANOVA's were performed to test the significance of saturation and hue on warmth/coolness ratings. Because there was no stimulus for 1050-R50B, two MANOVA's were done. The first one omitted all ratings for R50B, while the second one omitted all ratings for 1050. Both methods showed a significant effect of saturation on these ratings, $F(3,21) = 9.44$, $p < 0.001$, and $F(2,14) = 6.44$, $p = 0.01$, respectively. However, the effect of saturation appears secondary to that of hue. The largest difference between two points of different saturations at one hue is 1.88 (at Y between 20% and 50%) (see Table 2); however, the differences between the highest and lowest ratings of different hues at each level of saturation are greater. At 20% saturation the difference between the highest and lowest ratings (at Y50R and B50G, respectively) is 3.25; at 30% this difference is 3.85; at 40% it is 3.34; and at 50% (where the lowest rating is at B rather than B50G) it is 3.56. Therefore, while changes in saturation do affect warm/cool ratings, this effect is not as large as that of hue. This is supported by the significance of the main effect of hue in the aforementioned MANOVA's. When all ratings for R50B were omitted, the effect of hue was highly significant, $F(6,42) = 21.84$, p ¡ .001, as it was when the ratings at 1050 were omitted, $F(7,49) = 18.21$, $p < 0.001$. The interaction of saturation with hue was not significant in either of these analyses, $F(18,126) = 1.13$, ns, and $F(14,98) = 1.09$, ns, respectively.

Table 3 and Figure 4 show the mean rating for each hue over varying levels of lightness at a constant level of 50 percent saturation. Again, two MANOVA's were performed to assess the significance of changes in lightness and hue on these ratings. The main effect of hue was again significant in both analyses, $F(6,42) = 8.17$, $p < 0.001$ and $F(7,49) = 5.97$, $p < 0.001$, respectively. Although neither the MANOVA omitting ratings for R50B, $F(3,21) = 2.30$, ns, nor that omitting ratings at 1050, $F(2,14) = 2.94$, ns, were significant, the interaction between hue and lightness was significant, $F(18,126) = 2.86$, $p < 0.001$ when the ratings at R50B were omitted and $F(14,98) = 2,10$, $p < 0.02$ when ratings at 1050 were omitted. Increases in the percentage of blackness tended to produce cooler ratings, but this trend was by no means consistent with every increase in blackness. While at every hue, except R, the rating at 10% blackness was warmer than that at 40%, in the intervening increments ratings did not consistently drop with each 10% increase in blackness. For B50G the rating dropped when blackness was increased from 10% to 20%, but then rose again when it increased to 30% before dropping at 40%. For the G chips the rating increased when blackness increased from 10% to 20%, then decreased when it rose to 30%. The ratings for Y dropped with every increase in blackness except when blackness rose from 30% to 40%. The ratings for R increased with an increase from 10% to 20% blackness, then decreased at 30% before rising at 40%. Thus, there was no consistent change in the ratings when the percentage of blackness in the hue was varied, and the pattern of increasing and decreasing ratings varied with hue.

The relative effects of hue, lightness, and saturation are again seen in Figures 5 and 6, which provide alternate views of the data in Tables 2 and 3. The large effect of hue on warm/cool ratings is illustrated by the vertical separation of the response curves in both figures. Particularly striking is the clustering of the curves for R, Y50R, and Y at warmer ratings, most noticeably in Figure 5, but also, to a slightly lesser extent, in Figure 6. These results support past research showing that longer wavelengths are rated as warmer while shorter wavelengths are rated cooler (e.g. Ross, 1938).

The mean responses at each level of saturation and lightness (see Tables 2 and 3) were then averaged over all saturations and lightnesses to obtain one mean rating for each hue. The results are

Table 2: Mean warmth/coolness ratings for Experiment 1 at four levels of saturation and a constant blackness of 10%, and the largest differences between two hues at each level of saturation and between two saturation levels at each hue.

	Saturation				
Hue	20%	30%	40%	50%	Largest Difference
R50B	3.88	3.97	4.84		0.96
B	2.97	3.22	3.75	3.94	0.97
B50G	2.94	3.06	3.72	4.81	1.87
G	3.78	3.97	4.19	5.09	1.31
G50Y	4.16	4.38	4.59	5.41	1.25
Y	5.28	5.97	7.00	7.16	1.88
Y50R	6.19	6.91	7.06	7.50	1.31
R	5.62	6.19	6.62	7.00	1.38
Largest Difference	3.25	3.85	3.34	3.56	

depicted in Table 4 and Figure 7. A MANOVA of these average ratings again revealed a significant effect of hue, F(7,49) = 11.01, $p < 0.001$, indicating that ratings of warmth and coolness do depend on which hue is observed.

In an attempt to relate the warmth/coolness responses to the underlying opponent process, theoretical red-green (R-G) and blue-yellow (B-Y) opponent curves reflecting the underlying level of physiological activation were calculated. Using a hue cancellation technique, Jameson and Hurvich (1955, cited in Werner & Wooten, 1979) formulated opponent chromatic response functions for the average observer. Werner and Wooten (1979) compiled Jameson and Hurvich's data and those from two other studies into the average response functions shown in the second and third columns of Table 5 and in Figure 8. The chromatic valence is the responsivity of the opponent channel at a particular wavelength. The sign for each valence was selected arbitrarily with positive and negative signs indicating which part of the opponent process is activated at that particular wavelength. Thus, since red and green are not simultaneously activated in the opponent model, a positive value in this function indicates that red, rather than green, is being activated, while a negative value indicates that green, not red, is activated. Similarly, for the blue and yellow function, positive values represent activation of the yellow channel and negative values represent activation of the blue channel. These valences were then divided by the luminous efficiencies (shown in the fourth column of Table 5), obtained using heterochromatic brightness matching, by Wagner and Boynton (1972, cited in Wyszecki & Stiles, 1982), to obtain theoretical activation values for the R-G and B-Y opponent channels at each wavelength (see Table 6 and Figure 9).

Whereas the stimuli used by Wagner and Boynton were defined by their physical properties, the stimuli used in the present experiment were defined by their appearance. Thus, it was necessary to determine which wavelengths corresponded to the hues presented as stimuli in order to obtain an overall activation value for each of the eight hues. The overall level of activation was obtained by

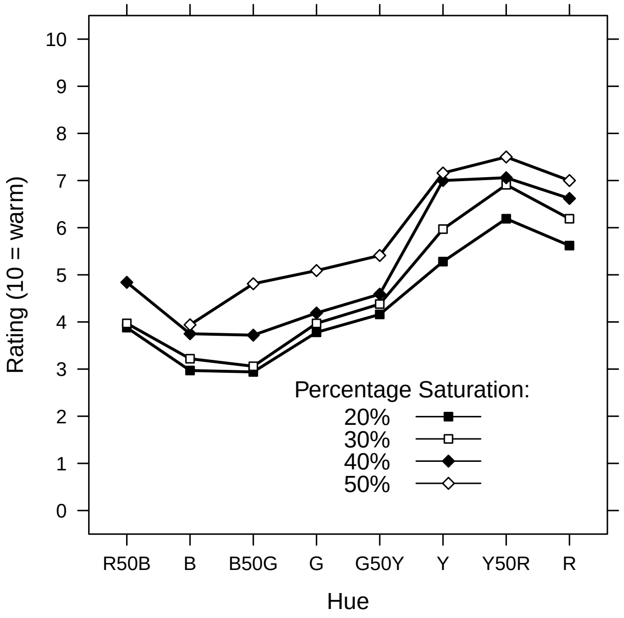

Figure 3: Mean warmth/coolness ratings from Experiment 1, as saturation level is varied between 20% and 50% and lightness is held constant at 10% blackness.

summing together the activation values for the two curves at a given wavelength. Activation values at unique blue and unique yellow were interpolated from the values on the B-Y curve at the wavelengths at which the R-G activation was approximately zero (475 nm and 575 nm, respectively) (see Table 6). The unique green activation value was determined in a similar manner except that the value was taken from the R-G curve where the B-Y activation was silenced (505 nm). Since there is no point where the B-Y activation curve is silenced in the longer wavelengths of the visible spectrum, the activation value for red was determined by summing the values on the two curves at the wavelength in the red range at which B-Y activation was minimized (640 nm).

Activation values for the other four hues were found using a slightly different approach. Since B50G had an equal amount of blue and green in it, the activation value was obtained by locating the wavelength at which the green and the blue activation values were the most similar (490 nm), then summing the two values. Likewise, the activation value for Y50R was the sum of the red and the yellow activation values at the wavelength at which they were most equal (600 nm). Similarly, since G50Y had equal amounts of green and yellow, this activation value would be the sum of the values of the green and yellow curves at the wavelength at which they were most similar (approximately 550 nm). However, since green had negative activation values while yellow had positive values, their sum at G50Y would be zero. Similar reasoning produces a value of zero for activation at R50B as well.

Once the activation values were obtained, the data were transformed so that both curves could fit the same scale. Although it was not specified during the experiment it was hypothesized that if a subject felt that a color was neither warm nor cold, he or she would give it a rating of 5, the number approximately in the middle of the scale (5.5 is actually the half-way point, but subjects

Table 3: Mean warmth/coolness ratings from Experiment 1, over changes in lightness at a constant saturation of 50%, and the largest differences between two hues at each level of lightness and between two lightness levels at each hue.

	Percentage of Blackness				
Hue	10%	20%	30%	40%	Largest Difference
R50B		5.31	4.59	4.97	0.72
B	3.94	3.81	3.69	3.03	0.91
B50G	4.81	4.25	4.41	3.62	1.19
G	5.09	5.19	4.75	4.88	0.31
G50Y	5.41	5.09	4.75	4.62	0.79
Y	7.16	6.31	5.31	5.47	1.85
Y50R	7.50	7.28	6.81	6.41	1.09
R	7.00	7.09	7.03	7.34	0.34
Largest Difference	3.56	3.47	3.34	4.31	

Table 4: Mean warmth/coolness rating and standard deviation for each hue averaged over all subjects, saturations and lightness levels in Experiment 1.

Hue	Warmth/Coolness Rating	Standard Deviation
R50B	4.59	0.57
B	3.49	0.40
B50G	3.83	0.70
G	4.57	0.58
G50Y	4.71	0.42
Y	6.07	0.78
Y50R	6.88	0.46
R	6.70	0.61

were requested to use integers). Therefore 5.0 was subtracted from each average rating to make zero equal to no warmth or coolness (the null point). Then, to match the ratings and activation values on comparable scales, the data were multiplied by a constant, the derivation of which is explained later in the text.

In an effort to match the data and the theoretical curves as closely as possible and to discover a systematic relationship between the two functions, the initial activation values were multiplied by various constants. In addition, since subjects were not informed that 5 was to be the value given to colors they felt had no thermal properties, different values near 5 were substituted to examine the effect on the correspondence of the curves. Of course, a better experimental design would include specifying a null point for subjects when they felt the color was neither warm nor cold so that this parameter would not need to be estimated. Each time the activation values were multiplied by a constant it was necessary to re-determine the activation values corresponding to the observed

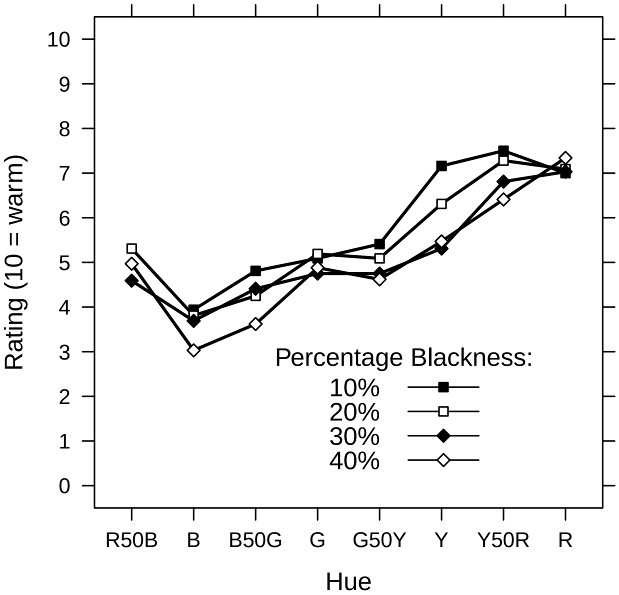

Figure 4: Mean warmth/coolness ratings from Experiment 1, at a constant saturation of 50% and over changes in blackness from 10% to 40%.

hues, while changing the null point required readjustment of the data. When either parameter was changed a new constant had to be computed using the methods previously outlined before the data could be plotted.

The closest obtained correspondence of the theoretical activation and the data is shown in Figure 10, with the R-G activation values multiplied by 1.4, the B-Y values by 1.0, and the null point at 5.3. The resulting activation values, corresponding wavelengths, adjusted data points (original ratings minus 5.3), and the adjusted data points after being multiplied by the obtained constant are given in Table 7. The constant was derived by dividing the activation value for B, the lowest activation value (-2.00), by the adjusted rating for B (-1.81) and the activation value for Y50R, the highest activation value (1.79), by its adjusted rating (1.58), then averaging these two values. Each adjusted data point was then multiplied by this constant. While a computer could likely obtain an even closer match between the opponent process model curves and the results from this study, these initial results suggest that the attribution of thermal properties to colors may be more than simply an associational process. Higher ratings of warmth corresponded with activation of the opponent chromatic channels in one direction, while the cooler ratings corresponded with levels of activation in the opposite direction.

Results from this part of the experiment also indicated that hue had a large effect on a subject's rating of the warmth or coolness of a color, with longer wavelengths receiving higher ratings of warmth. Lightness and saturation had some effect as well, but they were certainly minimized by the overwhelming effect of hue, a conclusion in accord with that of Ross (1938) and Wright (1962).

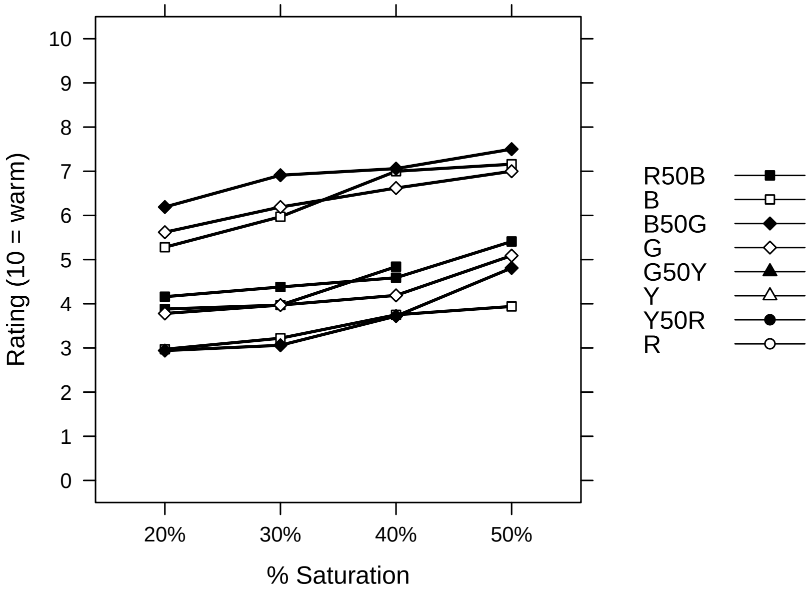

Figure 5: Warmth/coolness ratings by hue in Experiment 1, over four levels of saturation and a constant level of 10% blackness.

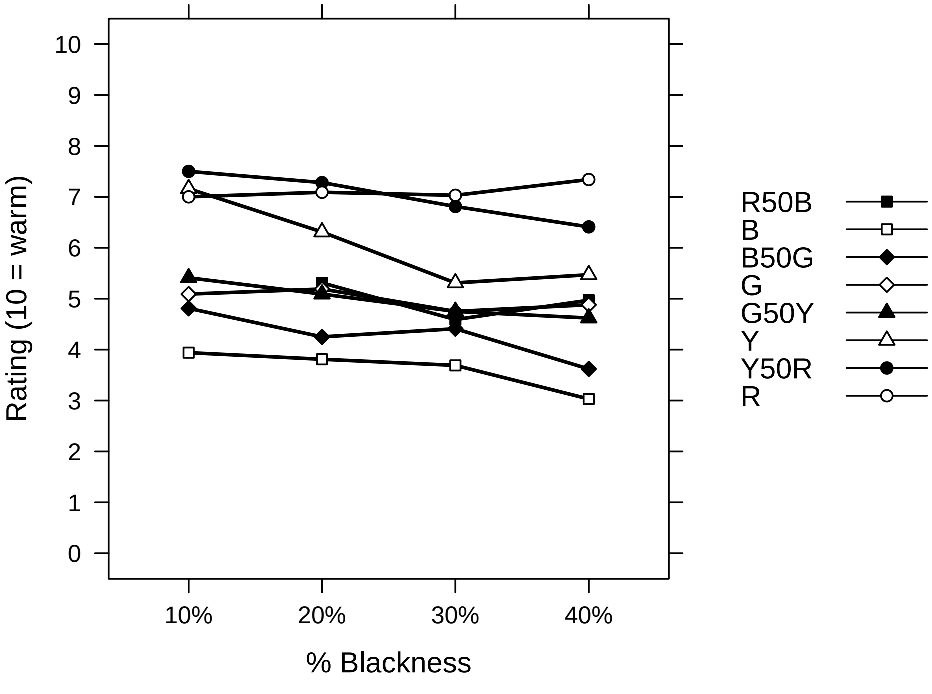

Figure 6: Warmth/coolness ratings by hue in Experiment 1, over four levels of lightness and a constant level of 50% saturation.

Lightness/Darkness

Table 8 and Figure 11 show the average light/dark responses averaged across subjects, then across saturations, and lightness levels. Although the curve is nearly flat, suggesting little effect of hue,

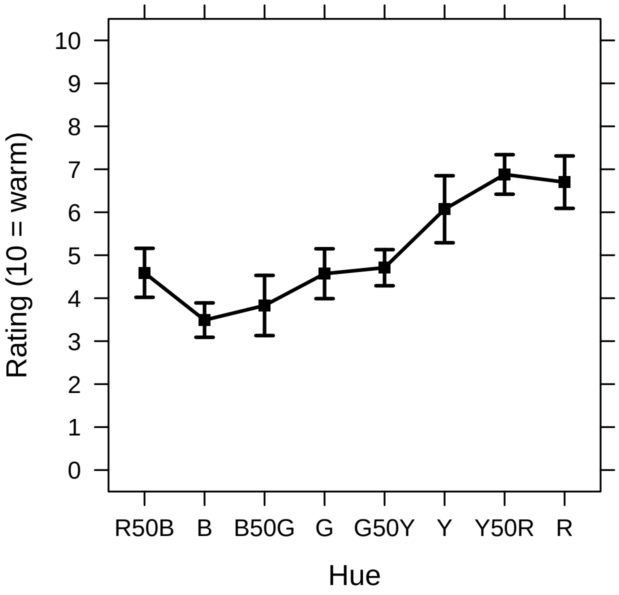

Figure 7: Mean warmth/coolness rating and standard deviation for each hue in Experiment 1, averaged over all subjects, saturations, and lightnesses. The small standard deviations indicated little variability across saturation and lightness levels.

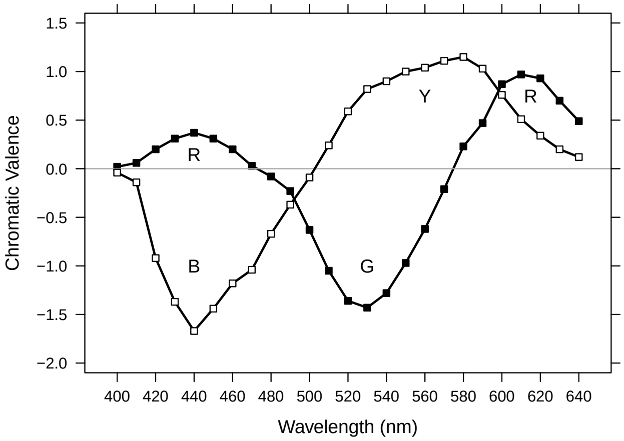

Figure 8: Average opponent chromatic valences for an equal-energy spectrum, from columns 2 and 3 of Table 5 (From Werner and Wooten, 1979). Black squares represent the red-green function while white squares represent the blue-yellow function.

there is a slight dip near G50Y and Y. This effect of hue was found to be significant, F(7,56) = 12.49, $p < 0.001$.

This same dip is illustrated in Table 9 and Figure 12 which show the effects on light/dark ratings of changes in lightness at a constant level of saturation. The separation of the lines in Figure 12 indicates that lightness affects these ratings in a consistent manner. As the percentage of blackness

Table 5: Average opponent chromatic valences and luminous efficiencies for wavelengths in the visible spectrum.

Wavelength (nm)	R-G Valence[1]	Y-B Valence	Luminous Efficiencies[2]
400	0.02	-0.04	0.03
410	0.06	-0.14	0.06
420	0.20	-0.92	0.09
430	0.31	-1.37	0.10
440	0.37	-1.67	0.17
450	0.31	-1.44	0.23
460	0.20	-1.18	0.31
470	0.03	-1.04	0.38
480	-0.08	-0.67	0.54
490	-0.23	-0.37	0.58
500	-0.63	-0.09	0.71
510	-1.05	0.24	0.82
520	-1.36	0.59	0.98
530	-1.43	0.82	1.07
540	-1.28	0.90	1.08
550	-0.97	1.00	1.06
560	-0.62	1.04	1.01
570	-0.21	1.11	1.00
580	0.23	1.15	1.01
590	0.47	1.03	1.04
600	0.87	0.76	1.01
610	0.97	0.51	0.97
620	0.93	0.34	0.90
630	0.70	0.20	0.81
640	0.49	0.12	0.61

[1] From Werner & Wooten (1979). [2] From Wagner & Boynton (1972, cited in Wyszecki & Stiles, 1982).

in the color increased by 10 percent, the average response increased close to one rating point: between 10 and 20 percent blackness the responses rose an average of 0.93 points; between 20 and 30 percent they rose an average of 0.99 points; and between 30 and 40 percent they rose an average of 1.05 points. Again, two MANOVA's were performed to test the significance. When ratings at R50B were omitted the effect of lightness was significant, $F(3,24) = 62.94$, $p < 0.001$, as was the effect when ratings at 1050 were omitted, $F(2,16) = 59.93$, $p < 0.001$. These analyses also revealed the significant effect of hue on lightness/darkness ratings, $F(6,48) = 10.84$, $p < 0.001$, and $F(7,56) = 9.95$, $p < 0.001$, respectively. However, while hue does significantly affect light/dark ratings, its effects appear to be secondary to those of lightness. The largest difference between ratings of one hue at two levels of lightness is 3.48, while the differences between hues at each level of lightness

Table 6: Calculated activation values for the red-green (R-G) and blue-yellow (B-Y) opponent channels in the average observer.

Wavelength	R-G	B-Y
400	0.56	-1.17
410	0.94	-2.25
420	2.18	-9.76
430	3.00	-13.20
440	2.19	-9.99
450	1.33	-6.29
460	0.63	-3.77
470	0.08	-2.77
480	-0.15	-1.24
490	-0.40	-0.63
500	-0.89	-0.12
510	-1.28	0.29
520	-1.39	0.61
530	-1.34	0.77
540	-1.19	0.83
550	-0.92	0.94
560	-0.61	1.03
570	-0.21	1.11
580	0.23	1.14
590	0.45	0.99
600	0.86	0.76
610	1.00	0.53
620	1.03	0.37
630	0.86	0.25
640	0.80	0.20

are generally much smaller (except for the difference between R and Y at 40% blackness). A significant interaction between lightness and hue, F(18,144) = 2.83. $p < 0 .001$ and F(14,112) = 3.23, $p < 0.001$, respectively, was also revealed in the previous analyses. Therefore, while both lightness and hue influenced the ratings independently, their combination had significant effects as well. This is evident from the fact that the same increase in blackness produced different increases in ratings at different hues.

The effect of increasing saturation on light/dark judgments is depicted in Table 10 and Figure 13. Here, too, there is a significant effect of saturation on the ratings, F(3,24) = 43.84, $p < 0.001$ when R50B is omitted and F(2,16) = 65.17, $p < 0.001$ when 1050 is omitted. However, each increase in saturation produced a smaller increase in ratings than did a comparable increase in the percentage blackness, which produced an increase of close to one rating point for every 10 percent increase. As saturation increased from 20 to 30 percent the rating rose an average of 0.68 points, while an increase from 30 to 40 percent raised the average response 0.73 points and an increase from 40 to 50 percent increased the rating an average of 0.70 points. Hue was again found to have a significant

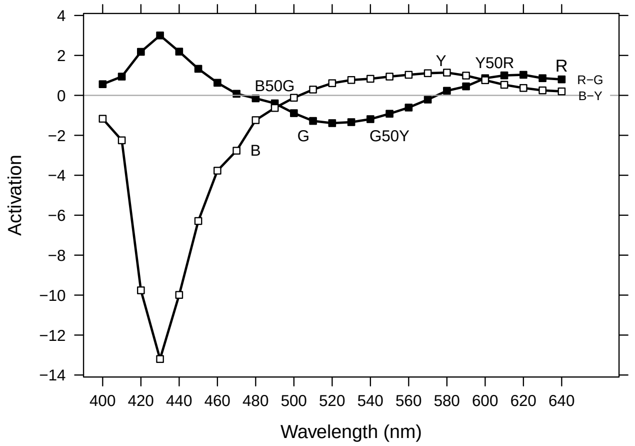

Figure 9: Activation curves for the red-green (R-G) and blue-yellow (B-Y) opponent channels in the average observer. Black squares represent activation values for the R-G channel and white squares represent activation values for the B-Y channel. R50B is extraspectral and, therefore, is not represented in the figure.

main effect, F(6,48) = 10.92, $p < 0.001$ when R50B ratings were omitted and F(7,56) = 8.36, $p < 0.001$ when 1050 ratings were omitted. Again, the effect of hue, although significant, appears to be smaller than that of saturation. The interaction between saturation and hue in both analyses was not significant, F(18, 114) = 1.31, ns, when R50B ratings were omitted and F(14, 112) = 0.74, ns, when 1050 was omitted.

Figures 14 and 15 depict the data from Tables 9 and 10 in another fashion. The overlapping of the response curves for each hue illustrates the smaller effect of hue, while the consistent increase of ratings with saturation and blackness illustrates the larger effects of these variables. The steeper slope of the response curves in Figure 14 as opposed to those in Figure 15 show the effect of lightness as larger than that of saturation. Therefore, unlike ratings of warmth and coolness, those of lightness and darkness are affected more by lightness and saturation than by hue.

One interesting point about these results is that both saturation and lightness affected the light/dark ratings in similar ways. Increases in saturation and in percent blackness produced darker ratings. A possible explanation is that the inexperienced subjects would not notice the difference between a change in saturation and one in lightness and would therefore react to these changes in the same way. Shepp (1991) argued that hue, saturation, and [lightness] (Shepp used the term brightness, but recent evidence, e.g. Sewall and Wooten, 1991, suggests that he was actually referring to lightness) interact so strongly that alterations in one dimension can greatly change the appearance of another. Burns and Shepp (1988, cited in Shepp, 1991) asked subjects to classify stimuli in a triad based on some shared dimension, then to name the dimension that the stimuli shared. Although subjects were trained before performing the task, they frequently named saturation as the shared dimension following a classification along the [lightness] dimension, and vice versa. It seems likely that subjects in the present experiment would share the same confusion of saturation and lightness. If so, changes in a color's saturation may alter the appearance of its lightness. Thus,

Table 7: Wavelengths corresponding to each hue: activation values after multiplying the R-G activation function by 1.4: adjusted data: and normalized data from Experiment 1.

Hue	Corresponding Wavelength	Activation Value	Adjusted Data[1]	Normalized Data[2]
R50B	400	0.00	-0.81	-0.86
B	475	-2.00	-1.81	-1.92
B50G	490	-1.19	-1.47	-1.56
G	505	-1.52	-0.73	-0.77
G50Y	550	0.00	-0.58	-0.61
Y	575	1.12	0.78	0.83
Y50R	600	1.79	1.58	1.67
R	640	1.31	1.40	1.48

[1] Data after subtracting a null point of 5.3. [2] Adjusted data multiplied by 1.06.

Table 8: Mean lightness/darkness rating and standard deviation for each hue averaged over all subjects, saturations, and lightness levels in Experiment 1.

Hue	Lightness/Darkness Rating	Standard Deviation
R50B	4.76	2.25
B	4.70	1.92
B50G	4.56	1.81
G	4.47	2.05
G50Y	4.03	1.77
Y	4.21	1.72
Y50R	4.68	1.60
R	5.07	2.08

it may be saturation or lightness that affects these ratings, not both of them. If subjects were also instructed to rate the saturation of the colored chips they may have responded differently than they would to a comparable change in lightness. If so, the effects on light/dark ratings of saturation and lightness could be differentiated more clearly. Although the results did not appear to support a general effect of hue on lightness/darkness judgments, the dip of the response curves near G5OY and Y (see Figure 11) produced a significant effect. Although it is possible that hue does affect light/dark ratings, another possibility is that hue has no effect and that the dip, and the significant effect of hue, may have been due to inequalities in saturation and lightness of the stimuli under the particular viewing conditions used in this experiment. It was subsequently discovered that the lamp recommended for use with the NCS atlas and, therefore, the lamp used in this experiment, CIE illuminant C, was slightly different from that used in calibrating the NCS atlas. As a result, the stimuli chosen for equal saturation and lightness were not necessarily equated under this different viewing condition.

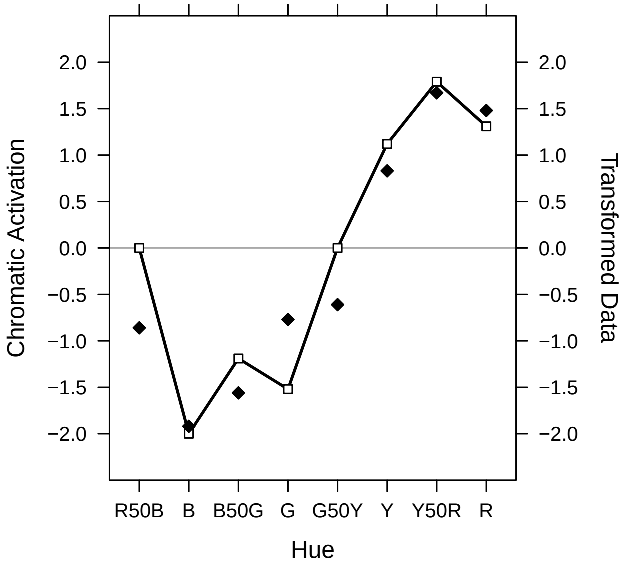

Figure 10: Comparison between the theoretical chromatic activation of the opponent channels at each hue and the obtained data for each hue in Experiment 1, after multiplying the R-G activation curve by 1.4 and using a null point of 5.3.

Experiment 2

This experiment was performed to address the two issues of 1) differentiating saturation and lightness effects on light/dark judgments, and 2) the possible inequality of stimuli in the previous experiment along the dimensions of saturation and lightness. If subjects are instructed to rate the saturation of a colored chip while lightness is varied, a better understanding of the effects of each can be obtained. If ratings of saturation vary when lightness, but not saturation is varied it is likely that subjects are responding to both saturation and lightness in similar ways and, as a result, their effects cannot be disentangled. In addition, recalibration of the stimuli for equal saturation and lightness under CIE illuminant C may eliminate the dip in the light/dark response curves from the previous experiment.

Method

Subjects

Eleven students aged 18–30 participated in this experiment. All subjects had normal color vision and were paid for their participation.

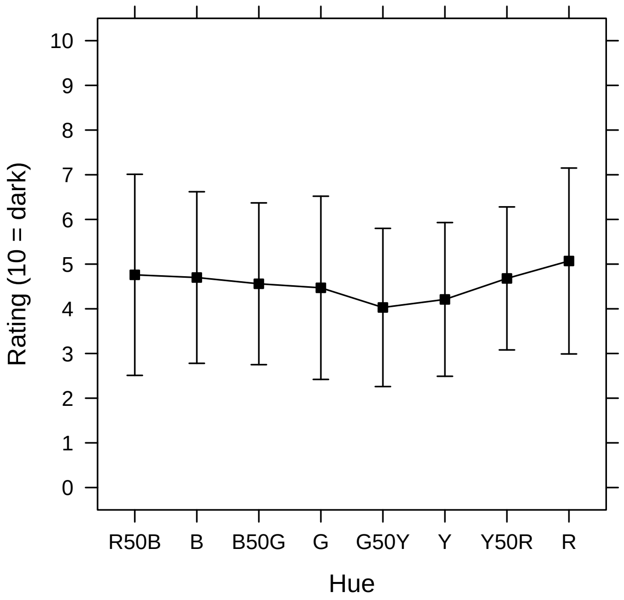

Figure 11: Lightness/darkness responses and standard deviations averaged over all subjects, saturations, and lightness values in Experiment 1. The large standard deviations represent the variability across saturation and lightness levels, indicating that these variables had a large effect on the ratings.

Materials

Materials were identical to those in Experiment 1 except that different chips were used. Two sets were used in this experiment; the first, which subjects rated for saturation, consisted of the same chips used in the first experiment except that, in the interest of time, only the four elementary hues (R, Y, B, G) were used. Thus, there were 28 stimuli varying in hue, saturation, and lightness. The second set, which subjects rated for lightness/darkness, consisted of the eight original hues matched for saturation and lightness under CIE Illuminant C. Four experienced observers used a step-by-step matching procedure to obtain chips matched for two levels of saturation and two levels of lightness. This set contained a total of 24 chips, three from each hue. The list of these chips is given in Appendix C.

Apparatus

The apparatus was identical to that in the first experiment.

Table 9: Mean lightness/darkness ratings from Experiment 1, over changes in lightness at a constant saturation of 50%, and the largest differences between two hues at each level of lightness and between two lightness levels at each hue.

	Percentage of Blackness				
Hue	10%	20%	30%	40%	Largest Difference
R50B		5.72	6.19	8.03	2.31
B	4.36	5.47	6.58	7.53	3.17
B50G	4.64	5.42	5.94	7.28	2.64
G	4.19	5.00	6.50	7.61	3.42
G50Y	3.47	4.75	5.64	6.78	3.31
Y	4.14	4.89	5.86	6.22	2.08
Y50R	4.39	5.36	6.42	6.78	2.39
R	4.83	5.61	7.03	8.31	3.48
Largest Difference	1.36	0.97	1.39	2.09	

Procedure

Each session was identical to those of the first experiment except that the subjects rated the lightness/darkness of the chips in one series and the saturation of those in the other series. A scale of 1 to 10 was also used for the saturation ratings, with 1 specified as not at all saturated and 10 as very saturated. If subjects were not familiar with the term saturation in reference to color, it was explained to them as in the introduction of this paper. One set of chips (either the series rated for saturation or that rated for lightness) was presented four times, followed by four presentations of the other series. Which series was shown first was decided randomly for each subject.

Results and Discussion

Data for each subject were averaged over all four trials to yield a mean rating for each chip. Individual mean ratings for each chip are given in Appendix C (light/dark ratings) and Appendix D (saturation ratings).

Saturation

Table 11 and Figure 16 show the ratings averaged across subjects for changes in lightness at a constant saturation. The values of 1.23, 1.32, 0.98, and 1.48 as the largest differences between

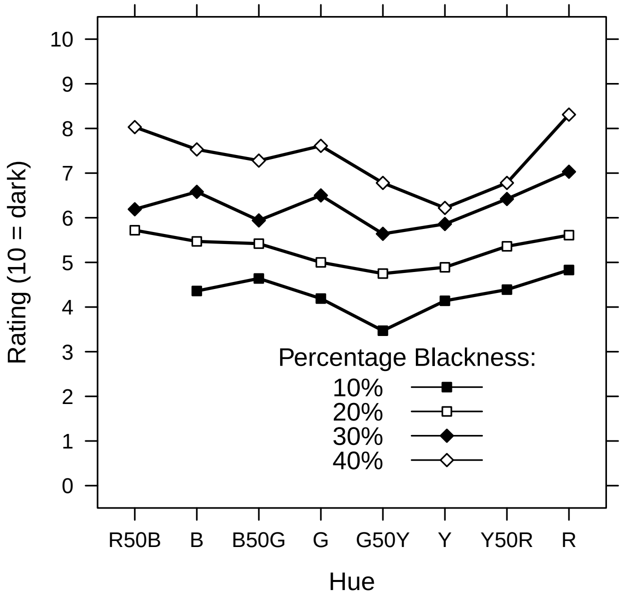

Figure 12: Mean lightness/darkness ratings from Experiment 1, at a constant saturation of 50% and over four levels of lightness.

two hues at 10%, 20%, 30%, and 40% blackness, respectively, illustrate the significant effect of hue on ratings of saturation, F(3,30) = 4.12, $p < 0.02$. However, this effect is again secondary to the effect of lightness, F(3,30) = 102.02, $p < 0.001$, (except at Y where the effect of lightness is comparable to that of hue at all levels of lightness) as shown by the values of 3.71, 4.05, and 3.21 as the largest differences between the two levels of lightness at B, G, and R, respectively. The convergence of the ratings of all levels of lightness at Y suggests that changes in lightness at this particular hue do not appear to change the saturation as much as at other hues, where lightness has a large effect. This interaction between lightness and hue was highly significant, F(9,90) = 6.70, $p < 0.001$. Saturation, too, had a larger effect than hue on saturation ratings, as shown in Table 12 and Figure 17. While both saturation and hue had significant main effects, F(3,30) = 140.72, $p < 0.001$, and F(3,30) = 15.78, $p < 0.001$, respectively, the largest difference between two levels of saturation at one hue was 3.38, while the largest difference between hues at one level of saturation was 1.52. Thus, as would be expected, saturation had the largest effect on ratings of saturation. The interaction between saturation and hue was not significant, F(9,90) = 1.05, ns.

Changes in saturation and lightness produced similar changes in ratings for both saturation and the light/dark judgments of the first experiment. When asked to rate the saturation, subject's mean ratings increased with lightness even when saturation was held constant. Likewise, when lightness was held constant and saturation varied, ratings of the lightness/darkness of the colors increased with increasing saturation. Ideally the same subjects would have given both the light/dark ratings of the first experiment and the saturation ratings, but in the interest of time this was not possible. Nevertheless, in support of Shepp's (1991) assertion that changes in one dimension of a color often change the appearance of other dimensions, results suggest that subjects could not separate the changes in saturation from those in lightness.

Table 10: Mean lightness/darkness ratings for Experiment 1 at four levels of saturation and a constant blackness of 10%, and the largest differences between two hues at each level of saturation and between two saturation levels at each hue.

	Saturation				
Hue	20%	30%	40%	50%	Largest Difference
R50B	2.22	2.81	3.61		1.39
B	2.33	2.92	3.69	4.36	2.03
B50G	2.17	2.81	3.64	4.64	2.47
G	1.97	2.61	3.44	4.19	2.22
G50Y	1.86	2.47	3.22	3.47	1.61
Y	2.00	2.67	3.19	4.14	2.14
Y50R	2.47	3.17	4.14	4.39	1.92
R	2.44	3.44	3.81	4.83	2.39
Largest Difference	0.61	0.97	0.95	1.36	

Lightness/Darkness

Table 13 and Figure 18 compare the mean light/dark judgments of Experiments 1 and 2. The ratings in Experiment 1 were based on chips equated for saturation and lightness in the NCS system, while those in Experiment 2 were based on chips equated under a viewing system slightly different from that of the NCS atlas. In Experiment 2 the effect of hue on lightness/darkness ratings was not significant, F(7,70) = 1.72, ns., indicating that the effect of hue was reduced by using chips equated for saturation and lightness under CIE Illuminant C. Therefore, it appears that when stimuli are properly equated for saturation and lightness under a particular viewing condition, hue does not play a significant role in lightness/darkness ratings. On the other hand, lightness and saturation were both shown by MANOVA's to have significant effects, F(1,10) = 164.79, $p < 0.001$, and F(1,10) = 133.63, $p < 0.001$, respectively, as depicted in Tables 14 and 15 and Figures 19 and 20. Table 14 and Figure 19 illustrate the effect of increasing saturation on lightness/darkness judgments. For every hue an increase in saturation produced a darker rating. However, the magnitude of this increase varied with hue, F(7,70) = 18.60, $p < 0.001$. As Figure 19 shows, the increase in ratings at B50G is much smaller than that for Y when saturation is increased. The effect of increasing blackness is shown in Table 15 and Figure 20. As with saturation, an increase in blackness produced a higher rating of warmth at every hue, but the increase in ratings was larger at B50G than at Y. This interaction between lightness and hue was also significant, F(7,70) = 7.12, $p < 0.001$.

Following methods similar to those outlined in the previous experiment, an attempt was again made to relate the lightness/darkness ratings to the opponent processes. Because the theory asserts that yellow is lighter than blue, the rating scale of the obtained data was reversed, so that 10 was very light and 1 was very dark, to correspond with the positive activation values for yellow. Therefore,

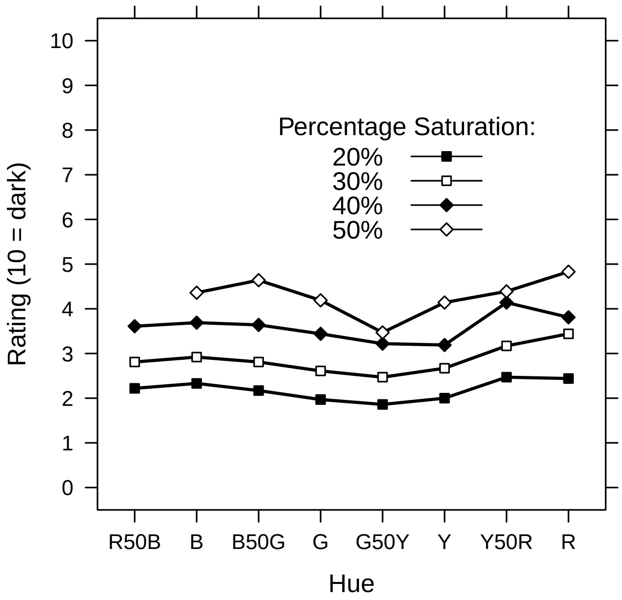

Figure 13: Mean lightness/darkness ratings from Experiment 1 at four levels of saturation and a constant level of 10% blackness.

the mean ratings were re-scaled by subtracting each rating from 10.00. The new ratings are shown in Table 16. These adjusted ratings were then compared to the opponent model, with the best correspondence between data and theory depicted in Figure 21. The best fit was obtained after multiplying both the R-G and the B-Y activation curves by 0.1 and using a null point of 5.3 (See Table 16 for resulting values).

Although the data and the theory appear to correspond very closely, it is important to note that multiplying the theoretical curve by a small enough number will result in a nearly flat curve. Because the response curve is nearly flat, this will necessarily result in a close correspondence between the curves. Therefore, a regression line through the data was compared to the theoretical curve. The regression line had a slope of 0.02, indicating a nearly horizontal curve. Both the regression line and the theoretical curve had r^2=0.11; therefore, the theoretical curve did not differ significantly from a straight, flat line. Since the best fit of the theoretical values to the data is a nearly flat line, ratings of lightness and darkness do not correspond with the opponent processes.

Experiment 3

This experiment essentially replicated that of the warmth/coolness part of Experiment 1 but introduced improvements in the methods. The chips from Experiment 2 which were equated for saturation and lightness under the viewing condition used were used as stimuli in this experiment to investigate the effects of properly calibrated stimuli on the warmth/coolness ratings. It was expected that any differences between these results and those from Experiment 1 would be small

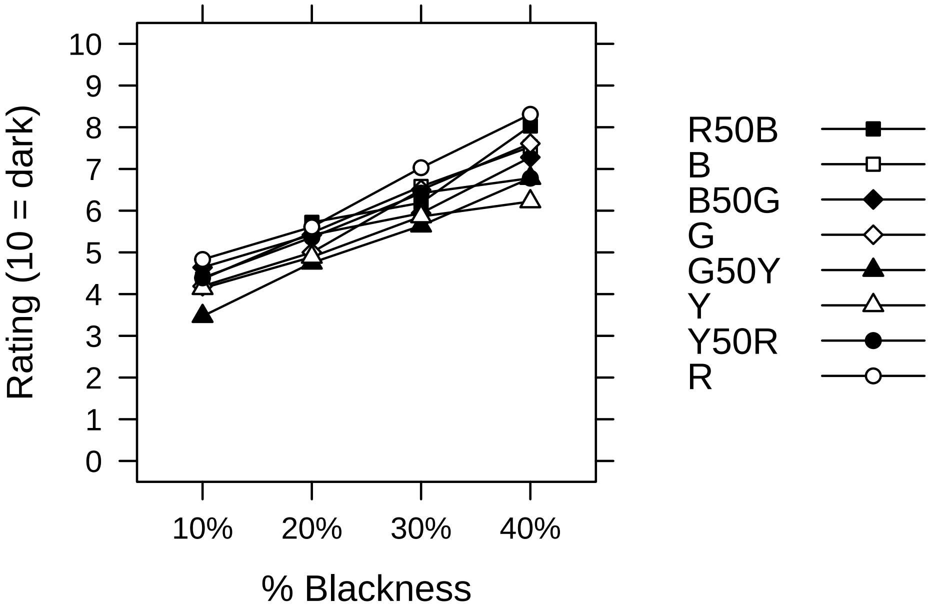

Figure 14: Ratings of lightness and darkness from Experiment 1, for each hue, at a constant level of 50% saturation and over four levels of lightness.

since saturation and lightness were found to be secondary to hue in determining warmth/coolness ratings. In addition, the null point at which the color appears neither warm nor cool was defined for the subjects in order to eliminate the necessity of estimating this parameter when comparing the data to the opponent channel activation.

Method

Subjects

Thirteen students, aged 16–21, with normal color vision participated in this experiment as part of a research participation requirement for Introductory Psychology.

Materials

The materials were identical to those used in Experiment 2.

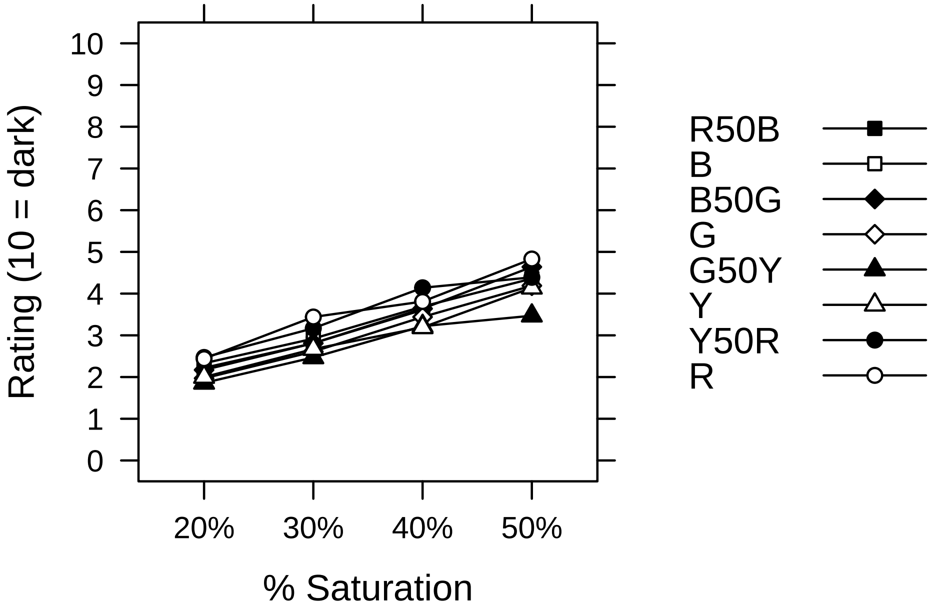

Figure 15: Lightness/darkness ratings from Experiment 1, for each hue, over four levels of saturation and a constant level of 10% blackness.

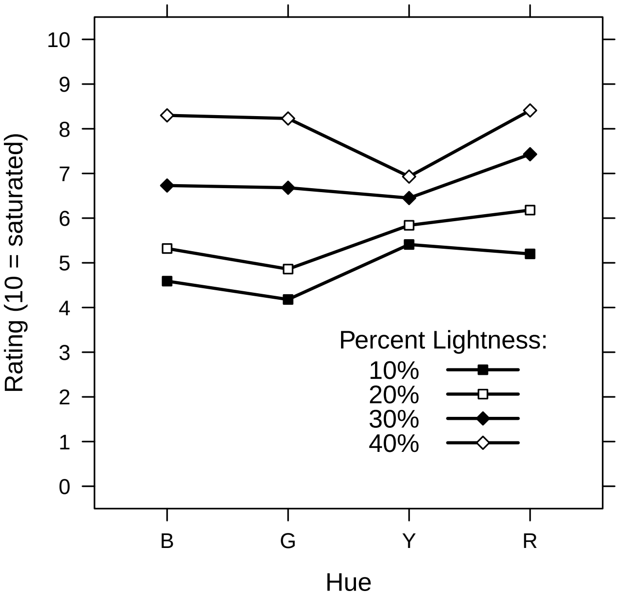

Figure 16: Mean saturation ratings from Experiment 2, at four levels of lightness and a constant saturation of 50%.

Apparatus

The apparatus was identical to that used in the previous two experiments.

Table 11: Mean saturation ratings for Experiment 1, over changes in lightness at a constant saturation of 50%, and the largest differences between two hues at each level of lightness and between two lightness levels at each hue.

	Percentage of Blackness				
Hue	10%	20%	30%	40%	Largest Difference
B	4.59	5.32	6.73	8.30	3.70
G	4.18	4.86	6.68	8.23	4.05
Y	5.41	5.84	6.45	6.93	1.52
R	5.20	6.18	7.43	8.41	3.21
Largest Difference	1.23	1.32	0.98	1.48	

Table 12: Mean saturation ratings in Experiment 1, at four levels of saturation and a constant blackness of 10%, and the largest differences between two hues at each level of saturation and between two saturation levels at each hue.

	Saturation				
Hue	20%	30%	40%	50%	Largest Difference
B	1.21	2.82	3.82	4.59	3.38
G	1.55	2.32	3.32	4.18	2.63
Y	2.30	3.48	4.84	5.41	3.11
R	2.41	3.52	4.41	5.20	2.79
Largest Difference	1.20	1.20	1.52	1.23	

Procedures

Each session was similar to those in the previous studies except that each subject rated only the warmth/coolness of the chips and rated each chip six times. In addition, subjects used a rating scale from -5 to +5, with zero defined as neither warm nor cool. For the first eight subjects, half used a scale with -5 designated as very cool and +5 as very warm, while the other half used a reversed scale, with -5 designated as very warm and +5 as very cool. However, three of the four subjects assigned the scale with -5 as very warm reported that thinking of warmth in terms of negative numbers was extremely difficult and made the task unnecessarily hard. Therefore, the remaining 5 subjects all used a scale with -5 designated as very cool and +5 as very warm.

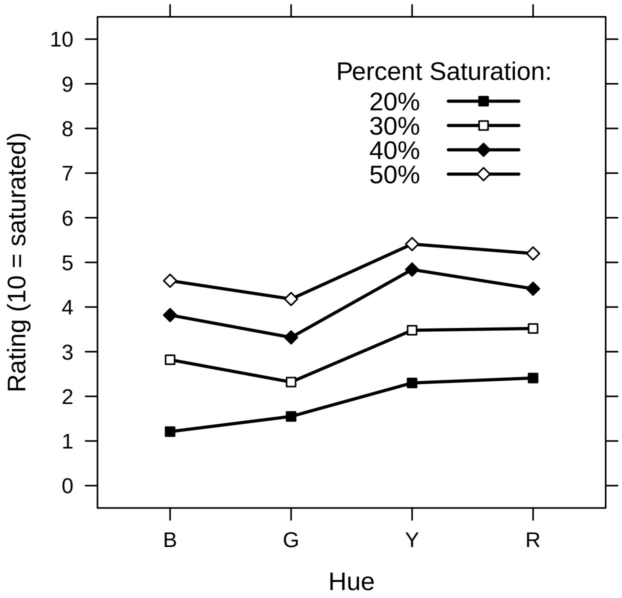

Figure 17: Mean saturation ratings from Experiment 2, over four levels of saturation and at a constant level of 10% blackness.

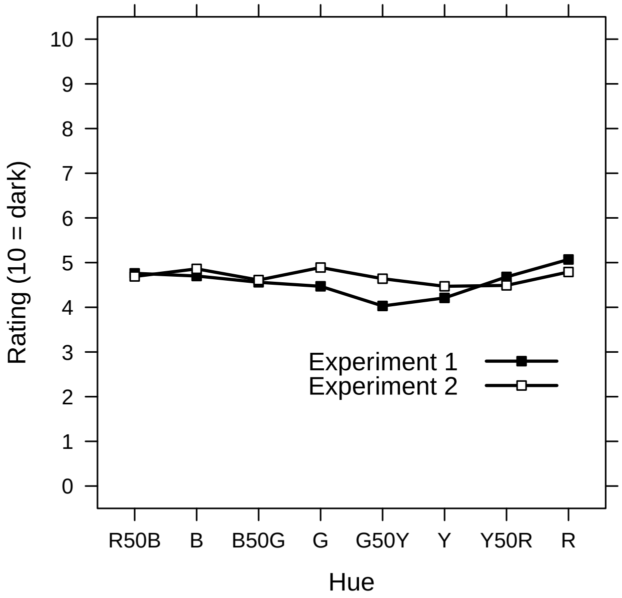

Figure 18: Mean lightness/darkness ratings averaged over all subjects, saturations, and lightnesses for Experiments 1 and 2.

Results

Because subjects who used the scale with -5 as very warm reported such difficulty in remembering that warmth corresponded to negative numbers, their data were discarded on the assumption that

Table 13: Mean lightness/darkness ratings averaged over subjects, saturation, and lightness: and standard deviations for Experiments 1 and 2.

Hue	Experiment 1	Experiment 2
R50B	4.76 ± 2.25	4.69 ± 1.86
B	4.70 ± 1.92	4.86 ± 1.53
B50G	4.56 ± 1.81	4.61 ± 2.02
G	4.47 ± 2.05	4.89 ±1.78
G50Y	4.03 ± 1.77	4.64 ± 1.80
Y	4.21 ± 1.72	4.47 ± 2.09
Y50R	4.68 ± 1.60	4.49 ± 1.94
R	5.07 ± 2.08	4.79 ± 2.19

Table 14: Mean lightness/darkness ratings for Experiment 2 at two levels of saturation and a constant level of lightness, the differences between the two levels at each hue, and the largest difference between two hues at each level of saturation.

Hue	Low	High	Difference
R50B	3.20	4.11	0.91
B	3.30	4.93	1.63
B50G	3.25	3.64	0.39
G	3.27	4.61	1.34
G50Y	2.84	4.66	1.82
Y	2.18	4.95	2.77
Y50R	2.73	4.18	1.45
R	2.75	4.50	1.75
Largest Difference	1.12	1.31	

they were more likely to reverse the scale, introducing added variability unrelated to their intended ratings, into their data. For the remaining nine subjects data were averaged over all six trials to produce each individual's mean rating for each chip (See Appendix E). These mean ratings were then averaged across subjects.

Table 17 and Figure 22 display the mean ratings, averaged across subjects, for the two levels of saturation. The shift from a lower to a higher level of saturation consistently produced warmer ratings, except at B where the rating shifted to 0.35 rating points cooler. A MANOVA again produced significant main effects for both saturation and hue, as in Experiment 1, F(1,8) = 9.89, $p < 0.02$, and F(7,56) = 27.64, $p < 0.001$, respectively. However, in this experiment, the interaction between saturation and hue was also highly significant, F(7,56) = 4.43, p = 0.001. The difference between ratings at the two levels of saturation tended to be higher for the warmer hues than for the cooler ones. Thus, as saturation increased, the increase in warmth was larger for the hues already rated as warm than for the cooler hues.

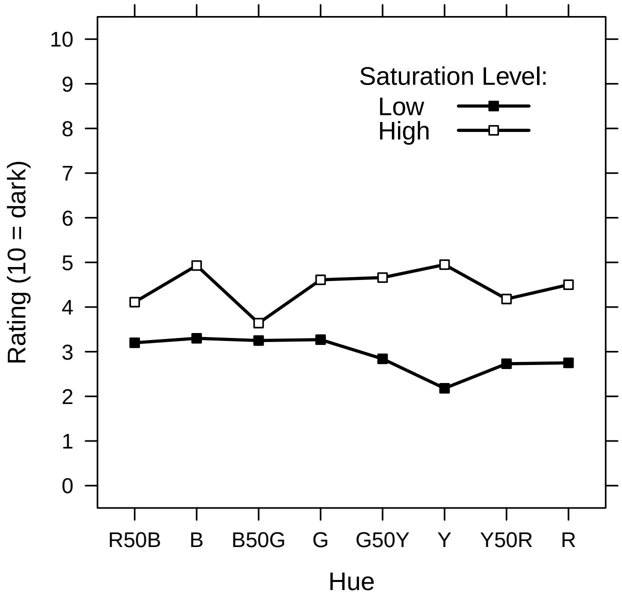

Figure 19: Mean lightness/darkness ratings from Experiment 2, at two levels of saturation and a constant blackness of 10%.

The effects of changes in lightness and hue are illustrated in Table 18 and Figure 23. Again, differences in hue significantly affected the warmth/coolness ratings, F(7,56) = 33.31, $p < 0.001$, With the coolest ratings at B and the warmest at Y50R and R. The main effect of lightness was not significant, F(1,8) = 0.20, ns, but the interaction between lightness and hue was, F(7, 56) = 3.59, p = 0.003. As in the case of increasing saturation, an increase in blackness produced a slightly cooler rating at B. In addition, the increase in blackness corresponded with cooler ratings for both Y and Y50R. However, since there was no systematic relationship between the shifts in ratings at each hue, the nature of this interaction is unclear.

Ratings were then averaged over all levels of saturation and lightness, producing the mean ratings for each hue depicted in Table 19 and Figure 24. As Figure 24 shows, the ratings followed the same general trend as in Experiment 1. An attempt was again made to relate these results to the theoretical activation of the opponent channels. Because the instructions in this experiment defined the null point for the subjects, no estimation of this parameter was required. Thus, the data from Table 19 were simply normalized to fit the same scale as the activation values. The activation values were obtained in the manner described in the results and discussion of Experiment 1, with the R-G and B-Y response functions both multiplied by 1.0. The resulting activation values, along with the corresponding wavelengths and the normalized data are presented in Table 20, with the activation values and normalized data plotted in Figure 25. As this figure shows, the correspondence between the theoretical activation of the opponent channels and the obtained warmth/coolness ratings is very close.

The results from this experiment support the contention that hue is the most important factor in determining the perceived warmth or coolness of colors (Wright, 1962; Ross, 1938). Hues with

Table 15: Mean lightness/darkness ratings for Experiment 2 at two levels of lightness and a constant level of saturation, the differences between the two levels at each hue, and the largest difference between two hues at each level of lightness.

	Blackness Level		
Hue	Low	High	Difference
R50B	4.11	6.77	2.66
B	4.93	6.36	1.43
B50G	3.64	6.93	3.29
G	4.61	6.80	2.19
G50Y	4.66	6.43	1.77
Y	4.95	6.27	1.32
Y50R	4.18	6.57	2.39
R	4.50	7.11	2.61
Largest Difference	1.31	0.84	

wavelengths longer than 550 nm (the wavelength corresponding to G50Y) were rated as warmer than those with wavelengths shorter than 550 nm, while G50Y was rated as neutral. This result qualifies Ross' (1948) assertion that all colors from pure yellow through red are seen as warm while all colors from green-yellow to bluish-magenta are seen as cool, as well as Tatibana's (1937) finding that red through yellow hues are warm while blue is cold. Contrary to the general conclusion that red is rated as the warmest color (Lewinski, 1938; Wright, 1962), the present study showed that an orange hue consisting of 50 percent red/5O percent yellow was the warmest. Furthermore, while Wright (1962) claimed that as hue progressed around the Munsell color circle from red to blue warmth ratings should become progressively cooler, the present study showed that ratings first increased from red to orange, then steadily decreased until blue, where they rose again toward purple. However, the rating of blue as the coldest color is in agreement with these past studies.

The present results also agree with Ross' (1938) and Wright's (1962) conclusion that as saturation increases ratings of warmth tend to increase as well. Furthermore, the present study showed that this increase depends on which hue is observed. The difference in ratings between levels of saturation was generally higher for the warmer hues than for the cooler hues.

On the other hand, lightness alone does not affect warmth/coolness ratings, a finding in contradiction with Wright's (1962) claim that increasing darkness produces warmer ratings. There was no consistent trend in ratings as the level of blackness was changed. Three of the hues, B, Y, and Y50R had lower ratings of warmth when blackness increased, while the other five had higher ratings.

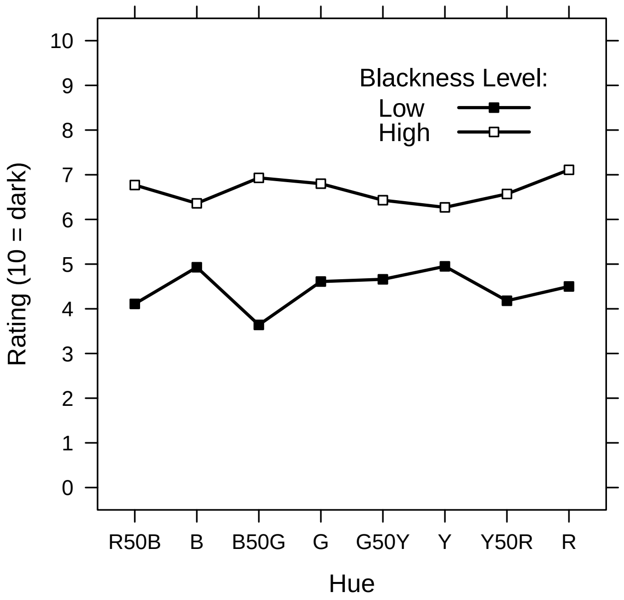

Figure 20: Mean lightness/darkness ratings from Experiment 2, at two levels of lightness and a constant saturation of 50%.

1 General Discussion

Results from the latter two experiments support the distinction between warm and cool colors, but not between intrinsically light and dark colors. While this paper discusses three studies, the results of the last two supersede those of the first since the stimuli used in the first experiment were found to be unequated for saturation and lightness under the viewing condition used.

Contrary to the observations of intrinsically light and dark colors, the distinction between them was not empirically supported. When stimuli were properly calibrated for saturation and lightness, ratings of lightness and darkness were significantly affected by changes in both saturation and lightness, but not by differences solely in hue. However, while increases in saturation and in blackness produced darker ratings, the size of the increase in ratings depended on which hue was observed. For example, when saturation increased from a lower to a higher percentage, the increase in darkness ratings was much greater for 100 percent yellow than for 50 percent blue/5O percent green. Conversely, when the percentage of blackness increased, the increase in darkness ratings was much greater for 50 percent blue/50 percent green than for 100 percent yellow. While these interactions between saturation and hue and lightness and hue are significant, their exact nature is yet unknown and warrants further investigation. At any rate, the intrinsic lightness or darkness of colors was not found to exist in this study as the lightness/darkness response function of average ratings at each hue approximated a flat line. It is possible that the distinction originally made between intrinsically light and dark colors arose from an observation that the yellows seen in nature tend to be brighter and less saturated than the blues. As Von Bezold (1876) explained, ”Yellow asserts its characteristic hue best of all at a very high degree of brightness, violet at a very

Table 16: Activation values after multiplying the R-G and B-Y functions by 0.1, re-scaled data, adjusted data, and normalized data for Experiment 2.

Hue	Activation Value	Re-scaled Data[1]	Adjusted Data[2]	Normalized Data[3]
R50B	0.00	5.31	0.01	0.01
B	-0.20	5.14	-0.16	-0.17
B50G	-0.01	5.39	0.09	0.10
G	-0.11	5.11	-0.19	-0.20
G50Y	0.00	5.36	0.06	0.06
Y	0.11	5.53	0.23	0.24
Y50R	0.17	5.51	0.21	0.22
R	0.10	5.21	-0.09	-0.10

[1] Data after reversing the scale. [2] Adjusted data using a null point of 5.3. [3] Adjusted data multiplied by 1.06.

low degree" (p. 99). Thus, we may think the best example of a yellow is lighter than the best example of a blue, but the lightness or darkness of a hue is not an intrinsic property of that hue. As we have shown, when a yellow and blue are equated for saturation and lightness, no differences exist in their perceived lightness or darkness. Thus, we reserve the terms light and dark for use in describing the variations in any one color as its saturation and lightness vary.

Although the distinction between intrinsically light and dark colors was not substantiated, the separation of hues into warm and cool was. As hue varied throughout the spectrum at eight equal phenomenological steps, from a purplish color at 50 percent red/50 percent blue to 100 percent red, the warmth/coolness response function followed an S-shaped curve, with the coolest rating at 100 percent blue and the warmest at 50 percent yellow/50 percent red. As in past research (Wright, 1962; Ross, 1938), hue was shown to be the main factor in determining whether a color is warm or cool.

In addition to the differences in hue, the ratings of warmth and coolness were influenced by changes in the saturation of each hue. As the amount of saturation in each hue increased, the ratings of warmth increased as well, except at 100 percent blue where the rating became cooler with an increase in saturation. While comparable changes in the percentage of blackness in each color produced no consistent trends, the interaction of lightness with hue did play a significant role. Although for most hues the rating at a low percentage of blackness was warmer than that at the higher percentage of blackness, this was not the case for three of the eight hues at which an increase in lightness corresponded with cooler ratings.

While these and past experiments have empirically demonstrated that colors can be separated into warm and cool hues, the question regarding the origin of these evaluations is still unanswered. Does the color actually evoke a physiological response in the observer which causes them to classify it as warm or cool? Does it actually cause a change in perceived temperature of a surface or

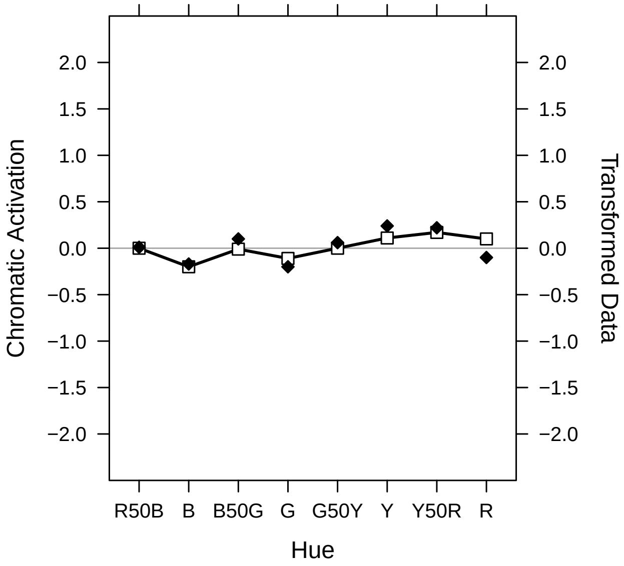

Figure 21: Comparison between the theoretical chromatic activation of the opponent channels and the obtained data (after being re-scaled) from Experiment 2, after multiplying the R-G and B-Y activation curves by 0.1 and using a null point of 5.3.

surroundings associated with it, or does it simply give a visual appearance of warmth? Is there something inherent in the color that causes us to classify it as warm, or is our association of color with temperature simply a cognitive process? These questions are not answered in any simple manner. Gerard (1958) obtained both physiological and affective responses to colors from his subjects. For all physiological measures (blood pressure, palmar conductance level, respiration rate, EEG, muscle potentials) except heart rate, he found that subjects exhibited greater reactions to red than to blue or white.

In addition, ratings of the affective responses to color consistently portrayed red the most negatively. Thus, while his results appear to indicate that colors both appeared to have emotional qualities and actually produced physiological reactions, it is not clear whether these physiological responses occurred at the same time as the cognitive associations with temperature, or whether one caused the other. On the other hand, Fanger, Breum and Jerking (1977) found that subjects preferred significantly warmer ambient temperature when exposed to blue than red light but did not find any differences in the physiological measures when exposed to these lights. In this case, the colors appear to have given the suggestion of warmth or coolness, but with no actual physiological response. However, other studies have obtained significant differences in physiological responses when subjects were exposed to different colors (Jacobs and Hustmeyer, 1974; Wilson, 1966; for a more complete review see Kaiser, 1984). Because of these conflicting results, the specific physiological effects of exposure to colors have been unclear. Does the warmth/coolness response result from physiological activation or is this physiological activation, along with the warmth/coolness response, a product of cognitive processes?

Results from these experiments may suggest an answer to this question. The remarkable corre-

Table 17: Mean warmth/coolness ratings for Experiment 3 at two levels of saturation and a constant level of lightness, the differences between the two levels at each hue, and the largest difference between two hues at each level of saturation.

	Saturation		
Hue	Low	High	Difference
R50B	-1.54	-0.98	0.56
B	-2.61	-2.96	-0.35
B50G	-2.83	-2.37	0.46
G	-1.28	-0.96	0.32
G50Y	-0.41	0.17	0.58
Y	1.56	2.39	0.83
Y50R	2.04	3.39	1.35
R	1.02	2.26	1.24
Largest Difference	4.87	6.35	

Table 18: Mean warmth/coolness ratings for Experiment 3 at two levels of lightness and a constant level of saturation, the differences between the two levels at each hue, and the largest difference between two hues at each level of lightness.

	Blackness Level		
Hue	Low	High	Difference
R50B	-0.98	-0.72	0.26
B	-2.96	-3.74	-0.78
B50G	-2.37	-2.04	0.33
G	-0.96	-0.26	0.79
G50Y	0.17	0.67	0.50
Y	2.39	1.80	-0.59
Y50R	3.39	3.02	-0.37
R	2.26	3.43	1.17
Largest Difference	6.35	7.17	

spondence between the obtained ratings of warmth and coolness and the activation levels in the opponent channels, derived from the Opponent Process Theory, suggests that the attribution of thermal properties to colors may be linked to the low-level physiological processes involved in color perception. Higher ratings of warmth corresponded with levels of activation of the opponent channels in one direction, while cooler ratings corresponded with activation in the opposite direction. This suggests that a link to the activation level of the opponent channels, rather than the psychological quality of hue, drives the association of temperature with color, and that the association is more than simply a cognitive process. Perhaps the disparity in the results from past studies

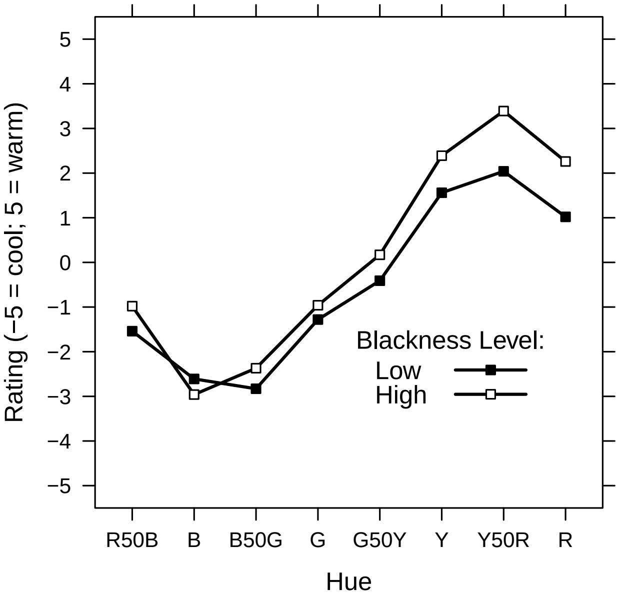

Figure 22: Mean warmth/coolness ratings from Experiment 3, over two levels of saturation and a constant level of 10% blackness.

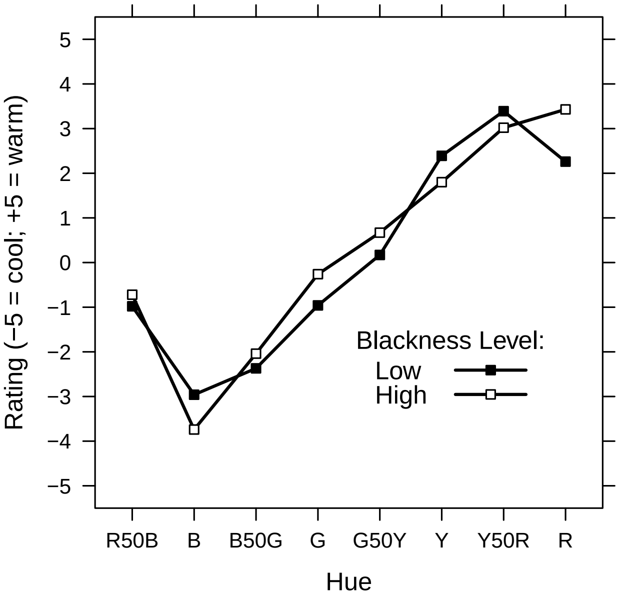

Figure 23: Mean warmth/coolness ratings from Experiment 3, over two Ievels of blackness and a constant level of 50% saturation.

of physiological responses would be reduced if one could measure the physiological activation at a lower level.

This proposed link between the opponent channel activation and the warmth/coolness responses

Table 19: Mean warmth/coolness rating and standard deviation for each hue averaged over all subjects, saturations, and lightness levels in Experiment 3.

Hue	Warmth/Coolness Rating	Standard Deviation
R50B	-1.08	0.42
B	-3.10	0.58
B50G	-2.41	0.40
G	-0.83	0.52
G50Y	0.14	0.54
Y	1.91	0.43
Y50R	2.81	0.70
R	2.23	1.21

Table 20: Hues and their corresponding wavelengths, activation values, and normalized data for Experiment 3.

Hue	Wavelength	Chromatic Activation	Normalized Data[1]
R50B	400	0.00	-0.66
B	475	-2.00	-1.89
B50G	490	-1.03	-1.47
G	505	-1.08	-0.51
G50Y	550	0.00	0.09
Y	575	1.12	1.17
Y50R	600	1.61	1.71
R	640	0.99	1.36

[1] Data from Table 17 multiplied by 0.61.

could be further strengthened by an investigation into the effects of changing luminance on 4 warmth/coolness ratings. Limitations of the NCS system did not allow manipulation of the intensity, or brightness, of the stimuli, but using lights, rather than surfaces, as stimuli would eliminate this restriction. If the link between the opponent channel activation and warmth/coolness responses exists, as the luminance of the light increases, the rating of warmth should increase as well. With greater intensity, more photons are absorbed by the eye, thereby increasing the activation levels; if these levels are linked to ratings of warmth and coolness, a comparable increase in perceived warmth should occur as well. However, until further studies are conducted we can only postulate that the attribution of thermal properties to colors is more than simply a cognitive association. While the results from Ross' (1938) study strongly suggest that the association of colors with objects or conditions having thermal properties plays a large role in whether a color is rated as warm or cool, he admits that it is not conclusive whether the attribution of temperature to colors

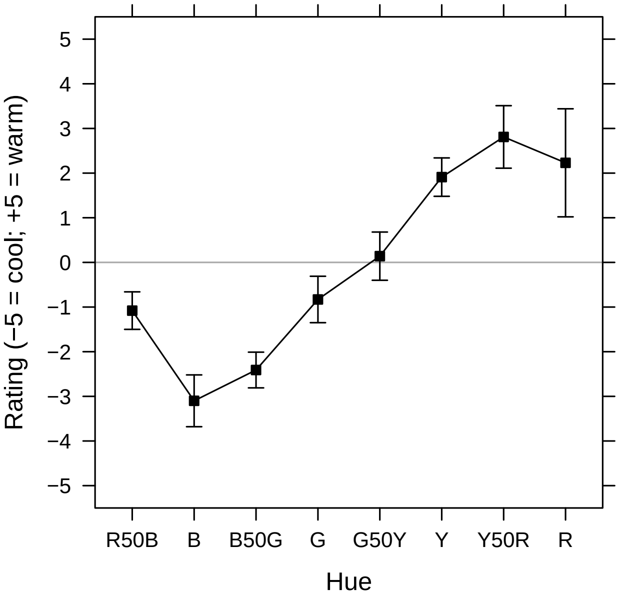

Figure 24: Mean warmth/coolness ratings and standard deviations from Experiment 3, averaged over all subjects, saturations, and lightness levels.

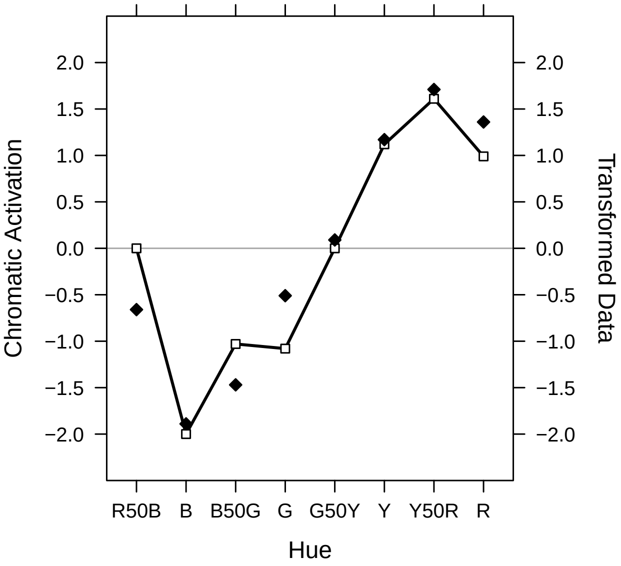

Figure 25: Comparison between the theoretical activation values of the opponent channels and the obtained data in Experiment 3. The R-G and B-Y activation functions were multiplied by 1.0 and the null point was specified as zero in the instructions to subjects.

is the consequence of ontogenetic factors only. While the association hypothesis undoubtedly has some value, the present results suggest that phylogenetic factors may be involved as well.

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