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SHORT COMMUNICATION

COLOR RESEARCH AND APPLICATION WILEY

Warm and cool reheated

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Abstract

Among more conventional perceptual attributes, such as hue brightness and saturation, color is universally assigned a value along a warm/cool dimension. The source of this aspect of color experience is uncertain and a subject of current debate in color science. An unpublished study from the late twentieth century has recently appeared in an online archive that makes publicly available the results of an extensive set of measurements that document the variation of warm/cool values throughout color space and shows that they relate simply to the sum of the red-green and blue-yellow opponent-color activations (red+yellow vs. blue+green), which the authors suggest is consistent with a sensory basis for this distinction.

KEYWORDS

color appearance, scaling, warm/cool

Color is conventionally defined as 3-dimensional. The sums of 3 independent primary lights in an additive color space specify lights that match based on the independent activation of the long-, medium-, and short-wave-length sensitive (L,M,S) cone photoreceptors. The cone signals are in turn combined in the retina to form 3 primary or "cardinal" mechanisms that convey cone-antagonistic (LvsM or SvsLM) and luminance (L + M) signals. Perceptually, attributes of hue, saturation and brightness suffice to characterize the color appearance of uniform surfaces. These attributes can be parameterized in terms of 3 bipolar color dimensions: spectrally opponent red-green and yellow-blue and spectrally non-opponent white-black. Nevertheless, colors are also reliably judged as having other attributes described variously as affective, emotional, thermal, cognitive, etc.[1] Hering[2] proposed that "certain colors also possess intrinsic lightness values." What is the basis for these additional dimensions of color experience?

One quality ubiquitously ascribed to color is its value along a warm/cool dimension;[3] warm colors are generally associated with predominantly long-wavelength lights and cool with short-wavelength spectra. This distinction has long been embraced in the visual arts[4] and in some industrial applications and may be closely associated with the widely-used "orange-teal" color scheme.[5] This opponent-like dimension of color appears to be fundamental and independent of culture.[6,7] A long-standing issue concerns whether it is of sensory or cognitive origin. Is the warm/cool distinction a constraint imposed by the structure of sensory coding,[8] a cognitive construct,[9] a characteristic of the stimuli, how effectively we can label and communicate about them[10] or a combination of all of these explanations?[5] To the extent that our sensory apparatus has evolved to be tuned to the characteristics of the environment and our behavioral interactions with it,[11–13] this may turn out to be a chicken and egg question.

Most studies referring to warm versus cool have used it to allude to the idea that there is a superordinate division of color,[7,10,14] while the actual specification of what constitutes a warm vs. cool sensation remains poorly characterized (though some descriptive models have been proposed[1]). However, in reviewing this literature we came across references to an unpublished but occasionally cited thesis completed nearly 30 years ago (in 1994) by Elan Katra working with Billy R. Wooten at Brown University. The study likely would have remained in obscurity in Brown's John Hay library except that the work had ignited the interest of the late color philosopher C.L. Hardin, who wrote extensively about it.[3,15–17] The work has now appeared online on an OpenSource archive.[18] The study included three experiments in which lightness/darkness and warm/cool ratings were obtained from observers presented with chips from the Natural Color System (NCS) atlas that varied in hue, saturation and lightness. The mean rating data by subject and chip are available in supplementary tables at https://osf.io/s5pav/ in a format permitting further analyses by interested investigators.

In the initial experiment, 8 hues, with equal perceptual spacing around the color circle, were tested at equal saturation over 4 lightness levels and equal lightness over 4 saturation levels. Warmth/coolness depended principally on hue with only minor variations with lightness and saturation. Warmth was maximal at an orange hue and coolness at blue. The hue that was neither warm nor cool had equal proportions of yellow and green, more or less independently of saturation and lightness. Testing this invariance using a more densely sampled set of colors could have interesting implications for assessing the extent to which the putative warm/cool dimension exhibits additivity or nonlinearities as characterized for other dimensions of color appearance.[19–21] A second equilibrium warm/cool color should appear in the purplish region, but their sparse sampling of hues did not permit identifying this.

A slight variation in lightness with hue was observed with minimum lightness near the warm/cool equilibrium color. The authors noted, however, that the lamp recommended for viewing the NCS chips (CIE illuminant C) was not the same as that under which the atlas was originally calibrated and standardized. To address the possibility that their results were influenced by this difference, they asked an independent group of subjects to rate the chips for lightness and saturation, in order to select a set of colors that were on average perceptually equal along these attributes. The initial rating experiments were then repeated with a third group of subjects using these *perceptually* calibrated surfaces. Under these circumstances, the variations in lightness ratings of the hues at equal saturation and lightness disappeared, thus, demonstrating the absence of intrinsic lightness values with hue. Importantly, the results with respect to the warm/cool ratings continued to stand; that is, the relation between the perceptual chromatic opponent activations and the warm/cool ratings was unchanged.

There are several notable features of these results. First, they provide a quantitative data base that systematically and thoroughly documents this universal but poorly understood dimension of color experience. While the data are based on subjective ratings, these have been shown to correspond closely to results obtained using more rigorous scaling methods.[22–24] Individual data and comparisons within and across observers are reported in the study. Observers were generally consistent at judging this dimension – indicating that the warm-cool construct showed inter-subject agreement and psychological validity. Second, their analyses constitute one of the first attempts to relate warm/cool judgments to fundamental visual mechanisms. The orange peak for warm places the axis intermediate to Hering's red-green and blue-yellow dimensions. And while not considered in their analyses, the dimension is also distinct from the cardinal axes, which vary through gray from red to cyan (LvsM) or purple to chartreuse (SvsLM). Instead, the warm-cool valence represents a combination of red with yellow, and green with blue. Why should these combinations have significance? One possibility is that they describe the properties of surfaces. For example, Gibson et al.[6] analyzed a large database of images and proposed that objects are more likely to be warm hues while backgrounds cool. Another possibility is that they refer to illuminants. The blue-yellow axis is closely aligned with the daylight locus,[25,26] but the orange glow of fire and the transitional hues of sunset also have potential physiological and psychological importance.[27]

The authors took their analysis a step further to show that the warm-cool ratings were not just intermediate to the red-green and blue-yellow axes but could be predicted from them. Specifically, the settings closely followed the summed activations of the average RG and BY chromatic valence functions based on independent studies of hue cancellation.[28] This result is replotted from their study in Figure 1, to show the warm-cool rating as a function of the dominant wavelength of each chip tested (chip designations indicated on the top scale). The red and blue

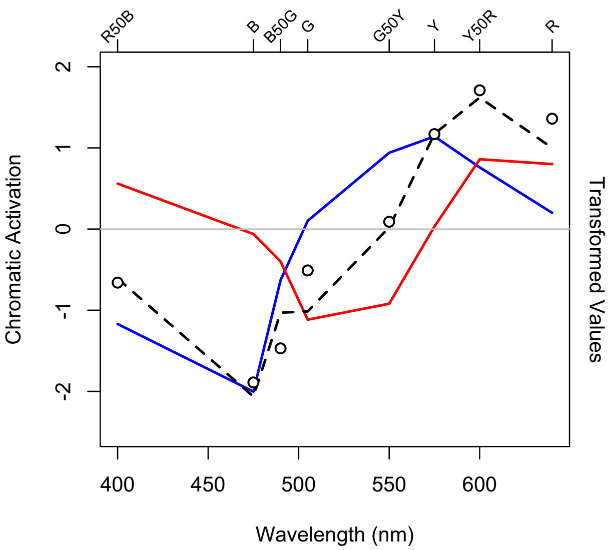

FIGURE 1 Similarity of average warm/cool ratings (unfilled points) with the sum of average hue-cancellation based opponent-color activation functions (dashed black lines; $r^2 = 0.96$) replotted from Katra et al.[18] The calculated activations of red-green (red lines; $r^2 = 0.23$) and yellow-blue (blue lines; $r^2 = 0.66$) functions based on average hue cancellation functions are shown for comparison.

lines indicate the calculated activations of red-green and yellow-blue functions, respectively, at equal luminance. The points show the ratings transformed to be on a similar scale as the activations, at the values tested. Neither the peaks nor the crossings of either chromatic activation function match those of the ratings. On the other hand, a sum of these activations (black dashed line) does follow these values closely, supporting that the warm/cool dimension depends on the activations of both chromatic mechanisms.

It was this final point that most interested Hardin—for it suggested that the warm-cool distinction was not simply a cognitive construct but might have a more elemental origin in sensory processing. However, in the 30 years since the work was completed, the status of Hering's mechanisms has itself become increasingly questioned.[29–35] Moreover, while the concordance between the average warm-cool and summed RG and BY functions is striking, it is not clear that it holds at an individual level, because the focal stimuli for even nearby hues, like orange and red and yellow, are surprisingly independent.[36] Nevertheless, the availability of this study may rekindle interest in the questions surrounding the origin and sense of the warm/cool color dimension and reheat debates on what it means. And this is perhaps the most important lesson. How many other insights into the hot topics of the day lie cold and hidden because – for whatever reason – they were not ultimately published?

AUTHOR CONTRIBUTIONS

All three authors contributed to the writing and editing of the article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Perceived Lightness/Darkness and Warmth/Coolness in Chromatic Experience at https://osf.io/s5pav/.

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