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Asymmetries in blue–yellow color perception and in the color of 'the dress'

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The perception of color poses daunting challenges, because the light spectrum reaching the eye depends on both the reflectance of objects and the spectrum of the illuminating light source. Solving this problem requires sophisticated inferences about the properties of lighting and surfaces, and many striking examples of 'color constancy' illustrate how our vision compensates for variations in illumination to estimate the color of objects (for example [1–3]). We discovered a novel property of color perception and constancy, involving how we experience shades of blue versus yellow. We found that surfaces are much more likely to be perceived as white or gray when their color is varied along bluish directions, compared with equivalent variations along yellowish (or reddish or greenish) directions. This selective bias may reflect a tendency to attribute bluish tints to the illuminant rather than the object, consistent with an inference that indirect lighting from the sky and in shadows tends to be bluish [4]. The blue–yellow asymmetry has striking effects on the appearance of images when their colors are reversed, turning white to yellow and silver to gold, and helps account for the variation among observers in the colors experienced in 'the dress' image that recently consumed the internet. Observers variously describe the dress as blue–black or white–gold, and this has been explained by whether the dress appears to be in direct lighting or shade (for example [5]). We show that these individual differences and potential lighting interpretations also depend on the special ambiguity of blue, for simply reversing the image colors causes almost all observers to report the lighter stripes as yellowish.

The original impetus for our work was a demonstration of color afterimages that was also popular on the internet, which involved adapting to the photographic negative of a portrait (Figure 1A). If one fixates the nose for 30 seconds and then looks at a blank part of the page, an afterimage is perceived. The afterimage is the opposite of the adapting image, and thus reveals the original colors of the portrait. Yet what struck us was the impression that the yellow and brown tones in the original appear more colorful than the complementary bluish tints of the negative. This difference is not due to familiarity or lighting cues, because we also observed that it persists when the pixels in the image are scrambled, and reflects reversal of the hue and not the brightness. It is also not due to spatial structure or chromatic aberration, because the differences persist even in uniform fields (Figure 1B,C).

Figure 1. Examples of blue-yellow asymmetries in images.
(A) Colors of a positive image and its negatives. The negative on the left appears less saturated than the adjacent original, and this is due to inversion of the image hues (third image) and not the luminance (fourth image). (B) The perceived color differences in these images persist when the pixels are scrambled or (C) when only the average chromaticity is displayed, and thus do not depend on familiarity or scene cues. (D–F) Further examples of images with chromatic contrast inverted. (D) The steel-gray vessels (left) change to bronze (right), and (F) silver coins (left) turn to gold (right). (E) In the dress, stripes that different observers variously perceived as white or blue in the original image (left) become unambiguous shades of yellow (right). (G) When the color saturation is amplified, increasing blueness is attributed primarily to biased lighting (left), but increased yellowness is attributed to the object (right) (see also Figures S1 and S2). Panel A reproduced with permission from Anjali Webster; panel E reproduced with permission from Cecilia Bleasdale.

To quantify these effects, observers were asked to name the color of noise or uniform patches that varied in chromaticity in different directions and contrasts in the hue circle (see Supplemental Information). When the patch was brighter or darker than the background, the range of chromaticities labeled as white was strongly expanded along a bluish axis, revealing a strong bias to label blue chromaticities as white (Figure S2). This range far exceeds the differences required to tell two 'whites' apart, and thus is not a failure of discrimination. The bias disappears when the test patch is equal in luminance to the background, differs from measures of threshold discrimination or standard metrics of suprathreshold saturation (Figure S1), and is selective for a chromatic axis to which cells early in the visual system are not tuned [6], arguing against sensitivity differences or an early nonlinearity in neural coding as a basis for the effect. This was further confirmed in studies of chromatic adaptation to alternating blue and yellow fields, which resulted in afterimages consistent with their linear average. The bias thus appears to reflect a 'high-order' inference about color, but one which does not require cues to the lighting or viewing geometry that are important to many demonstrations of color constancy [7].

In actual images, the blue–yellow asymmetry leads to large and surprising effects on the perceived color of surfaces (Figure 1D–G). Informal reports from observers showed that the bluish tints present in steel or silver appear largely unnoticed, yet transform to strong shades of bronze or gold when the color content is inverted. This perceptual asymmetry also accounts for the finding that yellowish sepia tones appear more colorful than an equivalent bluish tint, while blue shades such as shadows appear less colorful [4]. Moreover, even when blues are exaggerated, we observed they tend (unlike yellowish tints) to be perceived as a property of the lighting rather than the surfaces.

Similar effects underlie the colors seen in 'the dress' image that recently took the internet by storm. The lighter stripes of that image are reported as either blue or white, revealing dramatic individual differences. Many vision scientists noted that the different percepts probably depend on whether the dress is perceived to be in direct yellowish light (thus blue and black) or bluish shade (white and gold) [5]; however, an additional factor is the bluish tints in the image. When the color content is inverted, the stripes appear vivid yellow (Figure 1E). In a survey of 87 college students, observers were evenly split over the color of the lighter stripes in the original image (45% white, 44% blue), yet there was nearly unanimous agreement that the color-reversed stripes were shades of yellow or gold (94%), with no individual reporting white.

This pattern was confirmed in a second sample of 80 observers, who also judged additional images of the dress which were manipulated to increase or decrease the physical saturation of the colors. Surprisingly, many continued to call the lighter stripes white even when the color contrast was increased three-fold. Conversely, almost all observers reported that these stripes appeared yellowish when their colors were inverted, even when the color contrast was cut in half (Figure S2H). Large individual differences were also found in the achromatic boundaries measured in the color naming task (Figure S2E,F), with observers varying in how much chromatic contrast was needed before they labeled the patches as blue or yellow. The individual boundaries for blue or yellow did not predict observers' percepts of the dress. However, a significant interaction was found between the blue versus yellow boundaries and the dress percepts, such that observers who saw the dress as white and gold were more likely to have larger blue–yellow asymmetries in their color naming ($F(1,39) = 7.02$, $p = 0.012$). Thus, an important contributing component of the color appearance of the dress, and why it varies across observers, is the relatively greater ambiguity in the blue–white boundary, which may increase the tendency to perceptually discount the blue.

Natural lighting from the sun and sky varies from yellow to blue [8], and observers are more tolerant (and differ more from each other) when judging what looks white along the blue–yellow axis [9]. Our findings, along with other recent work [10], reveal important asymmetries within this axis. The different phenomena we explored may all reflect an inference that indirect lighting and shadows are bluish, and a bias to attribute that blueness to the lighting rather than the surface, even when the surface is shown in isolation from all scene cues.

SUPPLEMENTAL INFORMATION

Supplemental information includes experimental procedures, results and two figures and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2015.05.004.

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