Nous allons vous demander de commenter trois articles ayant étudié expérimentalement la controverse concernant la couleur perçue d'une robe dont la photographie a circulé largement sur les réseaux sociaux (#TheDress). Brièvement, les différents observateurs étaient en désaccord radical sur la couleur de cette robe.

Commentaire (20 pts, 4 pts par question) :

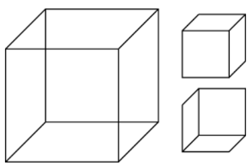
1) Dès le 19ème siècle, Helmholtz propose l'idée « d'inférence inconsciente » pour décrire la perception chez l'Homme. L'idée centrale est que nous incorporons de façon impérative des éléments supplémentaires aux signaux sensoriels pour percevoir le monde qui nous entoure.
Commentez, en soulignant notamment pourquoi la nature physique du processus perceptif rend cette hypothèse plausible.
Voyez-vous une filiation avec une ou des théories cognitives récentes de votre choix ?

2) Comment le problème d'inférence se pose dans le cas de #TheDress décrit dans les articles proposés pour le commentaire ? Quelles sont les propriétés particulières de la photographie qui ont, selon les auteurs, causé ce phénomène ?

3) Décrivez les aspects méthodologiques qui ont permis de caractériser de façon psychophysique le phénomène, et contribué à préciser sa nature sensorielle ou décisionnelle ?

4) Une classe de stimulus donnant lieu à diverses interprétations, comme par exemple le cube de Necker ou le vase de Rubin (voir ci-dessous), a été étudiée depuis de nombreuses années. En quoi la perception de #TheDress est-elle similaire ou différente de ces stimuli dits « bistables » ?

5) Selon les données présentées, pensez-vous que les biais observés sont à court ou à long terme ? En quoi de tels biais pourraient être utiles pour l'étude expérimentale (e.g. bases cérébrales, etc.) de la perception ?

Cube de Necker



Vase de Rubin

Current Biology
Magazine

CellPress

Correspondence

The many colours of 'the dress'

Karl R. Gegenfurtner[1], Marina Bloj[1,2], and Matteo Toscani[1]

There has been an intense discussion among the public about the colour of a dress, shown in a picture posted originally on Tumblr (http://swiked.tumblr.com/post/112073818575/guys-please-help-me-is-this-dress-white-and; accessed on 10:56 am GMT on Tue 24 Mar 2015). Some people argue that they see a white dress with golden lace, while others describe the dress as blue with black lace. Here we show that the question "what colour is the dress?" has more than two answers. In fact, there is a continuum of colour percepts across different observers. We measured colour matches on a calibrated screen for two groups of observers who had reported different percepts of the dress. Surprisingly, differences between the two groups arose mainly from differences in lightness, rather than chromaticity of the colours they adjusted to match the dress. We speculate that the ambiguity arises in the case of this particular image because the distribution of colours within the dress closely matches the distribution of natural daylights. This makes it more difficult to disambiguate illumination changes from those in reflectance.

As Newton remarked, colour is not a property of an object. It arises when a surface is illuminated and light is reflected into the eye of an observer, who interprets the light distribution of the whole scene and assigns a colour to the object. Remarkably, humans and animals are very good at assigning constant colours to objects, even though the retinal light stimulus is the ever-changing product of illumination and reflectance. A simple adaptation mechanism can explain this colour constancy to a large extent, but there are numerous other factors at work [1]. How can constancy then fail so badly in the case of this dress?

Constancy fails in the first place because the stimulus is not the real dress, but a photograph in which the automatic white balance setting of the camera did not match the true illumination of the scene. Once the image was taken, the colours that would be perceived by most observers when viewing the dress in real life (blue and black) are no longer perceptually available to the majority of observers. Different people see different colours when viewing the photograph; and that opens many interesting questions that have fascinated the public and scientists alike.

Clearly, physical factors play a role. When viewing the image on LCD screens at different viewing angles, vastly different colours emerge. Different viewing sizes certainly add to the variability [2]. However, even when viewing the image on the same device, from the same distance at the same angle, differences emerge. These must be due to the visual system of different observers performing different computations. What are these differences then, and how might they arise?

In the first few days following the posting, we made measurements in our lab of the colour percepts of 15 observers. The observers viewed the image of the dress on a well-calibrated colour display under controlled lighting conditions. They had the task of adjusting the colour of a disc, displayed on the same screen,

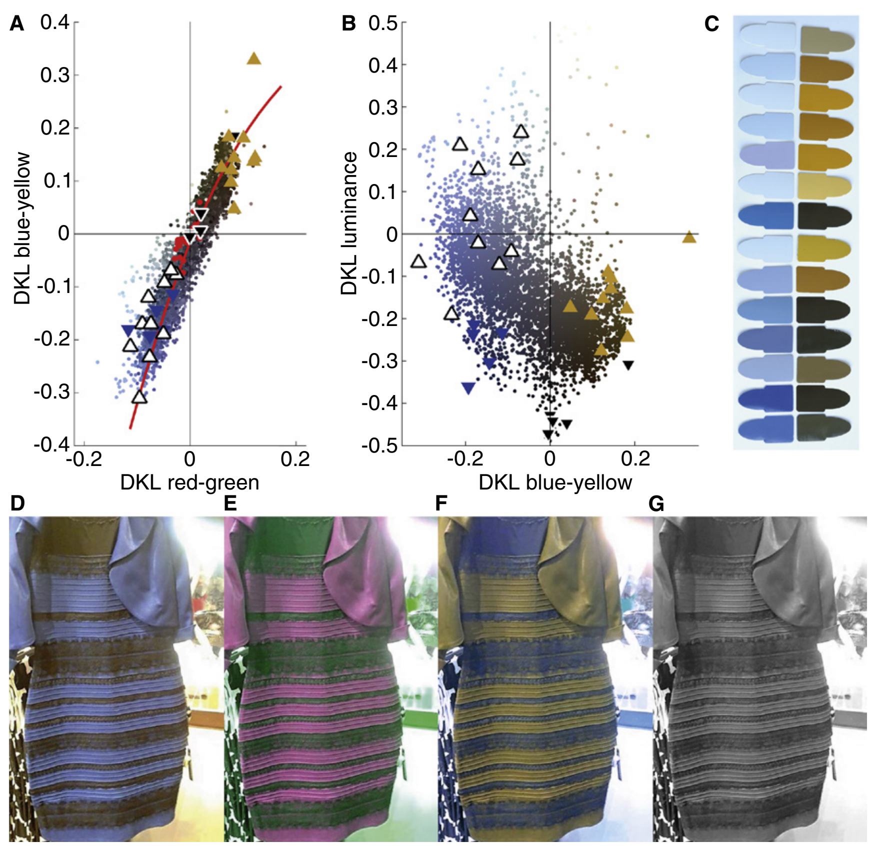


Figure 1. Color matches and manipulated images.
Distribution of coloured pixels within the dress in (A) chromaticity and (B) luminance, together with the colour matches of 15 observers. Dress matches (triangles) are shown in blue and lace matches in black for the observers perceiving the dress as 'blue and black', and in white and orange for the observers perceiving the dress as 'white and gold'. Red dots illustrate the variability of grey point matches, data replotted from [7]. The red curve indicates the daylight locus [4]. (C) Photograph of the Munsell selections for 14 of the same observers in the order of their luminance screen matches. The bottom five rows show selections of observers who reported seeing the dress as blue and black. (D) Original image. (E) All colour pixels within the dress were rotated 90 degrees in colour space, and (F) by 180 degrees. (G) Greyscale image. Further details available in Supplemental Information. Dress image reproduced with permission from Cecilia Bleasdale.

so that it would match for them the colour of the dress [3]. We also had them match the colour of the lace parts of the dress. In a separate task, we asked them to select from the Munsell Glossy collection the chip that best matched their recollection of the dress and lace colours (see Supplemental Information).

Displaying the participants' matches in colour space, we can infer that there is a continuous distribution of colour percepts, rather than a bimodal one, which might have been expected from the two labels colloquially used ('white and gold' versus 'blue and black'). Secondly, the dress matches for the two different groups of observers overlap to a large degree in Figure 1A, where only chromaticity is considered (t_{13} = 0.06, n.s.). They separate well when the luminance of the matches is taken into account in Figure 1B (t_{13} = 4.56, $p < 0.001$). This is also borne out by their choices of Munsell chips (Figure 1C) that largely overlap in Chroma and Hue for both groups, but differ in Value (Supplemental Information). Thirdly, the distributions of colours within both the dress and the lace fall near the same line through the origin of colour space (Figure 1A). This line is very close to the daylight locus, the set of all illuminant colours from yellow to blue that occur during the course of a day [4,5].

We can conclude from these results that different observers indeed perceive different colours when looking at the picture of the dress. However, the differences do not arise with respect to hue or saturation, but are mainly due to the perceived differences in lightness. The question should thus not be whether the dress is blue or white, but whether it is light blue or dark blue. Despite the continuous choice of matching colours, observers are consistent in calling the dress 'white' when their match lies above a certain luminance, and 'blue' when it lies below. We can thus exclude the possibility that observers would simply differ in their colour naming conventions and use different labels for identical percepts. This finding is in agreement with previous colour naming studies where remarkably high levels of consistency were observed between and within participants [6].

We are left with the open question how different people arrive at different conclusions when interpreting the same sensory data. The distribution of dress pixels along the daylight locus might be coincidental, but there is some evidence that this would make it much harder for the observers to disentangle illumination colour from object reflectance [7,8]. The bright blue tones present in the image could equally well be due to a dark bluish illumination on a white dress, or to a blue dress under a neutral bright light. Indeed, we have shown in a recent study [7] that observers differ mainly along this direction when they have to adjust the colour of a surface to appear neutral grey (Figure 1A). Under conditions of high uncertainty, as found in the photograph, observers may differ quite substantially in their assumptions about the colour temperature and intensity of the light source. This in turn affects their perception of the surface colours within the scene.

If the particular colour direction is indeed of importance, then the uncertainty should vanish if different colours are chosen for the dress, as for example in Figure 1D–G. When viewing the dress with the rotated colour distribution (E), none of our observers kept naming the dress 'white'. It was seen as 'pink' or 'red', presumably because there is no uncertainty anymore about reflectance and illumination. This is also the case when the colours in the image are rotated by 180 degrees. In this case, the chromaticities still fall on the daylight locus, but the luminances no longer correspond to the natural variations of sunlight. During the course of a day, more yellowish sunlight goes along with lower intensities [4,5]. Asymmetries between bluish and yellowish illuminations have been reported before [8,9]. Thus, it seems that observers do use this correlation to disentangle illumination and surface reflectance. Interestingly, most of the variation is also lost in the grayscale image to the right, where all our observers name the dress as 'light grey' or 'silver', but not 'white'. It seems to be the covariation of luminance and colour that is required to elicit ambiguity about the dress. The popular image of this dress has shown impressively that our perception of the world is not just a result of physical properties recorded by our senses. Rather, we make assumptions about the world that guide the interpretation of sensory data, and these assumptions can be quite different for different individuals.

SUPPLEMENTAL INFORMATION

Supplemental Information includes experimental procedures, one figure and one table and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2015.04.043.

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REFERENCES

1. Hurlbert, A. (2007). Colour constancy. Curr. Biol. *17*, R906–R907.
2. Poirson, A.B., and Wandell, B.A. (1993). Appearance of colored patterns: pattern—color separability. J. Opt. Soc. Am. A Opt. Image Sci. Vis. *10*, 2458–2470.
3. Toscani, M., Valsecchi, M., and Gegenfurtner, K.R. (2013). Optimal sampling of visual information for lightness judgments. Proc. Natl. Acad. Sci. USA *110*, 11163–11168.
4. Wyszecki, G., and Stiles, W.S. (1982). Color Science, second edition (New York: Wiley).
5. Granzier, J.J., and Valsecchi, M. (2014). Variations in daylight as a contextual cue for estimating season, time of day, and weather conditions. J. Vis. *14*, 22.
6. Olkkonen, M., Witzel, C., Hansen, T., and Gegenfurtner, K.R. (2010). Categorical color constancy for real surfaces. J. Vis. *10*, 1–16.
7. Witzel, C., Valkova, H., Hansen, T., and Gegenfurtner, K.R. (2011). Object knowledge modulates colour appearance. i-Perception *2*, 13.
8. Pearce, B., Crichton, S., Mackiewicz, M., Finlayson, G.D., and Hurlbert, A. (2014). Chromatic illumination discrimination ability reveals that human colour constancy is optimised for blue daylight illuminations. PLoS One *9*, e87989.
9. Delahunt, P.B., and Brainard, D.H. (2004). Does human color constancy incorporate the statistical regularity of natural daylight? J. Vis. *4*, 1.

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Striking individual differences in color perception uncovered by ‘the dress’ photograph

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Katherine L. Hermann†,
and Bevil R. Conway*

‘The dress’ is a peculiar photograph: by themselves the dress’ pixels are brown and blue, colors associated with natural illuminants [1], but popular accounts (#TheDress) suggest the dress appears either white/gold or blue/black [2]. Could the purported categorical perception arise because the original social-media question was an alternative-forced-choice? In a free-response survey (N = 1401), we found that most people, including those naïve to the image, reported white/gold or blue/black, but some said blue/brown. Reports of white/gold over blue/black were higher among older people and women. On re-test, some subjects reported a switch in perception, showing the image can be multistable. In a language-independent measure of perception, we asked subjects to identify the dress’ colors from a complete color gamut. The results showed three peaks corresponding to the main descriptive categories, providing additional evidence that the brain resolves the image into one of three stable percepts. We hypothesize that these reflect different internal priors: some people favor a cool illuminant (blue sky), discount shorter wavelengths, and perceive white/gold; others favor a warm illuminant (incandescent light), discount longer wavelengths, and see blue/black. The remaining subjects may assume a neutral illuminant, and see blue/brown. We show that by introducing overt cues to the illumination, we can flip the dress color.

Popular accounts suggest that ‘the dress’ (Figure 1A,B) elicits large individual differences in color perception [2]. We confirmed this in a survey of 1,401 subjects (313 naïve; 53 tested in laboratory; 28/53 re-tested). Subjects were asked to complete the sentence: “this is a ________and____________ dress” (see Supplemental Experimental Procedures in the Supplemental Information).

Overall, 57% of subjects described the dress as blue/black (B/K); 30% as white/gold (W/G); 11% as blue/brown (B/B); and 2% as something

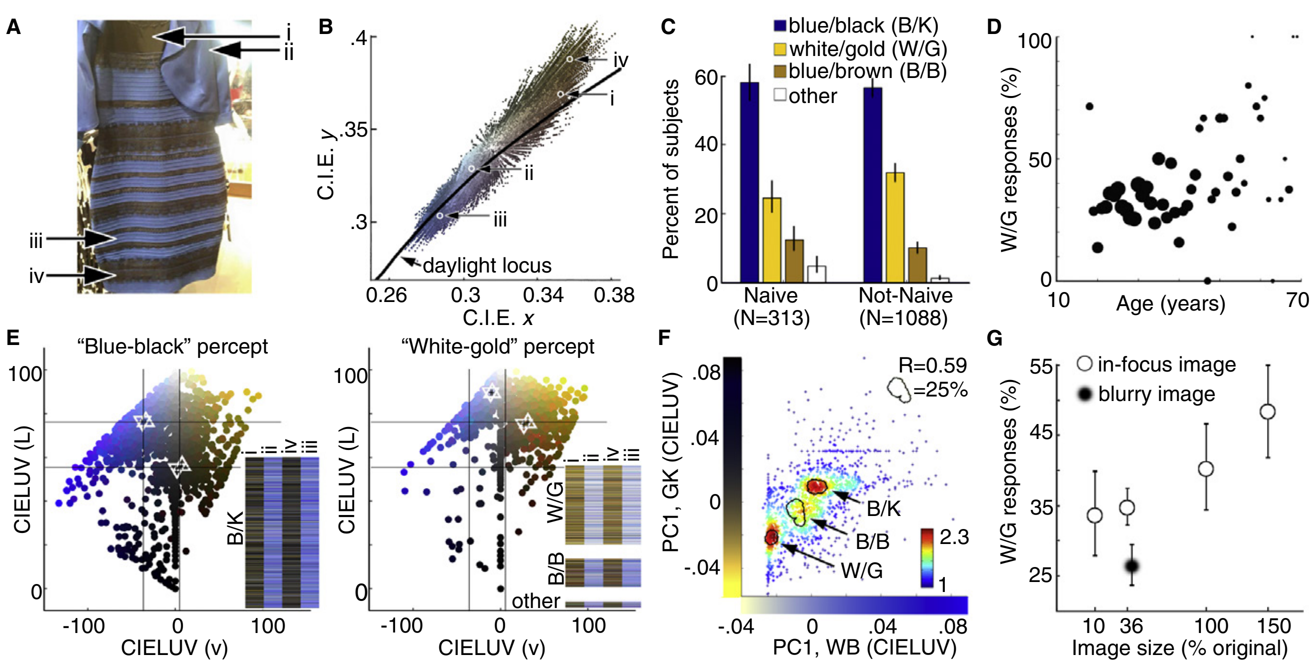

Figure 1. Striking differences in color perception of the dress.
(A) Original photograph. (B) Pixel chromaticities for the dress. (C) Histogram of color descriptions for naïve (N = 313) and non-naive (N = 1088) subjects. Error bars are 95% C.I. (D) Of subjects who reported W/G or B/K (N = 1221), the odds of reporting W/G increased by a factor of 1.02 per unit age, p = 0.0035, 95% C.I. [1.01–1.03] (Table S1). Symbol size denotes number of subjects (largest dot=76; smallest dot=1). (E) Color matches for regions i, ii, iii and iv (panel A), sorted by color description (B/K, left; W/G, right). Symbols show averages (upward triangles, regions i and ii; downward triangles, regions iii and iv), and contain 95% C.I.s of the mean. Grid provides a reference across the B/K and W/G panels. Insets depict color matches for individual subjects in each row, sorted by description. (F) Color matches for region (i) plotted against matches for region (ii) for all subjects (R = 0.59, p < 0.0001). Contours contain the highest density (25%) of respondents obtained in separate plots (not shown) generated by sorting the data by description (B/K, W/G, B/B). The first principal component of the population matches to (i,iv) defined the y axis (gold/black, ‘GK’); the first PC of the population matches to (ii,iii) defined the x axis (white/blue, ‘WB’). Each subject’s (x,y) values are the PC weights for their matches (Supplemental Experimental Procedures). Color scale is number of subjects. (G) Among W/G or B/K respondents, percent of W/G responses increased with image size (N = 235, 10% of original image; N = 1223, 36%; N = 245, 100%; N = 215, 150%; p < 0.0001, OR = 1.004 [1.002–1.007]). The horizontal dimension of the image was about 2°, 7.2°, 20°, and 30° of visual angle. Blurring the image biased responses towards B/K (N = 1048, image was 41% of original size ; Chi-square, p < 0.0001). Dress image reproduced with permission from Cecilia Bleasdale.

else. Redundant descriptions, such as 'white-golden' or 'white-goldish', were binned. Naïve and non-naïve populations showed similar distributions (Figure 1C), although non-naïve subjects used a smaller number of unique descriptions (Figure S1A in Supplemental Information). When country (Figure S1B) was removed from the logistic regression (Table S1), experience became a predictor: non-naïve subjects were more likely to choose B/K or W/G, over B/B or other ($p = 0.021$, Wald chi-square; Odds Ratio (OR) = 1.53, 95% C.I. [1.06–2.17]). These results show that experience shaped the language used to describe the dress, and possibly the perception of it. Males were less likely than females to report W/G over B/K ($p = 0.019$, OR = 0.75, [0.58–0.95]). Moreover, the odds of reporting W/G increased with age (Figure 1D). Of non-naïve subjects, 45% reported a switch since first exposure. Three of 28 subjects retested in the laboratory reported a switch between sessions. Subjects whose perception switched were more likely to report B/K ($p = 0.0003$, OR = 0.60 [0.46–0.79], where W/G = success).

Subjects were asked to match the dress' colors. Blue pixels (regions ii and iii, Figure 1A) were consistently matched bluer by subjects reporting B/K and whiter by subjects reporting W/G, whereas brown pixels (i,iv) were matched blacker by subjects reporting B/K and golden by subjects reporting W/G (Figure 1E; Figure S1C). For a given region, average color matches made by W/G perceivers differed in both lightness and hue from matches made by B/K perceivers (p values < 0.0001). Intra-subject reliability was significant (Figure S1D,E). Across all, matches for (i) were predictive of matches for (ii); moreover, the density plot showed three peaks (Figure 1F; Figure S1F,G). These peaks correspond to the highest density of W/G, B/K, and B/B responders (contours in Figure 1F), suggesting that the brain resolves the image into one of three stable percepts. Thus, 'the dress' appears to be analogous to multistable shape images, such as the Necker cube.

We suspect that priors on both material properties [3,4] and illumination [5] are implicated in resolving the dress' color. In the main experiment, the image was 36% of the original size so that the entire image could fit on most displays. In a follow-up experiment (N = 853 additional subjects), the fraction of W/G respondents rose with increasing image size (Figure 1G). This suggests that high-spatial frequency information (a cue to dress material), more evident at larger sizes, biases interpretation toward W/G. To further test this, we determined responses to a blurry image: the fraction of W/G respondents dropped. Subjects also rated the illumination for the dress and two test images showing the dress under cool or warm illumination (Figure S2A). Judgment variance was higher for the original than for either test (cool, $p = 10^{-5}$; warm, $p = 10^{-7}$, F-test), but similar for the tests ($p = 0.08$), suggesting that illumination in 'the dress' is ambiguous. When the dress was embedded in a scene with unambiguous illumination cues, the majority of subjects conformed to a description predicted by the illumination (Figure S2B).

A color percept is the visual system's best guess given available sense data and an internal model of the world [6]. Visual cortex shows a bias for colors associated with daylight [7,8]; this bias may represent the brain's internal model. We hypothesize that some brains interpret the surprising chromatic distribution (Figure 1B) as evidence that a portion of the spectral radiance is caused by a color bias of the illuminant [1] (see Supplemental Information for further discussion). Some people may expect a cool illuminant, discount short wavelengths, and perceive white/gold; others may favor a warm illuminant, discount longer wavelengths, and see blue/black. The remaining people may assume a neutral illuminant and see blue/brown. But what causes the individual differences? People experience different illuminants and adapt [9]. If exposure informs one's prior, we might predict that older subjects and women are more likely to assume sky-blue illumination because they are more likely than younger subjects and men to have a daytime chronotype [10]. Consistent with this prediction, women and older people were more likely to see white/gold. Conversely, night owls may be more likely to assume a warmer illuminant [2] common for artificial light, and see blue/black. Alternatively, all people may have a similar prior on the illuminant, but different priors on other aspects of the scene that interact to produce different percepts of the dress.

SUPPLEMENTAL INFORMATION

Supplemental Information, including two figures, one table, supplemental experimental procedures, supplemental discussion, and supplemental references, can be found online at http://dx.doi.org/10.1016/j.cub.2015.04.053.

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REFERENCES

1. Conway, B.R. (2015). Why do we care about the colour of the dress? The Guardian *http://www.theguardian.com/commentisfree/2015/feb/27/colour-dress-optical-illusion-social-media*.
2. Rogers, A. (2015). The science of why no one agrees on the color of this dress. Wired *http://www.wired.com/2015/02/science-one-agrees-color-dress/*.
3. Zaidi, Q. (2011). Visual inferences of material changes: color as clue and distraction. WIREs Cognitive Science, John Wiley & Sons, Ltd. Volume 2, November/December *2011*, 686–700.
4. Witzel, C., Valkova, H., Hansen, T., and Gegenfurtner, K.R. (2011). Object knowledge modulates colour appearance. iperception *2*, 13–49.
5. Bloj, M.G., Kersten, D., and Hurlbert, A.C. (1999). Perception of three-dimensional shape influences colour perception through mutual illumination. Nature *402*, 877–879.
6. Brainard, D.H., Longere, P., Delahunt, P.B., Freeman, W.T., Kraft, J.M., and Xiao, B. (2006). Bayesian model of human color constancy. J. Vis. *6*, 1267–1281.
7. Lafer-Sousa, R., Liu, Y.O., Lafer-Sousa, L., Wiest, M.C., and Conway, B.R. (2012). Color tuning in alert macaque V1 assessed with fMRI and single-unit recording shows a bias toward daylight colors. J. Opt. Soc. Am. A Opt. Image Sci. Vis. *29*, 657–670.
8. Conway, B.R. (2014). Color signals through dorsal and ventral visual pathways. Vis. Neurosci. *31*, 197–209.
9. McDermott, K.C., Malkoc, G., Mulligan, J.B., and Webster, M.A. (2010). Adaptation and visual salience. J. Vis. *10*, 1–32.
10. Adan, A., Archer, S.N., Hidalgo, M.P., Di Milia, L., Natale, V., and Randler, C. (2012). Circadian typology: a comprehensive review. Chronobiol. Int. *29*, 1153–1175.

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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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REFERENCES

1. Wollschlager, D., and Anderson, B.L. (2009). The role of layered scene representations in color appearance. Curr. Biol. *19*, 430–435.
2. Bloj, M.G., Kersten, D., and Hurlbert, A.C. (1999). Perception of three-dimensional shape influences colour perception through mutual illumination. Nature *402*, 877–879.
3. Lotto, R.B., and Purves, D. (1999). The effects of color on brightness. Nat. Neurosci. *2*, 1010–1014.
4. Churma, M.E. (1994). Blue shadows: physical, physiological, and psychological causes. Applied Optics *33*, 4719–4722.
5. Corum, J. (Feb 27, 2015). Is That Dress White and Gold or Blue and Black? In New York Times.
6. Conway, B.R. (2014). Color signals through dorsal and ventral visual pathways. Vis. Neurosci. *31*, 197–209.
7. Shevell, S.K., and Kingdom, F.A. (2008). Color in complex scenes. Annu. Rev. Psychol. *59*, 143–166.
8. Mollon, J.D. (2006). Monge (The Verriest Lecture). Vis. Neurosci. *23*, 297–309.
9. Chauhan, T., Perales, E., Xiao, K., Hird, E., Karatzas, D., and Wuerger, S. (2014). The achromatic locus: effect of navigation direction in color space. J. Vis. *14*, doi: 10.1167/14.1.25.
10. Pearce, B., Crichton, S., Mackiewicz, M., Finlayson, G.D., and Hurlbert, A. (2014). Chromatic illumination discrimination ability reveals that human colour constancy is optimised for blue daylight illuminations. PLoS One *9*, e87989.

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