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The many colours of 'the dress'

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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 fi 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,

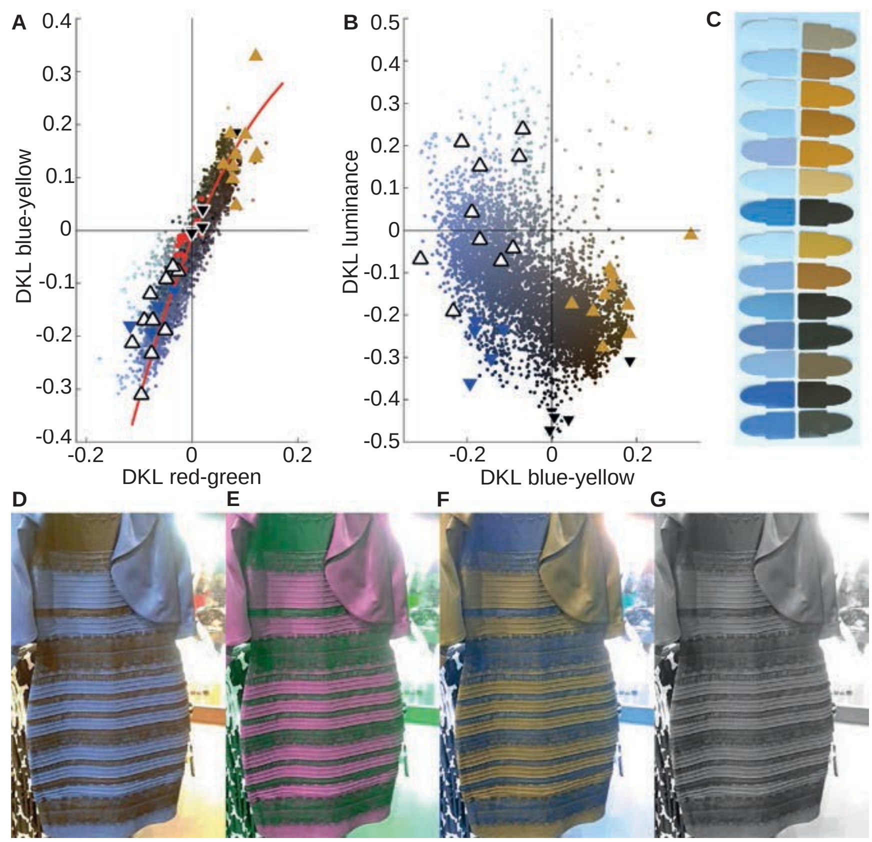

Figure 1. Color matches and manipulated images.
Distribution of coloured pixels within the dress in (A) chromaticity and (B) luminance, together with the colour matches of 15 observers. Dress matches (triangles) are shown in blue and lace matches in black for the observers perceiving the dress as 'blue and black', and in white and orange for the observers perceiving the dress as 'white and gold'. Red dots illustrate the variabil ity 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 lumi nance 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 refl 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.

Acknowledgments

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Supplemental Information: The many colours of the dress
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Supplemental Experimental Procedures

Fifteen observers took part in the experiment. All of them had seen the dress before in online media. We asked them initially what colour they saw it, and then proceeded to the monitor matching task. Observers (between 22 and 54 years of age) were lab members, including 2 of the authors, or undergraduate students paid for their participation. All observers had normal colour vision as tested with Ishihara plates and normal or corrected-to-normal visual acuity.

The adjustment stimuli were presented on a calibrated Eizo Color Edge CG245W monitor (10 bits per colour channel). Observers sat in a dark room with their head stabilized by a chinrest. The distance between forehead and the centre of the screen was 38 cm,

Participants were instructed to adjust the colour of a 6° visual angle disk (Ø) to either “match the colour of the cloth” or “match the colour of the lace” (see Figure S1). In order to facilitate the navigation though the colour dimensions, adjustments were done in CIE L*C*h* colour space which is developed to be approximately perceptually uniform. This space is the cylindrical representation of the CIE L*a*b* [S1]. By adjusting the hue (h*), saturation (C*), and lightness (L*) each observer produced one single match for the cloth and one single match for the lace. The linear R, G and B values of the matches were recorded for further analysis and are listed in Table S1 below.

After participants completed their screen matches they were taken to an office illuminated with natural daylight and asked to select the coloured chips that best matched their recollection of the cloth and lace of the dress. Instructions emphasized a material match by asking observers to imagine selecting the cloth and lace samples they would use to order the dress as they remembered it. Chips from the

Munsell Book of Color, Glossy Edition were laid in bins and participants had unlimited time to make their selection. Only 14 of the 15 observers participated in this phase of the experiment.

For analysis, the R, G, and B values of the screen matches were transformed into a common colour-opponent space [S2]. To do so, we first subtracted 0.5 from the R,G,B vectors that were scaled between 0 and 1. New opponent coordinates were calculated as L+M = 0.28 R + 0.66 G + 0.06 B, L-M = 0.74 R - 0.62 G - 0.12 B, and (L+M)-S = 0.30 R + 0.64 G - 0.94 B, where L, M, and S are the excitation of long-, medium-, and shortwave-sensitive cones. These are the coordinates used in Figures 1A and 1B. For the creation of the images shown in 1E and 1F, the luminance component was held fixed, but the hue angle in the plane spanned by L-M and (L+M)-S was rotated by 90 degree and 180 degrees, respectively. For the image in Figure 1F, luminance was held constant and the chromatic coordinates set to 0.

Supplemental Table

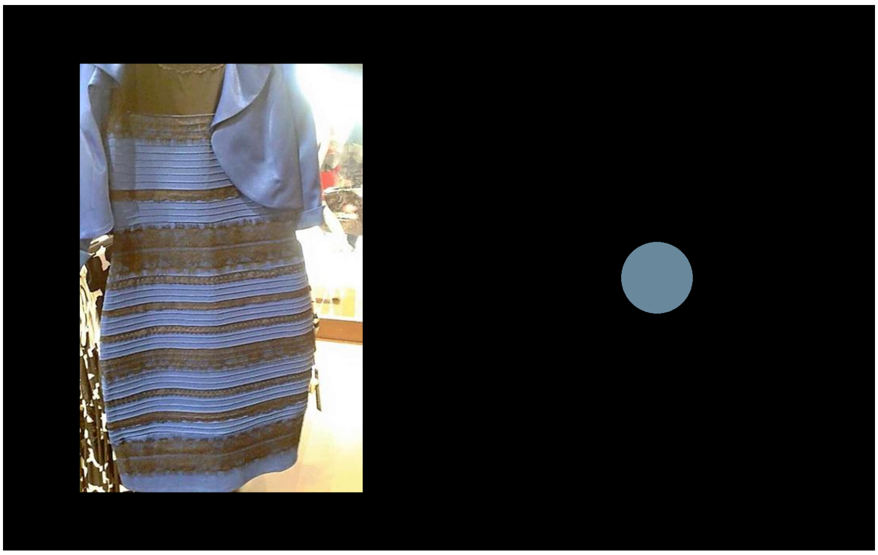
Table S1: For each observer we indicate their self-classification as "blue-black" (BB) or "white-gold" (WG), specify the R, G, and B values of their matches to cloth and lace, and the Munsell notation of their chosen chips. There is very little difference in Hue selection for either the cloth or lace with nearly all variation in participants selection being in the Value and Chroma of the chips. The difference between the two groups was significant for Munsell Value (t_{12}=3.74, $p<0.01$) but not for Chroma (t_{12}=2.03, n.s.). As reported in the main text, for the screen matches, the difference in chromaticity was not significant. To allow for one-dimensional testing, we projected the chromaticity coordinates onto a line with a slope of -2, which approximates the major axis of the distribution of dress colours in Figure 1A. The primaries of our monitor had C.I.E. xyY values of R = (0.6804, 0.3073, 30.94), G = (0.2029, 0.6968, 74.22), B = (0.1527, 0.0505, 6.74).

Group	Cloth				Lace			
	Munsell	R	G	B	Munsell	R	G	B
BB	7.5PB 4/12	0.08	0.15	0.33	5Y 3/2	0.03	0.03	0.03
WG	N/A	0.65	0.68	0.75	N/A	0.52	0.38	0.28
BB	7.5PB 4/6	0.24	0.27	0.38	5Y 2/2	0.07	0.07	0.07
WG	5PB 4/8	0.36	0.44	0.74	2.5Y 2/2	0.32	0.25	0.07
BB	7.5PB 6/4	0.22	0.26	0.44	2.5Y 4/4	0.26	0.18	0.01
WG*	5PB 8/4	0.50	0.54	0.73	10YR 5/10	0.29	0.21	0.11
WG	2.5PB 8/2	0.36	0.45	0.55	2.5Y 6/10	0.59	0.48	0.16
BB	7.5PB 3/12	0.14	0.21	0.34	2.5Y 2/2	0.08	0.05	0.05
WG	2.5PB 9/2	0.59	0.66	0.82	10YR 6/12	0.44	0.35	0.23
WG	7.5PB 6/8	0.25	0.31	0.54	10YR 5/8	0.40	0.34	0.22
BB	5PB 5/6	0.18	0.31	0.46	2.5Y 2/2	0.07	0.05	0.01
WG	10PB 7/8	0.40	0.50	0.64	10YR 6/12	0.38	0.29	0.21
WG	2.5PB 9/2	0.42	0.47	0.55	2.5Y 7/8	0.51	0.36	0.26
WG	5PB 8/4	0.61	0.73	0.92	10YR 5/8	0.41	0.30	0.15
WG	2.5PB9/2	0.71	0.75	0.81	2.5Y 6/4	0.41	0.30	0.28

* This participant's perception of the dress can vary between blue-black and white-gold. She indicated that while doing the adjustment she saw the dress as WG and is classified as such.

Supplemental Figure

Figure S1: The picture of the dress (24.1° by 32° visual angle) was displayed on the left hand side of an otherwise dark screen. The matching disc (6° visual angle) was shown at the centre of the right hand side, centrally aligned with the image



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