Temporal brightness illusion changes color perception of “the dress”

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“The dress” has provoked intensive commentary among psychophysicists, especially in relation to color vision. Researchers have shown that manipulating illuminance cues can influence the perceived colors of the dress. Here we investigate whether illusory shifts in brightness can shift color perception of the dress. Drifting achromatic gratings with fast off and fast on shading profiles are known to give an illusion of brightening or darkening, respectively. We superimposed rotating sawtooth gratings on a series of dress images that morphed from extreme white/gold through to blue/black. In a sample of 18 adults (11 with white/gold dress percept and seven with blue/black percept), a two-alternative, forced-choice constant stimulus task measured the morphed image point at which each observer was equally likely to categorize the dress as white/gold or blue/black (the point of subjective equality or PSE). Despite manifest individual differences in the PSE, the two sawtooth temporal profiles consistently changed the perceived colors of the dress. Perceptual dimming shifted color categorization toward blue/black whereas perceptual brightening shifted color categorization toward white/gold. We conclude that color categorization is influenced substantially by illusory shifts in brightness.

Introduction

In early 2015, an image of a dress seen by some as white/gold (w/g) and others as blue/black (b/bl) became an Internet phenomenon. Widespread interest in “the dress” is most probably due to the veridical sense of personal perception combined with the categorical nature of color naming. A special issue of *Current Biology* (June 29, 2015) received contributions from several well-known color vision researchers (Gegenfurtner, Bloj, & Toscani, 2015; Lafer-Sousa, Hermann, & Conway, 2015; Winkler, Spillmann, Werner, & Webster, 2015). These communications suggested individual differences in the perceived dress color are likely to reflect differences in color constancy mechanisms, whereby the perceived colors of objects remain relatively stable under varying illumination conditions, specifically in relation to the priors used for interpreting
the illumination of the dress (Brainard & Hurlbert, 2015). However, it is unclear whether the neural mechanisms underlying perception of the dress reflect differences in low- or high-level color constancy mechanisms.

The light reflected to the eye from an object depends on both the constant surface reflectance properties of the object and the variable spectrum of illumination (Mollon, 2006). Neural mechanisms for color constancy resolve these signal ambiguities so that even under changing illumination, a lemon will generally appear yellow. The image of the dress poses a difficult problem for our color constancy mechanisms: first, because the white balance of the photo does not match the illumination of the scene and, second, because the distribution of pixel colors in the image matches the distribution of daylight colors (Gegenfurtner et al., 2015). Hence, individual differences could result from different interpretations of the illumination cues in the image such that individuals who assume warm or cool illumination sources will perceive the dress as blue or white, respectively (Brainard & Hurlbert, 2015). Consistent with this idea, the degree of ambiguity in color naming is reduced when observers are shown a cropped image of the dress with fewer illumination cues. Furthermore, when comparing groups of w/g and b/bl perceivers, differences in color matching mostly involve lightness rather than chromaticity per se (Gegenfurtner et al., 2015).

The distribution of colors is likely to explain why this particular image revealed individual differences in color categorization (Brainard & Hurlbert, 2015). The pixel chromaticities of the dress image cluster along the CIE natural daylight locus. Observers’ judgments of unique white (Bosten, Beer, & MacLeod, 2015) and discrimination of illuminance changes (Pearce, Crichton, Mackiewicz, Finlayson, & Hurlbert, 2014) are poorer in the oblique (blue/yellow) direction than in the cardinal directions of color space. Bosten et al. (2015) suggested that the daylight locus may be important for generating individual differences in perception of the dress colors because the pixel chromaticities and illuminance cues in the image produce two different but similarly likely priors: one that the illuminant is blue, the other that it is yellow. Findings from Winkler et al. (2015) reveal asymmetries in this axis; when the colors of the dress are inverted, the vast majority of observers see the fabric as yellow or gold with no observers interpreting the fabric as white. This suggests a tendency to attribute blueness to lighting as opposed to surface properties. In support of the idea that perceived illumination is important, Chetverikov and Ivanchei (2016) found that the proportion of observers who see the dress as w/g versus b/bl changes depending on viewing illumination.

We were interested in whether brightening and darkening illusions would alter chromatic perception of the dress, particularly in terms of color naming. It is well known that fast off and fast on temporal sawtooth profiles give an illusion of brightening or darkening, respectively (Bosten & MacLeod, 2013; Cavanagh & Anstis, 1986). The large spatial extent of sawtooth adaptation aftereffects suggests a mechanism with large receptive fields; however, the lack of interocular transfer suggests a low-level neural locus (Anstis & Harris, 1987). Although psychophysicists have suspected retinal involvement in sawtooth brightening illusions, a recent toad eyecup study (Riddell, Hugrass, Jayasuriya, Crewther, & Crewther, 2016) showed that ramped stimuli associated with brightening and darkening percepts produce greater and lesser plateau direct-coupled electroretinogram potentials, respectively. If shifting apparent brightness can shift observers’ color judgments, this would suggest that achromatic mechanisms play an important role in modulating perception of the dress colors. Such modulation is bottom up and at variance with theories that emphasize the role of frontal and parietal regions in determining perception of the dress colors in a top-down fashion (Schlaffke et al., 2015). Furthermore, it would suggest that individual differences in dress color interpretation could be due, in part, to differences in brightness perception between observers.

Although most of the literature has focused on individual differences in perception of the dress, we took a different approach by investigating whether changing the apparent brightness can change perception of the dress colors within individual observers. Our first aim was to obtain a psychophysical measure of observers’ biases toward w/g or b/bl perception. To achieve this, we took images of the dress that were white-balanced to appear unambiguously w/g or b/bl. We then created a series of images that morphed from w/g to b/bl with the original dress at the 50% morph level. This allowed us to identify the morph level at which observers are equally likely to report the dress as w/g or b/bl (the point of subjective equality or PSE) with PSE scores further away from 50% indicating a greater degree of perceptual bias. Our main aim was to measure the effects of apparent brightening and dimming on color categorization by superimposing fast off and fast on rotating gratings on a selection of morphed dress images (see Supplementary Movie 1). Based on previous work (Chetverikov & Ivanchei, 2016), we expected fast off stimulation (apparent brightening) to decrease the likelihood of b/bl perception and fast on stimulation (apparent dimming) to increase the likelihood of b/bl perception.
Methods

Participants

Eighteen adults (12 female) aged between 18 and 50 (M = 26.4 years, SD = 9.4) gave written informed consent for the experiment, which was conducted with the approval of the Swinburne Human Research Ethics Committee and in accordance with the code of ethics of the Declaration of Helsinki. All participants had normal (or corrected-to-normal) visual acuity and normal color vision as tested with an online Farnsworth D15 color vision test (http://www.colorblindness.com/2009/03/10/online-farnsworth-d-15-dichotomous-color-blindness-test/). All participants completed the color vision test on the same monitor under the same lighting conditions; however, given that the monitor was not specifically calibrated for color vision testing, the test may not be sensitive to small deviations in color vision.

Stimuli

We used the original photo of the dress (Copyright 2015, Cecilia Bleasdale) as well as two disambiguated versions (Figure 1a) that had been white-balanced in Photoshop to produce white fabric (gold lace) or black lace (blue fabric). The morphing program Fantamorph (www.abrosoft.com) was used to interpolate from the disambiguated w/g version (0% morph) to the original image (50% morph) and then to the disambiguated b/bl version (100% morph). The resulting 100 images were exported for use in the experimental tasks. In the constant stimulus task, rotating radial gratings (amplitude: 0.2, frequency: 5 Hz) were superimposed on the dress images (amplitude: 0.8) to produce either fast on or fast off temporal profiles (see Figure 1b). To control eye fixation and minimize optokinetic nystagmus, we used rotating radial gratings rather than drifting gratings. As a control condition, we also used a matched triangle wave grating that did not change in apparent brightness for clockwise/counterclockwise rotation.

A ColorCal MkII (Cambridge Research Systems) was used to record chromaticity and luminance from four pixels (circled in red on Figure 1a) across 21 morph levels of the dress (Figure 1c through e). The rotating gratings do not change the net luminance of the image; hence, grating contrast was set to zero for the colorimetric measurements. As illustrated in Figure 1c, luminance decreases smoothly from the disambiguated w/g image (0% morph) through to the b/bl image (100% morph). Chromaticity for the sampled pixels also changed smoothly along the CIE x- and y-axes (Figure 1d and e).

Procedure

The testing room was dark with only a dim light coming from the display computer screen. The participant’s head was stabilized on a chin rest at a viewing distance of 53 cm. Stimuli were displayed on an Acer
in the PSE for the triangle-wave condition (superimposed on the dress. There was wide individual variation for the triangle-wave condition) when fast on and fast off gratings were presented using a DATAPixx display driver (24 bit) and VPixx software. Responses were recorded with a RESPONSEPixx response box.

An initial forced-choice decision allowed the participants to be divided into w/g and b/bl groups for the purpose of later analysis. Observers performed four adjustment trials to estimate the morph value at which perception changes between w/g and b/bl. The set of 15 morphed images selected for the constant stimulus task was centered on the observer’s adjusted level. Participants categorized a brief presentation (600 ms) of the dress image and superimposed grating as either w/g or b/bl. Each participant completed 540 trials involving 12 replications for 15 dress morph levels with the three superimposed radial grating profiles. Trials were counterbalanced for motion direction as well as ramped grating polarity. Results were plotted as the percentage of trials for which the observer reported a b/bl dress. These data were fitted with sigmoid functions, which were used to determine the PSE.

**Results**

Example psychophysics results for single w/g and b/bl observers are shown in Figure 2a and b, respectively. The psychometric curves for all participants are shown in Supplementary Figure 1. The probability of perceiving the dress as b/bl increased with progressive morphs toward the extreme b/bl image. Figure 1d shows that there was a large degree of individual variation with the PSE tending to occur at lower morph levels for the w/g observers than for the b/bl observers. The PSE values for the two groups were roughly separated around the original dress (50\% morph). Hence, the PSE can be used to quantify the strength of bias toward either w/g or b/bl interpretations with values farther away from the 50\% morph indicating a greater degree of bias.

Relative to the psychometric function for the triangle wave, the PSE shifted leftward with fast on stimulation and rightward with fast off stimulation (Figure 1c and d). If we look at the triangle-wave PSE for participant 16 (Figure 2b, PSE on the dark gray trace), we can see that adding fast on stimulation increased the likelihood of seeing b/bl to 79\% whereas adding fast off stimulation decreased the likelihood of seeing b/bl to 11\%. Averaged across all observers, fast on stimulation resulted in a 27\% (SE = 3.27%) increase in b/bl reports, and fast off stimulation resulted in a 28\% decrease (SE = 3.73\%) in b/bl reports (relative to the PSE with triangle-wave stimulation). In other words, illusory dimming made the dress appear more b/bl whereas illusory brightening made the dress appear more w/g.

As brightening and darkening for ramped stimuli are not necessarily symmetrical in extent (Kremers, 2013), we made separate measurements of the change in PSE (relative to the triangle-wave condition) for the fast on and fast off conditions (see Figure 2c). The magnitudes of the PSE shifts were significantly greater than zero for both the w/g ($p < 0.001$ for fast on and fast off) and b/bl groups ($p < 0.005$ for fast on and fast off). A mixed-design ANOVA showed there was no significant difference in the size of the shift for the fast on or fast off conditions ($p = 0.25$, partial $\eta^2 = 0.08$), and there was no significant interaction between the effects of group (w/g or b/bl) and ramp polarity on the shift in PSE ($p = 0.56$, partial $\eta^2 = 0.02$).

Given that participants were asked to report “white”/gold or blue/“black,” there is a potential confound in interpreting the effects of fast on and fast off conditions...
off stimulation on the perceived dress colors. It could be that observers were responding based on the blackness or whiteness of the image rather than making judgments about the dress colors per se. To address this concern, we performed a follow-up experiment in which two observers (LH and JS) were briefly shown different morph levels of the dress with superimposed fast on or fast off rotating gratings. A small region of fabric or lace was circled to indicate the region of interest (ROI). After 1 s, the dress and grating images were removed, and observers selected the perceived color of the ROI from a row of color patches (sampled from the ROI across the morph levels). As illustrated in Figure 3, there were strong correlations between the patch color and perceived color. Importantly, the linear fits for fast on (dimmer) fell above the linear fits for fast off (brighter) for all four of the ROIs. This is consistent with our main finding that fast on stimulation makes the dress appear more b/bl and fast off stimulation makes the dress appear more w/g.

**Discussion**

The method of constant stimulus approach allowed us not only to identify whether an observer sees the dress as w/g or b/bl, but also to quantify how strongly biased they are toward either judgment. Changing the white balance of the image changed the proportion of observers who saw the dress as b/bl. This suggests that individual differences in dress color perception are better characterized along a continuum than between separate categorical groups. Our results explain previous reports that some observers are able to switch their color perception of the original dress image, and others remain firmly one way or the other (Lafer-Sousa et al., 2015). We demonstrate that “switchers” are not a special group; on the contrary, we were able to find white-balance points at which color categorization changed for even the most adamant w/g or b/bl observers.

As predicted, achromatic temporal sawtooth stimuli not only produced a brightening and darkening appearance of the dress, but it also measurably changed the color categorization. Fast off sawtooth stimulation consistently increased the likelihood of the dress appearing w/g, and fast on sawtooth stimulation consistently increased the likelihood of the dress appearing b/bl. For each observer, the effects of apparent brightening and dimming were strongest at the decision boundary (i.e., the PSE as measured in the triangle-wave condition). Sawtooth stimulation had little or no effect at morph levels farther away from this point. The degree of change in percept was relatively consistent across observers even for those who were strongly biased toward either interpretation.

There are several implications of our findings. First, it is clear that when presented with a smooth variation of dresses, one can consistently change participants’ color report by applying an achromatic overlay that produces illusory brightening and darkening (Cavanagh & Anstis, 1986). Given that observers who see the dress as w/g tend to have lower natural pupil sizes than b/bl observers (Vemuri, Bisla, Mulpuru, & Varadharajan, 2016), it is tempting to attribute our results to the effects of illusory brightening and dimming on pupil size (Laeng & Endestad, 2012). However, sawtooth brightening after-effects still occur when viewed through a small artificial pupil, so they do not depend on pupil size (Anstis, 1967). Furthermore, when Vemuri et al. (2016) administered drops to dilate the w/g observers’ pupils, there was no change in their perception of the dress colors.

Shifts in apparent brightness for sawtooth stimuli are likely to rely on relatively low-level neural mechanisms. Given the lack of interocular transfer and the large spatial scale of sawtooth brightening/dimming effects (Anstis & Harris, 1987), melanopsin-containing ganglion cells were an attractive candidate neural mechanism for the brightening effects. However, Bosten and Macleod (2013) found that s-cone isolating versions of a temporal sawtooth adaptation stimulus did not produce brightness shifts. Melanopsin-containing ganglion cells receive off input from the s-cones and on input from L and M cones; hence, if the effect relies on
these cells, one would expect illusory brightening and dimming to occur for s-cone–isolating stimuli. However, physiological evidence from an animal model shows that the site is likely to be outer retinal and probably photoreceptoral (Riddell et al., 2016). Given the large effects that we observed of fast off and fast on sawtooth stimulation on perception of the dress colors, it could be that low-level neural mechanisms underlie individual differences between b/bl and w/g observers.

In summary, our within-subjects study adds a complementary view to the literature on individual differences between w/g and b/bl observers. Only a small percentage of observers report being able to switch their perception of the original image between viewing sessions (Lafer-Sousa et al., 2015), yet our results imply that perceptual brightening and dimming can switch color perception for any observer, provided he or she is given a version of the image that lies close to his or her decision boundary (i.e., the PSE). Thus, it is likely that “switchers” are individuals for whom the decision boundary lies close to the original dress. Our findings reinforce the notion that the source of differences in color categorization does not lie in chrominance, per se, but rather in lightness (Gegenfurtner et al., 2015).

Furthermore, the ability to modify color percept through interfering with brightness perception indicates that in trying to better understand the dress phenomenon, we should seek ways of assessing low-level visual differences between participants.

**Keywords:** brightness illusion, the dress, color vision

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