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The dress and individual differences in the perception of surface properties

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ABSTRACT

This study investigates systematic individual differences in the way observers perceive different kinds of surface properties and their relationship to the dress, which shows striking individual differences in colour perception. We tested whether these individual differences have a common source, namely differences in perceptual strategies according to which observers attribute features in two-dimensional images to surfaces or to their illumination. First, we reanalysed data from two previous experiments on the dress and colour constancy. The comparison of the two experiments revealed that the colour perception of the dress is strongly related to individual differences in colour constancy. Second, two online surveys measured individual differences in the perception of colour-ambiguous images including the dress, in colour constancy, in gloss perception, in the subjective grey-point, in colour naming, and in the perception of an image with ambiguous shading. The results of the surveys replicated and extended previous findings according to which individual differences in the colour perception of the dress are due to implicit assumptions about the illumination. However, results also showed that the individual differences for other phenomena were independent of the dress and of each other. Overall, these results suggest that the striking individual differences in dress colour perception are due to individual differences in the interpretation of illumination cues to achieve colour constancy. At the same time, they undermine the idea of an overall perceptual strategy that encompasses other phenomena more generally related to the interpretation of illumination and surface properties.

1. Introduction

The photo of a dress (Swiked, 2015) has highlighted the importance of individual differences in perception because it revealed striking individual differences in colour perception: Many observers saw the dress blue and black, while almost all the others saw it white and gold (Bach, 2015; Brainard & Hurlbert, 2015; Gegenfurtner, Bloj, & Toscani, 2015; Lafer-Sousa, Hermann, & Conway, 2015; Macknik, Martinez-Conde, & Conway, 2015; Swiked, 2015). It has been shown that these striking individual differences are related to observers' implicit assumptions about the illumination of the scene on the photo (Chetverikov & Ivanchei, 2016; Hesslinger & Carbon, 2016; Toscani, Dörschner, & Gegenfurtner, 2016; Wallisch, 2017; Witzel, Racey, & O'Regan, 2017). However, it is not yet clear why different observers interpret the photo differently.

Some have argued that the individual differences in the perception of the dress are due to hard-wired, sensory differences in perceptual processing. This view is supported by evidence that twins tend to see the colours similarly (Mahroo et al., 2017), and that white-gold seers tend to have larger pupil sizes (Vemuri, Bisla, Mulpuru, & Varadharajan, 2016) and higher macular pigment optical density (Rabin, Houser, Talbert, & Patel, 2016). Moreover, the observation that the perception of the dress is related to gender and age might also be taken as evidence for hard-wired determinants, such as age-related changes in the eye (Lafer-Sousa et al., 2015; Mahroo et al., 2017; Moccia et al., 2016; Wallisch, 2017).

However, the observation that a few observers can switch between different perceptions speaks against a hard-wired origin of the individual differences (Bach, 2015; Lafer-Sousa et al., 2015; Witzel, 2015). Moreover, the ambiguity in the perception of the dress is rather specific to that photograph. Hard-wired dif-

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ferences cannot explain why the striking individual differences occur for this particular photo of the dress, but not in many other situations involving colour perception in everyday life (Bach, 2015; Witzel, 2015).

It has also been proposed that colour naming might play a role for the individual differences in the description of the dress (Bach, 2015). There are substantial individual differences in colour naming, even when using the most basic colour terms, such as yellow, green, blue, or purple (Lindsey & Brown, 2009; Olkkonen, Witzel, Hansen, & Gegenfurtner, 2010; Webster & Kay, 2007; Witzel & Gegenfurtner, 2013). A link between colour naming and reported dress colours is to some extent supported by the observation that reported dress colours are related to individual differences in blue ratings along a white-blue continuum (Hesslinger & Carbon, 2016). However, differences in category boundaries cannot account for the complete phenomenon because the black and gold categories are not adjacent and hence there is no direct boundary between them (Witzel, 2015). More importantly, it has been shown that the individual differences in reported dress colours constitute a continuous perceptual, rather than categorical linguistic phenomenon (Gegenfurtner et al., 2015; Lafer-Sousa et al., 2015; Witzel, Racey, & O'Regan, 2017). In sum, even if individual differences in hard-wired colour processing and in colour naming may have some influence on the perception of the dress colours they cannot account for the strong and surprising effects that are particular to the dress phenomenon.

An alternative view proposes that the perception of the dress colours in the photo is a special case of colour constancy (Bach, 2015; Brainard & Hurlbert, 2015; Macknik et al., 2015; Witzel, 2015; Witzel et al., 2017). Colour constancy allows observers to identify the colour of an object's surface despite the fact that changes in illumination can create dramatic changes in the sensory colour signal received at the retina (as quantified by colorimetric Tristimulus Values and cone excitations). According to this view, the illumination in the photo is ambiguous and observers unconsciously infer the illumination of the real three-dimensional scene.

This view is strongly supported by evidence on the relationship between perceived dress colours and the observers' implicit assumptions about the illumination of the scene on the photo (Chetverikov & Ivanchei, 2016; Hesslinger & Carbon, 2016; Toscani et al., 2016; Wallisch, 2017; Witzel et al., 2017). Moreover, seeing the real dress under normal viewing conditions (i.e. white light) does not yield any ambiguities: the dress is always seen as blue and black (Bach, 2015; Witzel, 2015), at least under neutral, broad-band illuminations (Hurlbert, Aston, & Pearce, 2016). An ambiguity in the colour perception of the real dress can only be achieved under particular illumination conditions (Hurlbert et al., 2016; Werner & Schmidt, 2016), which highlights the important role of the condition of illumination.

In order to account for individual differences in the perception of the dress, it has been speculated that these differences are due to individual differences in the subjective appearance of grey (Gegenfurtner et al., 2015; Lafer-Sousa et al., 2015; Winkler, Spillmann, Werner, & Webster, 2015). Individual differences in the subjective grey point are related to variations of colours along the daylight locus, which represents the colour changes of natural daylight (Bosten, Beer, & MacLeod, 2015; Chauhan et al., 2014; Witzel, Valkova, Hansen, & Gegenfurtner, 2011; Wuerger, Hurlbert, & Witzel, 2015). It has been proposed that these individual differences reflect different expectations, or *priors*, about the reference illumination, and that these different expectations could be related to the different interpretations of the dress colours (Gegenfurtner et al., 2015; Lafer-Sousa et al., 2015). One variant of this account suggested that the dress is related to different magnitudes of the *blue bias* (Winkler et al., 2015). According to the blue bias observers tend to judge a slightly bluish grey as completely grey (Weiss, Witzel, & Gegenfurtner, under review; Winkler et al., 2015; Wuerger, Hurlbert, & Witzel, 2015). However, existing evidence speaks against these ideas (Witzel et al., 2017; Wuerger et al., 2015).

According to still another view (Witzel, 2015; Witzel, Racey, & O'Regan, 2016; Witzel et al., 2017), the realism of the photo of the dress compels observers to spontaneously interpret the scene in one of two possible ways in order to make sense of the photo. The persistence of the perceived dress colours may be explained by observers getting locked into their initial interpretation and assumptions because they believe that this interpretation reflects the reality depicted on the photo. This idea is supported by observations according to which the perception of the dress may be shaped by prior experience with disambiguating images (Witzel, Racey, et al., 2016; Witzel et al., 2017) and one-shot learning (Drissi Daoudi, Doerig, Parkosadze, Kunchulia, & Herzog, 2017).

The observation that prior experience with disambiguating images influences the perception of the dress indicates the important role of top-down influences on the perception of the dress (Witzel, Racey, et al., 2016; Witzel et al., 2017). Further support for this idea comes from an fMRI study according to which white-gold seers have a stronger activation of brain regions critically involved in high-level processing, such as frontal and parietal brain areas (Schlaffke et al., 2015), from a study that found delayed visually evoked potentials in white-gold seers, which are indicative for the activation of higher cortical brain areas (Rabin et al., 2016), and from evidence for the role of beliefs about the real scene in the perception of the dress (Karlsson & Allwood, 2016).

One possibility is that the initial interpretation of the photo is as unpredictable as fluctuations in the perception of other bistable visual stimuli (Wexler, Duyck, & Mamassian, 2015). In this case, the individual variations of perceived dress colours would be random and not related to other phenomena. Alternatively, observers may differ more generally in the *perceptual strategies* by which they attribute features in two-dimensional images to the surfaces or to their illumination. In this case, the interpretation of illumination cues in the photo of the dress would be related to individual differences observed for other phenomena that involve the interpretation of cues to infer illumination and surface properties.

Individual differences have been observed for a whole range of such phenomena. First of all, substantial individual differences in colour constancy have been observed independently of the dress (Foster, 2011, for review; Granzier, Brenner, & Smeets, 2009; Granzier & Gegenfurtner, 2012, Fig. 13; Radonjic & Brainard, 2016; Witzel, van Alphen, Godau, & O'Regan, 2016). Moreover, a recent study found strong individual differences in gloss perception when stimuli were presented in two-dimensional photos, but not when observers saw the real three-dimensional stimuli (Hansmann-Roth, Pont, & Mamassian, 2015; Hansmann-Roth, Pont, & Mamassian, 2017). In the study of Lee and Smithson (2016) observers differed in whether they could use gloss information to discriminate changes in illumination from changes of surface colour. Häkkinen and Gröhn (2016) found pronounced individual differences in the way observers inferred shape from shading (Ramachandran, 1988). These individual differences could potentially be due to a fundamental difference in perceptual strategies concerning the interpretation of illumination and surface properties in two-dimensional images.

Here we tested whether the different kinds of individual variation discussed above are related to the differences in perception of the dress and to each other. For this purpose, we measured individual differences for different phenomena and tested whether they were correlated. In a first approach, we examined the relationship between individual variation in the perception of the dress and in colour constancy (see also Hurlbert et al., 2016). For this purpose, we reanalyzed two datasets collected in previous experiments,

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