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Spatial and temporal aspects of chromatic adaptation and their functional significance for colour constancy

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ABSTRACT

Illumination in natural scenes changes at multiple temporal and spatial scales: slow changes in global illumination occur in the course of a day, and we encounter fast and localised illumination changes when visually exploring the non-uniform light field of three-dimensional scenes; in addition, very long-term chromatic variations may come from the environment, like for example seasonal changes. In this context, I consider the temporal and spatial properties of chromatic adaptation and discuss their functional significance for colour constancy in three-dimensional scenes. A process of fast spatial tuning in chromatic adaptation is proposed as a possible sensory mechanism for linking colour constancy to the spatial structure of a scene. The observed middlewavelength selectivity of this process is particularly suitable for adaptation to the mean chromaticity and the compensation of interreflections in natural scenes. Two types of sensory colour constancy are distinguished, based on the functional differences of their temporal and spatial scales: a slow type, operating at a global scale for the compensation of the ambient illumination; and a fast colour constancy, which is locally restricted and well suited to compensate region-specific variations in the light field of three dimensional scenes.

1. Robust colour: constancy

Colour is one of the most salient features in natural scenes and a powerful cue for many visual tasks: for example, it facilitates signal detection (Chaparro et al., 1993), provides additional cues for figure-ground segmentation (Gegenfurtner & Kiper, 1992; Healy, 1989), feature binding (Mollon, 1989), and the detection of shadows (Kingdom, Beauce, & Hunter, 2004); furthermore, it improves object detection and recognition (Gegenfurtner & Rieger, 2000; Osorio & Vorobyev, 1996; Regan et al., 1998; Summer & Mollon, 2000; Tanaka & Presnell, 1999; Wurm, 1993) and augments our mental representation of objects by enhancing memory (Wichmann, Sharpe, & Gegenfurtner, 2002).

It can therefore be easily appreciated that colour perception, i.e., the cortical representation of chromatic features, needs to be reliable and robust. With the exception of selfluminant bodies like stars or bioluminescence (e.g. photophores of fireflies (*lampyridae*)), vision in natural scenes is derived from surface reflexion. Therefore, the biggest challenge for achieving a robust colour percept is the changing illumination: the spectral composition and intensity of the daylight changes greatly over the course of the day and so do the chromaticities of the surfaces. Furthermore, in three-dimensional scenes, the light field is inhomogeneous, by objects blocking the path of light (shadowing) as well as by secondary illumination through reflexions from other surfaces (inter-reflexions). However, the neuronal computation of colour ensures that objects can be recognised almost independently of changes in illumination (colour constancy; von Helmholtz, 1896). The importance of this phenomenon for the biological function of vision is underlined by the fact that most species with highly developed visual systems posses colour constancy, including other fish and amphibia (e.g. goldfish (Dörr & Neumeyer, 1996), frog (Maximov, 1989)) and invertebrates like bees (Chittka et al., 2014; Werner, Menzel, & Wehrhahn, 1988).

It has to be stressed, though, that the very term *colour constancy* is misleading, because – contraire to it's name – the performance of human (and animal) colour constancy is far from perfect. Depending on the actual experimental conditions and methods (complexity of the visual scene, adaptation time, and instructions), the reported success of colour constancy in two-dimensional structured patterns ranges between 20% in simple two-dimensional arrangements and 85% in three-dimensional, complex surrounds, whereby 100% is defined as perfect colour constancy (values taken from Table 1 in: Foster, 2011; pp. 683–686). It has been argued that a perfect compensation would be disadvantageous, because it would prevent the information about the illumination itself

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(but see Granzier & Valsecchi, 2014); however, it may simply be a consequence of insufficient or incorrect information available from the scene.

2. How is colour constancy achieved?: The importance of scene context

Achieving colour constancy essentially means, to uncover the spectral reflectance $R(\lambda)$ of a surface, which is invariant, from the reflected spectrum $S(\lambda)$, whereby $S(\lambda)$ is the product of $R(\lambda)$ and the spectrum of the illumination $I(\lambda)$ and is therefore variable. As can be easily seen, if neither $S(\lambda)$, nor $I(\lambda)$ are known, as in the case of the retinal input, the spectral reflectance $R(\lambda)$ of a surface cannot be directly derived from this equation. Processing of additional information is needed in order to normalize the signals.

There is general agreement that colour constancy is not the result of a single mechanism, but is achieved by a multitude of processes at all stages of the chromatic pathways (Foster, 2011; Kraft & Brainard, 1999; Maloney, 2002; Smithson, 2005). These include steps of sensory normalization in the retina, which are continued in the LGN and the primary visual cortex as well as input from cognitive stages, from which inferences can be drawn about the scene, the objects within and its light field. For example, recognizing an object with known colour allows inferences about the prevailing illumination (Granzier & Gegenfurtner, 2012); knowledge about the spatial layout of a scene allows its compensation based on previous experience with the light field in such scenes (Bloj, Kersten, & Hurlbert, 1999). However, the relative weight of theses contributions to colour constancy and their constraints still need to be determined. Other examples of useful information obtained in context are specular highlights, which are direct cues to the spectral composition of the illuminant (Lee, 1986), and exploiting higher-order scene-statistics (Golz, 2008; Golz & MacLeod, 2002).

Taken together, this means that all available information is used by the visual system in order to obtain a robust and reliable colour percept. Common to all strategies is the importance of information from local and wider scene context. In other words, colour constancy is a prime example for context related phenomena in colour vision. In the following I will focus on the sensory processes of colour constancy (thereafter called sensory colour constancy), namely context related adaptation, and illuminate the functional significance of their temporal and spatial properties for colour constancy in natural scenes.

The importance of scene context for colour constancy becomes immediately obvious when viewing a single, isolated stimulus (so called void-condition): here, colour corresponds directly to, and therefore changes with, the wavelength composition of the stimulus (Land & McCann, 1971; Valberg & Lange-Malecki, 1990; Zeki, 1983). The role of context for colour constancy has been highlighted by Edwin Land's Mondrian[1] demonstrations: a multicoloured arrangement of rectangular papers, like the one shown in Fig. 1, is illuminated by the light of three independently controlled projector lamps (one for green, red and blue light, each). By measuring the light reflected from each of the patches under different illuminations, Land and McCann (1971) demonstrated that the human perception does not primarily depend on the local light flux emitted from each patch. Extending the concept of constant ratios (Wallach & Galloway, 1946), Land and McCann proposed an algorithm which models colour constancy by computing and integrating local contrast signals (ratios) above a certain threshold across large parts of a visual scene ("Retinex Algorithm" Land, 1986a; Land & McCann, 1971). Daylight changes tend to leave the spatial ratios of light reflected from natural surfaces preserved (Nascimento, Ferreira, & Foster, 2002) and therefore, encoding colour by spatial ratios within the same spectral channels (chromatic and luminance) can indeed be a powerful tool for achieving colour constancy (Foster, Amano, & Nascimento, 2001; Foster & Nascimento, 1994; Hurlbert & Poggio, 1989; Hurlbert & Wolf, 2004; Nascimento, Ferreira, & Foster, 2002; see also review in Shevell & Kingdom, 2008).

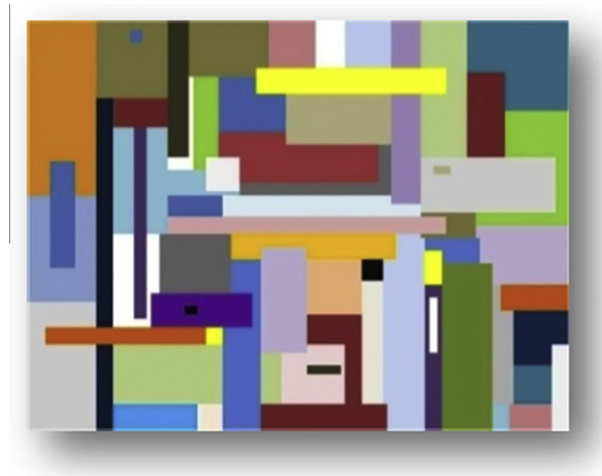

Fig. 1. A Mondrian-pattern.

3. Context in computational models of colour constancy

Computing ratios is also at the heart of many sensory based computational models for colour constancy. The models differ in the type of spatial and temporal filters used for the normalisation. For example, models using the von Kries coefficient law[2] (Ives, 1912; von Kries, 1905) compute local, temporal ratios; the group of Lightness Algorithms (for example the Retinex), on the other hand, computes ratios by spatially extensive operations using different forms of spatio/temporal filtering (see reviews in Foster, 2011; Hurlbert, 1986; Marr, 1976; Smithson, 2005).

The success of all these models critically depends on the selected reference, used for the normalization, mainly on the extent to which the reference signal contains information about the illuminant (allowing a so called "illuminant estimate"). Ideally, this reference would be one that contains the unbiased spectrum of the illuminant. If the chromatic average across all reflectances of a scene is neutral (obeying the so called grey world assumption), it follows that any deviation from a neutral chromaticity is caused by the illuminant and this can be used as a cue to its chromaticity. However, it should be noted that this does not actually *specify* the illuminant, which is a spectral distribution of energy as a function of wavelength, i.e. different metamers can give identical "illuminant chromaticities". The grey world assumption and operations for obtaining a space-average reference are therefore implemented in many algorithms (Buchsbaum, 1980; Land, 1983, 1986a, 1986b); note that for the validity of this argument it is not important that the scene average is actually neutral which is indeed not the case for most scenes, see (Webster & Mollon, 1997a, 1997b), as long as the average reflectance is sufficiently broadband and remains constant.

[1] Named (not quite correctly) after the dutch neo-plasticistic painter Piet Mondrian (1872–1944).

[2] Scaling of the cone absorptions by a factor which depends on the adapting light; originally developed to model the effect of adaptation to coloured lights, the coefficient law by von Kries (1905), has been modified by Ives (1912) and applied as a possible mechanism for colour constancy.