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Lightness perception for matte and glossy complex shapes

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ABSTRACT

Humans are able to estimate the reflective properties of the surface (albedo) of an object despite the large variability in the reflected light due to shading, illumination and specular reflection. Here we first used a physically based rendering simulation to study how different statistics (i.e. percentiles) based on the luminance distributions of matte and glossy objects predict the overall surface albedo. We found that the brightest parts of matte surfaces are good predictors of the surface albedo. As expected, the brightest parts led to poor performance in glossy surfaces. We then asked human observers to sort four (2 matte and 2 glossy) objects in a virtual scene in terms of their albedo. The brightest parts of matte surfaces highly correlated with human judgments, whereas in glossy surfaces, the highest correlation was achieved by percentiles within the darker half of the objects' luminance distributions. Furthermore, glossy surfaces tend to appear darker than matte ones, and observers are less precise in judging their lightness. We then manipulated different bands of the virtual objects' luminance distributions separately for glossy and matte surfaces. Modulating the brightest parts of the luminance distributions of the glossy surfaces had a limited impact on lightness perception, whereas it clearly influenced the perceived lightness of the matte objects. Our results demonstrate that human observers effectively ignore specular reflections while evaluating the lightness of glossy objects, which results in a bias to perceive glossy objects as darker.

1. Introduction

The light reaching the eye from a surface depends on the albedo of the surface, the illumination, the geometry of the surface, and the transmitting medium between the reflecting surface and the eye. In nature, geometries or illuminants typically cause luminance variations in the light reflected from the surface (i.e. shading), even when the surface is made of a single material. Apparently, human observers are able to perceive both lightness, defined as the apparent reflectance of an object's surface (not affected by shading), and brightness, defined as the apparent luminance, at the same time (Arend & Spehar, 1993). We can perceive brightness because otherwise we would not be able to perceive shading at all. Lightness constancy is the ability of our visual system to recover the albedo (diffuse reflectivity) of an object's surface despite changes in the environmental conditions. This task is far from trivial because surfaces with different albedos (e.g. one dark and one light surface) can produce luminance distributions that overlap to a large extent, due to the interaction between the surface geometry and the illuminant (shading). It is therefore interesting to study how the visual system discounts shading. In these terms, one potential contribution to lightness constancy is the ability to tell shading and albedo apart.

Several investigators proposed that in order to recover surface albedo, the visual system explicitly estimates and discounts the contributions of illumination and geometry to the observed luminances (e.g. Marr, 1982; Pizlo, 2001; Poggio & Koch, 1985; Poggio, Torre, & Koch, 1985). This approach is referred to as *inverse optics*. An alternative theoretical approach, proposes that the visual system uses simple image statistics to bypass this problem and estimate surface albedo directly (see for review: Fleming, 2014; Thompson, Fleming, Creem-Regehr, & Stefanucci, 2011). This *image statistics* approach is motivated by the sheer impossible difficulty of estimating the individual factors when naturalistically complex geometries are concerned. In fact, the majority of studies about lightness perception are based on simplified stimuli: flat matte surfaces placed on a single plane under diffuse illumination (for an overview, see Maloney & Brainard, 2010). Under these simplified conditions, edges were proposed as the crucial information to estimate the relative albedo of coplanar surfaces (Cornsweet, 1970; Land & McCann, 1971). Nishida and Shinya (1998) showed

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that more complex geometries can lead observers to produce large errors in matching the diffuse and specular reflectance components between different shapes (Nishida & Shinya, 1998). The pattern of errors in their study suggested that the reflectance matches were based on the similarity of the luminance histograms between the images. However, additional complexity can also provide additional cues to lightness perception. For instance, in simple conditions, when a matte planar surface is viewed in isolation, albedo and illumination are impossible to distinguish and isolated flat surfaces are perceived as white (Gelb, 1929). Nonetheless, observers can – to some extent – judge the lightness of relatively more complex surfaces, such as stucco, even if they are presented in isolation (Sharan, Li, Motoyoshi, Nishida, & Adelson, 2008). In these experiments, Sharan and colleagues tested lightness perception using photographs of real planar surfaces of matte and glossy materials, uniform in albedo. The additional complexity given by the mesostructure and the specular reflection enabled the observers to judge the albedo, despite the fact that the surfaces were presented in isolation. The authors observed that it is possible to predict lightness judgments based on the luminance histogram. Namely, they found that measured albedo and lightness (perceived albedo) correlate negatively with skewness, standard deviation and the 90th percentile of the surfaces' luminance distribution. In a companion paper, Motoyoshi and colleagues (Motoyoshi, Nishida, Sharan, & Adelson, 2007) showed that skewness correlates negatively with albedo and perceived lightness, and positively with the presence of specular reflections and perceived gloss.

We previously found that the highest percentiles of the luminance distributions of matte objects are particularly diagnostic for their albedo, and human observers tend to base their lightness judgments on them (Toscani, Valsecchi, & Gegenfurtner, 2013; Toscani, Valsecchi, & Gegenfurtner, 2015). It is not yet clear whether the visual system applies the same strategy when exposed to glossy surfaces. Intuitively, the brightest parts of the luminance distributions of glossy surfaces should be contaminated to a large extent by specular reflection. Consequently, specular highlights could be seen as a source of noise on the diffuse reflection, and a different heuristic could be used. In the present study we investigate what aspects of the luminance distributions are related to surface albedo and to human lightness judgments (separately for glossy and matte surfaces). More generally, we want to study how the presence of specular reflection impacts lightness perception, in terms of precision and appearance.

If lightness perception is indeed based on the brightest parts of the luminance distributions of both matte and glossy surfaces, the latter ones should appear lighter. If the specular highlights are discounted and the lightness judgments are based on the remaining parts of the distribution, glossy surfaces should appear darker, unless some active compensation takes place. However, comparing the lightness of glossy and matte surfaces is not a trivial task. Even equating the diffuse reflectance across gloss levels is not a trivial problem from a physical point of view. Diffuse reflectance can be defined as (1) the diffuse flux in proportion to the incident illumination, or (2) in proportion to a component of incident illumination that discounts the illumination lost through specular reflection. This distinction is crucial because one difference between diffuse and specular reflection is that in the former case, the light is reflected in all directions, whereas in the latter the direction depends on the surface normal and on the illuminant direction (Hero's law, see Heath, 1921). For this reason, specular highlights appear only reflected from the points of a glossy surface that project toward the point of view of the observer, and when the observer moves, the highlights appear on a different part of the surface. This implies that the light is specularly reflected by the whole surface, but the specular highlights of a certain region of the surface are visible only from the appropriate point of view. If we commit to the second definition of diffuse reflectance, given that part of the incoming light is specularly reflected from every point of the surface, glossy surfaces present areas where the radiance reflected is actually lower (lowlights, see Kim, Marlow, & Anderson, 2012), as compared to a matte surface with the same diffuse reflection component, and brighter areas where specular and diffuse reflection add when reaching the retina (highlights).

With respect to the precision of lightness judgments, we expect observers to be worse in judging glossy surfaces. This is because specular highlights tend to appear in the proximity of the luminance maxima in diffuse shading (Fleming, Torralba, & Adelson, 2004; Koenderink & van Doorn, 1980). Since those luminance maxima are the most informative about surface albedo, having them contaminated by specular highlights should reduce the precision of lightness judgments.

Here, in our first experiment we used a physically based rendering software (radiance – developed by Ward (1994)) to simulate a set of tridimensional models of objects, both with glossy or matte reflectance, and under different naturalistic illuminants. We then used a classification approach to assess to what extent each percentile of the surface luminance distribution predicts the surface albedo (Wiebel, Toscani, & Gegenfurtner, 2015). Similar to our previous study about matte surfaces (Toscani et al., 2013, 2015), we focused our analysis on the percentile statistics because they are directly available to the observer as luminance of a given section of the object surface, whereas for instance the mean luminance might not be represented in the image at all in the case of object images with very bimodal luminance histograms. We repeated this analysis on a smaller set of rendered scenes where we used a reduced set of "blobby" shapes (described later in detail). With this reduced set of shapes, we tested human participants in a lightness ranking task, aiming to compare their performance with the simulation results. We found the ranking task to be more natural than a standard lightness matching, and thus preferable given that lightness and color judgments are particularly sensitive to task instructions (Arend & Spehar, 1993; Schneider & von Campenhausen, 1998). We used the ranking results to study the importance of the different percentiles of the surfaces luminance distributions on lightness perception, and related this result with the one from the reflection simulations, similar to what we previously did with matte surfaces (Toscani et al., 2013, 2015). In a last experiment, we manipulated different bands of the surface luminance histograms to study the causal impact of the different percentiles on lightness perception (separately for gloss and matte surfaces).

2. Simulation of natural objects

We aimed to find out which aspects of the luminance distributions of complex surfaces are good predictors for surface albedo, separately for gloss and matte surfaces. The brightest parts of the luminance distributions of glossy surfaces are likely to be contaminated by specular reflections, which would constitute a source of noise in the estimation of the diffuse reflection. Conversely, the brightest parts of matte surfaces are the most informative about surface albedo (Toscani et al., 2013, 2015). Here we used a classification algorithm to study how the different percentiles of the surface luminance distributions perform in predicting the surface albedo. For the sake of generality, in our simulations we used a large collection of different tridimensional shapes rendered with several orientations, from several viewpoints, and embedded in several different light fields.

2.1. Methods

Renderings: We created our simulated scenes in an analogous way as Wiebel et al. (2015). We rendered 83 different virtual