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Visual perception of materials and their properties

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ABSTRACT

Misidentifying materials—such as mistaking soap for pâté, or *vice versa*—could lead to some pretty messy mishaps. Fortunately, we rarely suffer such indignities, thanks largely to our outstanding ability to recognize materials—and identify their properties—by sight. In everyday life, we encounter an enormous variety of materials, which we usually distinguish effortlessly and without error. However, despite its subjective ease, material perception poses the visual system with some unique and significant challenges, because a given material can take on many different appearances depending on the lighting, viewpoint and shape. Here, I use observations from recent research on material perception to outline a general theory of material perception, in which I suggest that the visual system does not actually estimate physical parameters of materials and objects. Instead—I argue—the brain is remarkably adept at building 'statistical generative models' that capture the natural degrees of variation in appearance between samples. For example, when determining perceived glossiness, the brain does not estimate parameters of the BRDF. Instead, it uses a constellation of low- and mid-level image measurements to characterize the extent to which the surface manifests specular reflections. I argue that these 'statistical appearance models' are both more expressive and easier to compute than physical parameters, and therefore represent a powerful middle way between a 'bag of tricks' and 'inverse optics'.

1. Background

Different materials—such as soap, velvet and pâté—have distinct physical and functional properties, which determine how we can use them; for example, whether they are good for washing, wearing or eating, respectively. Being able to visually distinguish between materials and infer their properties by sight, is invaluable for many tasks. For example, when determining edibility, we can make subtle visual judgments of material properties to determine whether fruit is ripe, whether soup has been left to go cold or whether bread is going stale. When walking or climbing, the ability to judge whether a surface is slippery or fragile is critical for selecting foot- and handholds. Evidently, material perception is useful. One obvious question this raises is, are we any good at it?

Everyday experience, suggests that we are. We effortlessly distinguish numerous different categories of material: textiles, stones, liquids, foodstuffs, and so on, and can recognize many specific materials within each class such as silk, wool and cotton. Indeed, it seems plausible that our capacity to categorize and recognize materials probably rivals our capacity to categorize and recognize objects—after all, every object is made out of some kind of materials, and we usually know which ones. Indeed, as Adelson (2001) points out, not everything that we can recognize is what we would normally call an 'object'. Some 'stuff'—like snow, sand or soil—is just 'stuff', without a clearly defined shape. In many cases such materials are not subject to key constraints—like cohesion and indivisibility—which we usually associate with 'objecthood'. Despite this, we usually experience no problems recognizing such materials.

There is experimental evidence to support the intuition that human observers are good at recognizing and categorizing materials. For example, Sharan, Rosenholtz, and Adelson (2009) have shown that subjects can identify a wide range of materials from photographs even with brief presentations. Recently, Fleming, Wiebel, and Gegenfurtner (2013) showed subjects photographs of materials from different categories and asked them to rate various subjective qualities, such as hardness, glossiness and prettiness. Even though subjects were not explicitly informed that the samples belonged to different classes, the subjective ratings of the individual samples were systematically clustered into categories, suggesting that subjects could theoretically classify materials through visual judgments of their properties.

At the same time, there is almost certainly more to material perception than our ability to categorize or recognize familiar materials. In general, without actually touching an object, we usually have a clear idea of what it would feel like were we to reach

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out and handle it: whether it would be hard or soft, rough or smooth, malleable or likely to crumble in response to force. Even with unfamiliar materials, we seem to be acutely aware of their specific visual and physical characteristics—is it sticky, runny, spongy, would it feel cold to the touch? We can usually answer such questions based on a material's visual appearance. In other words, in addition to recognizing and categorizing materials, we also form a vivid impression of their material properties.

In many cases, of course, physical and functional properties—such as density, thermal conductivity or toxicity—cannot be seen directly, so our impressions must presumably be learned associations. Nevertheless, many quite complex material properties do have a distinctive and vivid visual phenomenology: the frothy head of a freshly poured wheat-beer, for example, has a characteristic 'look', which is subjectively intimately associated with its physical properties. Because of this rich phenomenology, product designers go to great lengths in developing the visual 'look and feel' of consumer products, selecting and synthesizing specific materials to elicit a particular impression of the product as a whole. If we weren't highly sensitive to material appearance, it surely would not be profitable for companies to invest resources in perfecting complex paints and other surface finishing techniques. Indeed, material appearance plays a disproportionate role in the assignment of value to things. Precious metals and gemstones are not especially useful, yet they command high prices, largely because of their lustrous appearance. Again, humans appear to derive a compelling sense of material properties through vision.

There is a growing body of experimental evidence to back this up. For example, Sharan, Rosenholtz, and Adelson (2008) tested how well subjects distinguish between photographs of 'real' and 'fake' materials—for example real fruit vs. realistic wax simulacra—in brief presentations. They found that even with presentation times of just 40 ms, subjects were able to make remarkably precise descriptions of the properties of materials and were above chance performance at distinguishing between real and fake materials. This is impressive because the image differences between real and fake materials are usually far from trivial to define. Real and fake materials have highly variable but overlapping appearances, which cannot easily be distinguished based on the overall colour distributions, intensities, contrasts or spatial attributes of the images. Clearly there is *something* about the 'look' of the real and fake materials that subjects rapidly identify, but what exactly comprises these—often subtle—appearance differences is not at all clear. Nevertheless, the empirical finding supports the intuition that we can make often quite subtle judgments of material attributes.

Other work has focussed on the visual estimation of specific properties of materials, such as glossiness, translucency or surface roughness (for recent reviews see Anderson, 2011; Thompson et al., 2011 or Zaidi, 2011). For example, on the topic of glossiness, Nishida and Shinya (1998) showed that subjects can judge the specular reflectance of computer simulated glossy surfaces and Fleming, Dror, and Adelson (2003), showed that this ability generalizes across differences in lighting, as long as the illumination has statistical structure that is typical of the natural environment. Motoyoshi and Matoba (2012) showed that varying the statistical characteristics of the illumination has systematic effects on perceived glossiness, which can be predicted from the low-level properties of the image. Judgments of specular reflectance are affected by both binocular disparity and motion information (Blake & Bülthoff, 1990; Doerschner et al., 2011; Hurlbert, Cumming, & Parker, 1991; Koenderink & van Doorn, 1980; Muryy et al., 2013; Wendt, Faul, & Mausfeld, 2008), as well as the properties of highlights, including their brightness, position and orientation relative to diffuse shading on the surface (Beck & Prazdny, 1981; Berzhanskaya et al., 2005; Fleming, Torralba, & Adelson, 2004; Kim, Marlow, & Anderson, 2011; Marlow, Kim, & Anderson, 2012; Todd, Norman, & Mingolla, 2004). What cues does the visual system use to infer glossiness? Motoyoshi et al. (2007) found that glossy and matte stucco reliefs create different luminance (and sub-band) distributions, and suggested that the visual system could use the skewness of these histograms to distinguish between glossy and matte surfaces. They found that increasing the skewness of images of matte stucco reliefs made the surfaces appear glossy. However, others have noted that skewness is neither necessary nor sufficient to predict perceived glossiness, and have called into question the idea that such simple image statistics could account for surface perception more generally (Anderson & Kim, 2009; Kim & Anderson, 2010). Olkkonen and Brainard (2010, 2011) measured how perceived gloss varied as a function of illumination geometry, object shape and specular reflectance parameters, and also found that subjective matches were poorly predicted by summary statistics (like skewness) derived from the intensity histogram.

On the topic of surface roughness, several authors have discussed how the visual system estimates and represents the characteristics of surface relief (e.g., Padilla et al., 2008; Pont & Koenderink, 2005, 2008), although it remain unclear exactly which parameters of surface perturbations (e.g., scale, amplitude or profile) determine visual roughness, or indeed whether subjective roughness is a unitary quantity. Others have investigated how visual roughness relates to haptic impressions of roughness (Bergmann Tiest & Kappers, 2007), although it is still not clear how the brain compares or integrates the two. Ho, Landy, and Maloney (2006) have shown that subjects' judgments of surface roughness are systematically biased by the illumination. They found that glancing illumination angles make surfaces appear rougher than frontal illumination.

Numerous other studies have investigated how we perceive the lightness, colour and opacity of thin transparent filters (D'Zmura et al., 1997; Gerbino, 1994; Metelli, 1970, 1974a, 1974b; Robilotto, Khang, & Zaidi, 2002; Singh & Anderson, 2002a, 2002b). By studying the structure of images created by transparent surfaces, a number of authors have identified photometric and geometric conditions that cause the visual system to separate single image intensity values into multiple causal layers—a process known as 'scission' (Adelson & Anandan, 1990; Anderson, 1997, 2003; Beck & Ivry, 1988; Beck, Prazdny, & Ivry, 1984). For example, thin transparent layers tend to create 'X-junctions' in the image, where the boundary of the transparent layer crosses over contours in the background layer. However, solid transparent and translucent objects—like an ice-cube or wax candle—behave quite differently from thin transparent filters, and appear subjectively to transmit light even when these photometric and geometric image conditions are not met (Fleming & Bülthoff, 2005). With solid translucent materials, light scatters within the body of the object, leading to a characteristic soft, glowing appearance. It is known that perceived translucency is affected by the thickness of the material, the direction of illumination, and colour properties of the image. However, how the visual system distinguishes shading gradients that are caused by opaque reflectance from those that are caused by sub-surface scattering remains unclear, although shadow regions are likely to play a role, as these are the portions of objects that are most affected by light that has passed through the object (Fleming & Bülthoff, 2005). Motoyoshi (2010) notes that because translucency has much larger effects on shading than on specular highlights, relationships between shading and highlights provide important information about whether an object is translucent. He shows that varying the contrast (both magnitude and sign) and blur of the non-specular components of an object can dramatically alter its appearance from diffuse to translucent. Fleming, Jäkel, and Maloney (2011) showed that subjects could match the refractive index of solid transparent materials, although, again