The Challenge of our Known Knowns

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Abstract

The appearances of colored objects depend not only on their spectral power distributions, but also on their temporal and geometric surroundings, and on their surface properties. These latter characteristics include: successive contrast, simultaneous contrast, assimilation (sometimes called the spreading effect), gloss, translucency, and surface texture; these characteristics can often have a profound effect. Successive contrast can result in significant changes in lightness and color balance when shot-changes occur in motion-picture films and in television. Simultaneous contrast often has appreciable effects in the design of clothing and documents. Assimilation can alter the appearance of colors in signage, woven fabrics, and tapestries, for instance. The presence or absence of gloss is an important feature in industries such as ceramics, paper-making, and paint production, and can affect not only the apparent color, but also the apparent shape, of an object. Translucency has been found to be an important property in the foodstuff industry, being one of the factors affecting consumers' perception of quality. Surface texture can affect the recognition of objects very considerably; the difference, for instance, between a woven fabric and a metallic automobile finish is recognized very largely by their different surface textures. Although these effects are well known, they are almost entirely lacking any agreed quantitative measures or standards, and this is in spite of their great importance. Some suggestions are made for the way in which such measures might be provided.

Introduction

At a trial, an attorney was putting witnesses through an exacting cross-examination, and was taking great delight into forcing witnesses to admit that they did not remember every single detail of an accident. While the lawyer knew that no witness has a perfect memory, he had honed a skill in exploiting minor inconsistencies and lapses of memory in order to challenge the credibility of honest witnesses. After a series of scathing cross-examinations, he was looking forward to his examination of yet another witness. "Did you actually see the accident?" he asked. The witness responded with a polite, "Yes, sir." "How far away were you when the accident happened?" "I was thirty-four feet, seven and three quarter inches away from the point of collision." "Thirty-four feet, seven and three quarter inches?" the lawyer asked, sarcastically, "Do you expect us to believe that your memory is so good, and your sense of distance is so precise, that months after the accident you can come into court and give that type of detail?" The witness was unphased. "Sir, I had a hunch that some obnoxious, know-it-all lawyer would ask me the distance, and would try to make it seem like I was lying if

I could not give an exact answer. So I got a tape measure, and measured out the exact distance."

In this keynote we will be reviewing a number of factors that can have a profound effect on the appearance of colored objects, but for which agreed quantitative measures, although often desirable, are at present not available.

Successive contrast

When light falls on the retina of the eye it adjusts its sensitivity to compensate for the general intensity and color of the stimulation. This can occur in a few seconds or minutes, and the result can last for a similar time; this is termed *successive contrast*. A practical example of this is when an observer watches a television screen with a white point of color similar to that of D65 and then looks at objects in a room lit with light of significantly lower correlated color temperature, such as tungsten light or compact fluorescent lamps; in such cases, when the images of the objects fall in the area that had been used for viewing the television screen, they look yellower than normal. A quantitative representation of successive contrast would have to be a function of the luminance, chromaticity, and time of exposure of the adapting field. Such a representation has yet to be proposed.

Simultaneous contrast

The appearance of a color can be greatly affected by the presence of other colors around it; this is termed *simultaneous contrast* (or *chromatic induction*). Simultaneous contrast can result in large changes in the appearance of colors in items such as woven fabrics and tapestries. The French chemist Michel Eugène Chevreul[1], as director of Gobelin, the famous carpet manufacturer, was one of the first to investigate the phenomenon; in 1839 he introduced his law: 'two adjacent colors, when seen by the eye, will appear as dissimilar as possible'.

It is well known that a dark surround makes a color look lighter, and a light surround makes it look darker. But it is also true that a dark surround lowers apparent contrast. This contrast-lowering effect occurs quite strongly when pictures are projected in cinemas, and has to be countered by increasing the contrast of the picture being projected. The CIECAM02 color appearance model includes an allowance for this effect. In Figure 1 an example of simultaneous contrast affecting lightness is shown. Areas C and D reflect the same amount of light, but C, with its lighter surround, looks darker than D, with its darker surround; but the effect is much greater with areas A and B, which also reflect the same amount of light; this is because, in addition to simultaneous contrast, cognitive effects are present as the brain interprets the picture in terms of the recognition of objects.

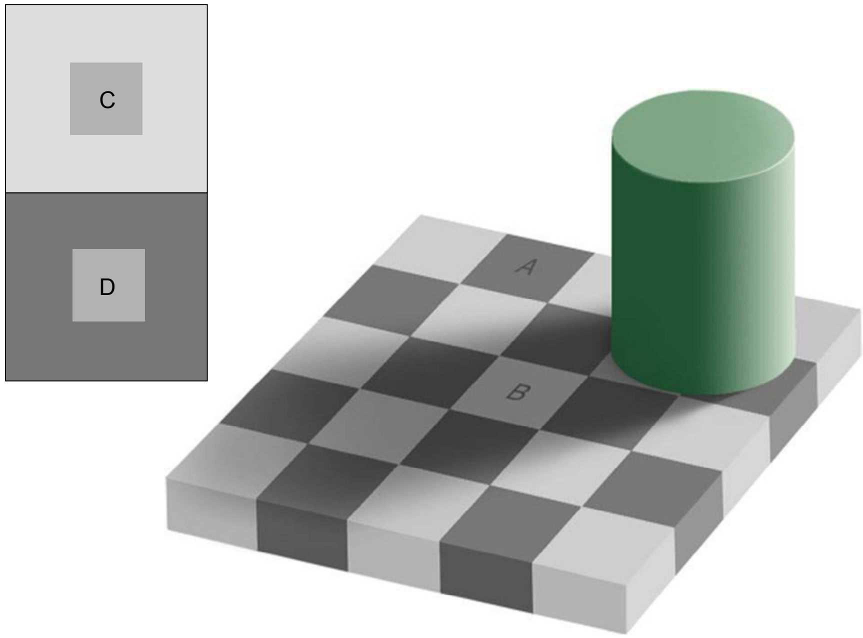


Figure 1. *The two areas labelled A and B reflect the same amount of light. But simultaneous contrast and cognitive effects make A look much darker than B. The effect of simultaneous contrast alone is shown by areas C and D, which also reflect the same amounts of light, but whose difference is not enhanced by a cognitive effect. (The chequerboard figure produced by Edward H. Adelson[2], 1993.)*

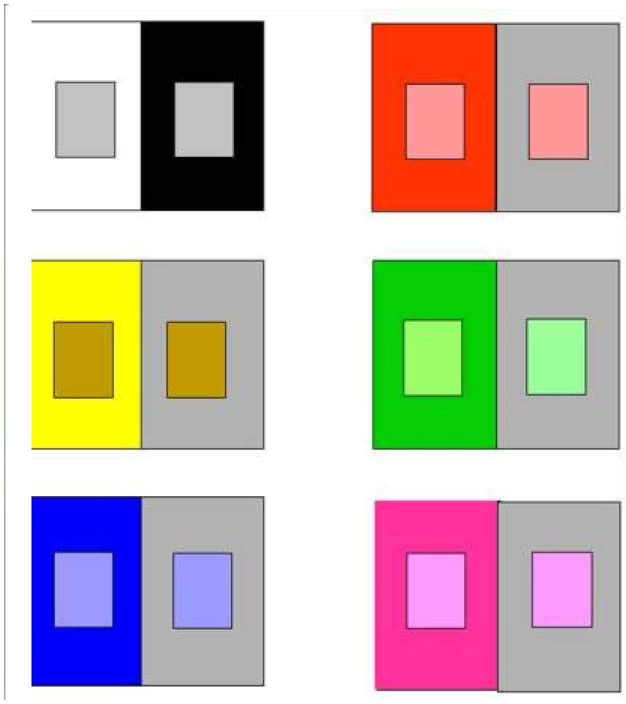
In Figures 2 and 3, the effect of simultaneous contrast on color is demonstrated. In Figure 2, although, in each of the six diagrams, the same ink is used for each pair of smaller rectangles, their backgrounds make them appear of different colors, because of simultaneous contrast. Proposals for predicting this type of effect have been made by several workers[3,4,5,6]. In Figure 3, in each of the six diagrams, the same ink is used to print both the crosses, but their backgrounds make them appear of different colors; the effect is much greater than in Figure 3, because of the greater contact of the backgrounds with the crosses. This demonstrates the important fact that that simultaneous contrast depends not only on the colors involved but also on their geometrical pattern.

A quantitative representation of simultaneous contrast that is comprehensive would have to be a function of the luminance factor and chromaticity of the adjacent areas, the extent of their contact, and an allowance for any cognitive effects. Such a representation has yet to be proposed.

Assimilation

When stimuli are seen at small angular subtenses, the opposite of simultaneous contrast can occur, when colors become *more*, instead of *less*, like their surroundings, an effect termed *assimilation* (or *spreading effect*).

In Figure 4 examples of assimilation are demonstrated. Each rectangle has the same background color as the rectangle beneath it. The white patterns on the upper rectangles make their background colors appear lighter; the dark patterns on the lower rectangles make their background colors appear darker. This is the opposite of the effect of simultaneous contrast, which would make the backgrounds of the upper rectangles appear darker, and those of the lower rectangles appear lighter. The magnitude of the effect shown in Figure 4 may be enhanced by viewing the patterns at a distance. Demonstrations of assimilation have also been published by Evans[8], and by Wright[9]. The likely causes of the effect include scattering of light in the eye, and the fact that the color difference signals in the visual system have lower resolution than that of the achromatic signal[10]. A quantitative representation of assimilation would have to be a function of the luminance factor, and chromaticity, of the adjacent areas, the extent of their contact, and the angular subtense of the elements. Such a representation has yet to be proposed.



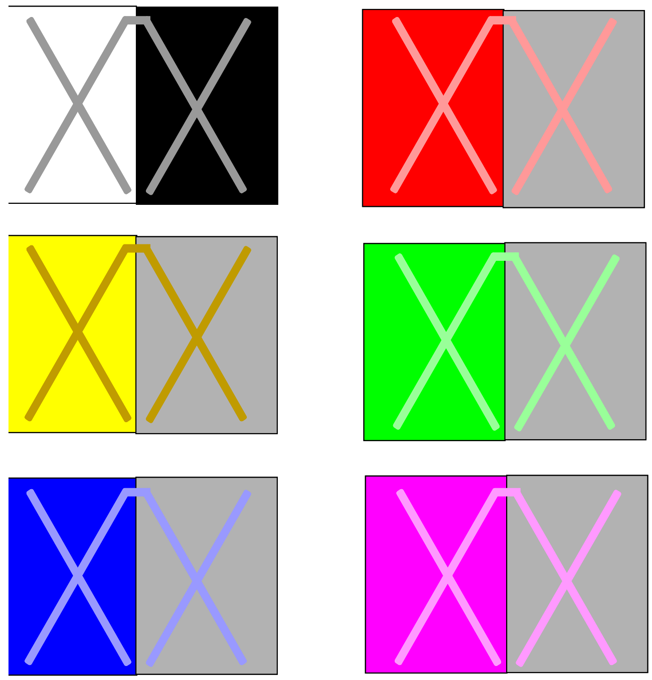


Figure 2. *In the top left-hand diagram the two smaller rectangles are printed with ink of the same color, but their backgrounds make them appear different, because of simultaneous contrast. Similarly, in the other five diagrams the colors in the smaller rectangles appear different although the ink used is the same for each pair.*

Figure 3. *In each of the six diagrams the two crosses are produced by the same colored ink (as can be seen at the top of each diagram), but simultaneous contrast makes the left-hand one look different from the right-hand one (after a similar figure in Albers[7]). The colors used for the crosses and the backgrounds are the same as in Fig. 2, but the differences in apparent color are much larger; this is because of the greater contact of the background with the crosses than with the rectangles. This demonstrates that simultaneous contrast is not only affected by the colors involved, but can also be strongly dependent on their geometric pattern.*

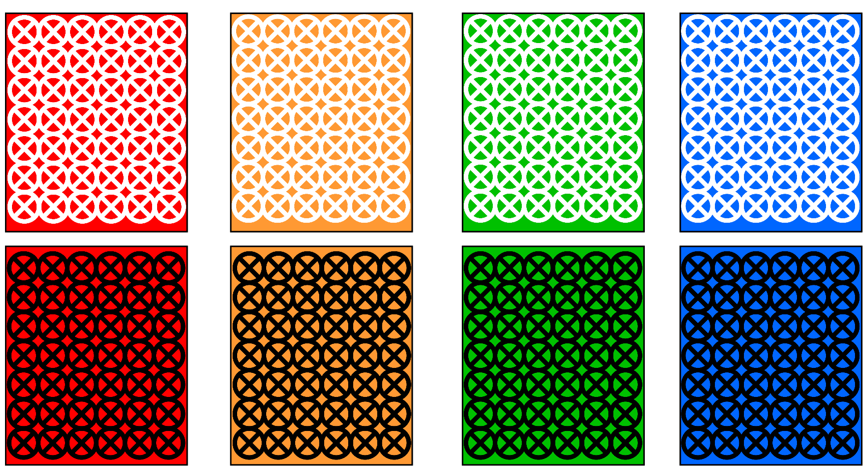


Figure 4. *Each rectangle has the same background color as the rectangle beneath it. The white patterns on the upper rectangles make their background colors appear lighter; the dark patterns on the lower rectangles make their background colors appear darker. This is the opposite of the effect of simultaneous contrast, which would make the backgrounds of the upper rectangles appear darker, and those of then lower rectangles appear lighter. The magnitude of the effect may be enhanced by viewing the patterns at a distance.*

Gloss

Gloss is usually associated with the way that light is reflected from the surface of an object at and near the specular, mirror angle, direction. Gloss is normally perceived independent of color; it may, however, be affected by the underlying color of the object or itself affect the perceived color of the object. In most circumstances, it is usual for the perception of gloss to be abstracted from the total visual experience as separate from color. Hunter and Judd[11] first defined specular gloss as the ratio of the light reflected from a surface at a specified angle, to that incident on the surface at the same angle, on the other side of the surface normal (Figure 5, top left). Hunter recognised, however, that the perception of gloss involves more than just the specular reflection[12].

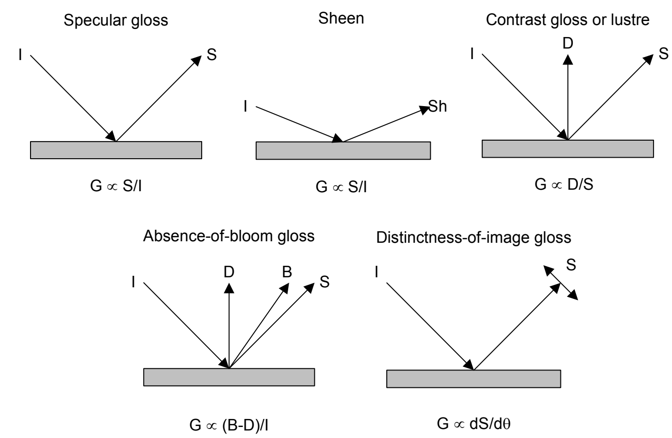


Figure 5. Hunter's five types of gloss, G, associated with the amounts of incident light, I, specularly reflected light, S, diffuse reflectance, D, and off-specular light, B.

If I is the amount of incident light, S is the amount of specularly reflected light, D is the diffuse reflectance normal to the surface, and B is the off-specular light, Hunter defined:

- specular gloss as proportional to S/I;
- sheen as proportional to S/I at grazing angles of incidence and viewing;
- contrast gloss or lustre as proportional to D/S;
- absence-of-bloom gloss (a measure of the haze or a milky appearance adjacent to the specularly reflected light) as proportional to $(B - D)/I$;
- and distinctness-of-image gloss as the sharpness of the specularly reflected light.

A surface can appear very shiny if it has a well-defined specular reflectance at the specular angle. The perception of an image reflected in the surface can be degraded by appearing unsharp, or by appearing to be of low contrast. The former is characterised by the distinctness-of-image gloss (Figure 5, lower right), and the latter by the haze or contrast gloss[13] (Figure 5, upper right). An added complexity is caused by surface non-uniformity leading to an effect known as orange peel. This effect can be caused, for example, by uneven coating of the acrylic overcoat on an automobile finish, leading to a relatively low frequency 'ripple'. It should be noted that it is not always the 'top' surface of a material that contributes to the gloss. The quality of the color image produced by inkjet printing technology varies, for example, depending on the type and quality of the substrate, the raw stock paper[14]. To get a high laydown of ink requires a relatively rough surface to give a high surface area on which to print; this, however, tends to be a relatively low gloss surface and so the print will not look 'photographic' or have a high gloss, unless other measures are taken to achieve this.

Many developments of gloss measurement have been carried out as part of the technical work of the American Society for Testing and Materials (ASTM International) commencing in 1925 with the instrument constructed by Pfund[15]. This used parallel light to illuminate the sample at 20° with a detector placed at 20° on the other side of the normal. Hunter and Judd later incorporated this design into an ASTM Method[16] which designates three angles (20°, 60°and 85°) for measurement, depending on the relative gloss of the surface. Measurements are made relative to a highly polished black glass standard with a refractive index of 1.567. The gloss of the standard is assigned a value of 100 for each geometry. In order to differentiate the gloss of different samples it is necessary to select the appropriate measurement geometry. The sample is first measured with 60° geometry. If the gloss value is higher than 70 (high gloss), then it is re-measured at 20° and if less than 10 (low gloss), it is re-measured at 85°.

The provision of perceptual correlates of the physical phenomenon known as gloss is not without its problems. Sève[17] noted that "the CIE had been grappling with the subject for over 20 years and, while they had produced a state-of-the-art report in 1986, little had changed in the interim period"! The biggest problem seems to be that the instruments currently available use an arbitrary choice of gloss scale and Sève proposed that the measurement of gloss be related to the measurement of luminance factor in the specular direction. This would enable the gloss values, measured at different angles of illumination, to be compared: with the present system, the scale at each measurement angle is separately normalised to have a maximum value of 100.

Obein, Knoblauch, Chrisment, and Viénot have argued that gloss is very much a 'second-order' visual attribute in that it results from an interpretation by the brain of first-order signals[18]. This implies that an observer must look at the surface of an object from two or three different angles to receive enough information to be able to attribute a value to the gloss of that surface. Their experiments showed that the scaled visual gloss of a set of custom designed black samples, obtained using a pair-comparison technique, was not linearly related to the corresponding values of Gloss Units obtained from a gloss meter (see Figure 6): for matt samples, and for very high gloss samples, the gain of the visual responses rises steeply. In the intermediate range, the two scales are almost linearly related.

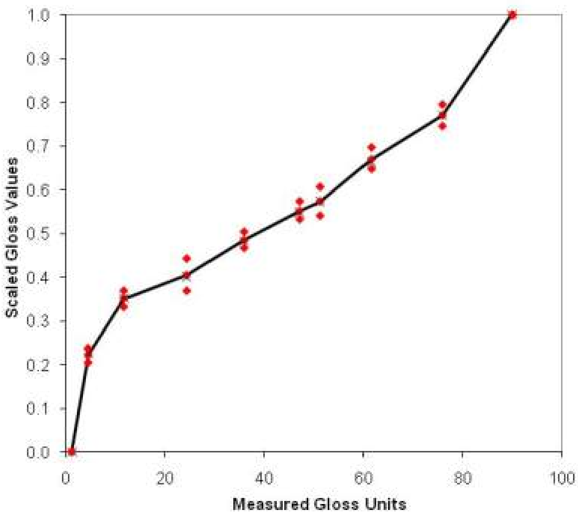


Figure 6. *Gloss as estimated by one observer: Scaled Gloss plotted against gloss measured at 60⁰ (Normalised Specular Gloss) for a series of black samples.*

Analysis of their data also shows that observers exhibit a form of gloss constancy[19]. When data obtained using two different observing angles, 60° and 20°, are plotted versus a unique abscissa, for example the sample number in the series, the two plots superimpose. This would indicate that, although the flux that is collected by the eye varies according to the angle of view, an observer is able to recover a visual gloss index that is inherent to the surface. Thus, just as observers can assign a unique color to a sample under lights of different spectral power distribution, they can also assign a gloss value to a surface despite changes in the geometry of illumination and viewing.

Further work by Ji, Pointer, Luo, and Dakin supports the above findings[20]. In addition, they found that the visual gloss was linearly related to the difference between the total specular-included and the specular excluded reflectance factors, ρ_{SPIN} and ρ_{SPEX} respectively.

Recent experiments by Leloup, Pointer, Dutré, and Hanselaer, have shown that the perception of gloss may be even more complex, and that the luminance distribution of the scene that contains the reflecting sample can influence the perception of gloss[21, 22]. In a light booth, Figure 7, two light sources were utilized, the mirror image of only one source being visible in reflection by the observer.

The luminance of both the reflected image and the adjacent sample surface could be independently varied by separate adjustment of the intensity of the two light sources. By the use of a number of samples (white, grey and black), a psychophysical function was derived that linearly related the visual gloss estimations given by the observers, G_{vis}, to the measured luminance of both the reflected image, L_{im}, and the off-specular sample background luminance, L_b,:

$$G_{vis} = 22L_{im}^{0.379} - 17L_b^{0.354} \quad (1)$$

This function is very similar to that introduced a number of years ago by Pellacini, Ferwerda, and Greenberg, who showed that contrast gloss, *CG*, could be expressed as a function of the specular, ρ_s and diffuse, ρ_d reflectance factors of a surface: it should be noted that L_{im} and L_b can be re-written in terms of these parameters[23].

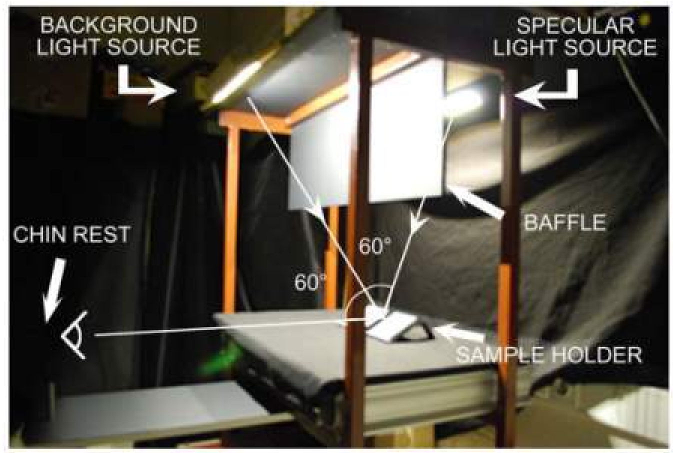


Figure 7. The test booth showing the light sources used to provide the specular and background illumination.

Thus, the conventional gloss meter, that makes measurements in terms of physically defined Gloss Units, at a number of specified angles, does not seem to give measures that relate to the perception of gloss, which might be better related to the contrast of the specular light to that of its surround, and is independent of angle.

A quantitative representation of gloss might therefore have to be a function not just of the luminance of the specularly reflected light but also a measure of the luminance distribution of the light that surrounds it.

Translucency

If it is possible to see an object or scene through a material then that material is said to be *transparent*. If is it is possible to see only a 'blurred' image through the material then it has a degree of *transparency*, the extent of which is a property of the particular material. This blurring, or loss of information, is due to the *diffusion* of light as it passes through the material[24].

These terms all imply a scattering or diffusing mechanism within the material but there is an important distinction between *clarity* and *haze*. Consider a target that consists of a series of sets of black and white bars, and each set is of a different spatial frequency. For a material with a high value of clarity and a low value of haze, it will be possible to discern a high spatial-frequency pattern irrespective of the contrast between the black and the white bars at the highest discernible frequency. For a material with a high value of haze but low value of clarity, it will be possible to distinguish only a blurred image at the higher frequencies, because the contrast between the black and white bars appears much reduced. Thus, the concept of translucency can perhaps be regarded as a descriptor of the combined effects defined above as clarity and haze. This implies that it is a more general term and, perhaps, should be limited to use as a subjective term, keeping clarity and haze as descriptors of objective, or measurable, correlates. Also of importance is *turbidity* which is defined as the reduction in transparency due to the presence of particulate matter in the material.

The ability to handle, specify, and predict, the light scattering and absorption properties of materials is vital to the solving of practical problems arising within many industries. These problems range from the calculation of how many layers of paint are needed to cover an existing but contrasting color, the selection of colorants and prediction of the concentration required to match an existing color, and the measurement of the color of many products in the food industry.

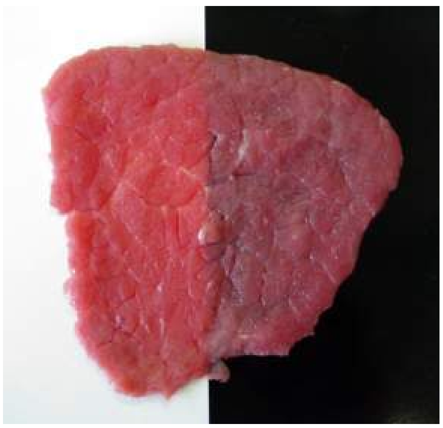


Figure 8. *A slice of beefsteak over a white and a black background. ©Bruce Moss, Queen's University Belfast.*

Solutions can often be found by the application of *Kubelka-Munk Analysis* which models the light reflected and transmitted by a medium in terms of its absorption K, and scattering S, coefficients[25]. In order to provide analytical solutions to the differential equations, a number of measurements of a thin layer of a sample are usually required, including that of the sample over a white and a black background, to enable K and S to be calculated (see Figure 8).

The relationship between the measurements obtained in terms of these values, and the perceptual response to the materials, are both interesting and varied. Many experiments relate to food products and range from the perception of flavour strength of orange juice[26], the ideal amount of milk to add to coffee[27], the quality of red wine[28], and the perceived quality of beer as a function of both color and cloudiness[29].

A quantitative representation of translucency might therefore have to be separate functions of clarity and haze but such a representation has yet to be proposed.

Surface Texture

The surface texture of materials is an all-together more difficult perception to quantify. The advent of digital imaging systems makes the acquisition of images of materials relatively easy, assuming due consideration is given to the resolution of the image capturing device, be it a digital camera or scanner. Characterising these images to give accurate CIE based colorimetry is now possible and the application of suitable analysis software is able to provide numbers that relate to the spatial distribution of the information in the image. Obtaining psychophysical responses to perceived texture is another matter because no defined taxonomy exists to describe the perception of spatial variation of information.

A more fundamental problem is to define the difference between pattern and texture. The former might be considered a fundamental attribute belonging to a material; the latter a parameter relating to the perception of that pattern, which will, amongst other variables, be a function of the viewing distance. Two distinctly different experimental approaches have been adopted in the investigation of surface texture. The first uses manufactured material, for example car panels coated with metallic or pearlescent pigments (see Figure 9), and has observers scale carefully defined parameters, for example, coarseness and glint.

Figure 9. *Typical car panel coated with a metallic pigment with an acrylic overcoat.*

The problem with this method is that the samples are often not easily quantified; the particle size of the pigment may be well controlled before coating, but the actual laydown of the coated pigment results in a random distribution. Images of the materials can be used to provide data for Fourier analysis which in turn provides values of the parameters that define the physics of the texture which can be related to the observer data. Work by Kitaguchi, Westland, and Luo explored this method and derived models that related perceived glint to the frequency spectrum of the spatial information [30].

The alternative approach is to mathematically define the test stimuli, often on a computer display, and vary them in a controlled manner to provide a range of stimuli that change in a systematic manner. The observers then provide values of perceptual attributes that relate to what they see and which can be correlated with the physical measures. For example, a series of stimuli, of which Figure 10 provides a small sample, were scaled for apparent surface roughness, directionality, and randomness. Models were then derived to predict those data based on the RMS value of the surface variability, standard deviation of the distribution of the angular variation of that variability, the central radial frequency used to derive the variability, and the bandwidth of that variation[31, 32, 33].

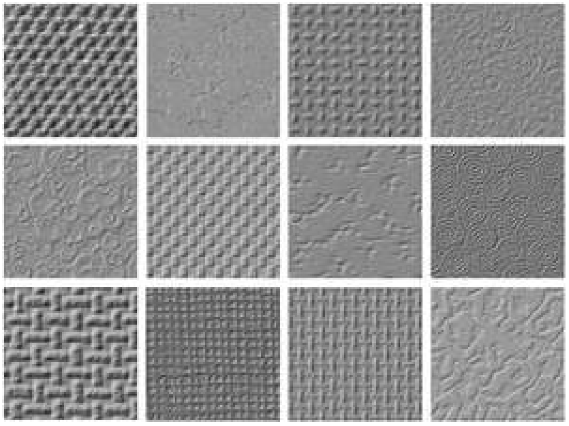


Figure 10. *A number of synthetic textures varying in roughness, direction and randomness.*

The measurement of surface texture is proving a difficult task. Perhaps a reason for this is to do with the requirement to make the measurements in the first place. Synthetic surfaces – plastics, fabrics and other materials – have led to many products that are intended to look real, or natural, and one way to achieve this is to ensure that the spatial distribution of information matches that of the real object. When surfaces of different materials, real or synthetic, are combined together, for example in the interior of an automobile, there is a requirement that they 'harmonise', or appear to fit together to give a pleasing overall impression of safety, comfort and, often, of quality. These are difficult concepts to measure.

At this stage in the experimental work, a quantitative representation of surface texture is difficult to predict and it seems likely that it will be application dependent.

Summary

This paper has described some of the appearance parameters of color, gloss, translucency, and surface texture. It must be recognised that these four variables rarely occur in isolation: for example, food products are usually colored, almost certainly translucent, exhibit spatial physical variation – surface texture – and often have a degree of gloss. The CIE has recognised this in the publication of a report describing a framework for the measurement of appearance and recommending further investigation of each of the variables, not only singly but in combination[34]. A color appearance model, CIECAM02, that derives correlates of perceived quantities from physical measurements, already exists[35]. Perhaps one day this model will be extended to include the prediction not only of gloss, translucency, and surface texture, but also combinations of these four parameters[36].

In addition, it has been suggested that 'appearance' is formed in the visual cortex, at a higher level than for example, color appearance – it is a cognitive effect. Thus, another possible way forward is to start co-operating with physiological and psychological studies in order to obtain correlation between 'optical property space' and 'cortical mechanism space'. This is represented by ongoing work in Division 1 *Vision and Colour* of the CIE.

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