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The perception of gloss: A review

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ABSTRACT

Gloss is a relatively little studied visual property of objects' surfaces. The earliest recorded scientific reference to gloss appears to have been by Ingersoll in 1921: studies at this time were based on the assumption that gloss could be understood as an inherent physical property of a surface, and the priority was to devise a satisfactory method and scale to measure it reliably. As awareness of the complexity of perception grew, efforts were made to distinguish different types of gloss, although these generally still took the form of a search for objective physical measures to be solved within the visual system by means of inverse optics. It became more widely recognised approximately 20 years ago that models of gloss perception based on inverse optics were intractable and failed to explain experimental findings adequately. A temporary decline in the number of published studies followed; however the last decade or so has seen a renewal of interest in the perception of gloss, in an effort to map what is now understood to be a complex interaction of variables including illumination, surface properties and observer. This appears to have been driven by a number of factors, as the study of gloss re-emerged from research into other surface properties such as colour and texture, with technological advances paving the way for new experimental techniques and measurements. This review describes the main strands of research, tracking the changes in approach and theory which have triggered new avenues of research, to the current state of knowledge.

1. Overview

The history of the study of gloss falls into a number of distinct phases: initially, the focus was on finding an objective measure by which materials and surfaces could be compared for physical gloss. Emphasis then shifted to the perceptual aspect of gloss following the work of Hunter (1937), with the recognition that it was more complex than a single physical measure could quantify. For a time continuing research persisted with the theory of a single objective measure of gloss that would supposedly be computed by the visual system using an inverse optics approach. However, the view steadily gained ground that multiple factors must be involved. Work by those such as Sève (1993) underlined the multidimensionality of gloss; the impossibility of obtaining satisfactory measurements using a single instrument to correlate with perceptual judgements; the intractability of an inverse optics approach; and the need for consistent terminology. Focus shifted to the consideration of multiple dimensions of gloss, and the relation between physical and perceptual scales. At the same time there was a separate proposal that the visual system made use of a statistical diagnostic solution, based on a single measurement of regularities in image statistics. However this was not supported and a consensus emerged that a multiple-dimension approach to perceptual gloss was most consistent with the full range of experimental findings. Rather than the visual system attempting to solve inverse optics, or trying to approximate physical dimensions by generalising statistical regularities in a scene, the system treats the multiple dimensions and features within the image as a whole, a gestalt, which leads to a perceptual judgement of glossiness.

2. Gloss as a single objective measurement

The earliest studies of gloss took it to be a single physical attribute and focused on how to measure it objectively. Ingersoll conducted one of the first studies, examining the measurement of gloss on paper with the use of a glarimeter (Ingersoll, 1921 – see Fig. 1a). Assuming that gloss could be entirely defined as the amount of specular reflectance of light compared to the amount of diffusely reflected light, the instrument calculated this proportion using a polarising filter (since specularly reflected light had been found to be almost completely polarised). This instrument was put into use in paper mills, in order to determine the quality of the paper produced. Pfund (1930) set out on a similar task, again proposing to measure the specular reflection of various materials. It was a general assumption at this time – and even for the next

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few decades – that a single objective index of gloss existed, that could be measured and manipulated. This desire for a single measurable feature of gloss evidently transferred to the perceptual domain of study. Despite the fact that numerous papers subsequently identified differences in perceptual experience of gloss, most research concentrated on the standardisation of measurement and the search for a reliable physical index that the visual system could measure or at least estimate.

3. Additional factors vs. inverse optics

Pfund did, however, acknowledge that there were additional factors involved in perceptual gloss, as it was already established that when observing two materials with identical surface characteristics (and thus ratio of specular to diffuse reflectance), the darker surface would appear glossier. A role for contrast between specular reflection and diffuse reflectance of the surrounding was already evident – yet this was not taken into account in the search for an adequate measurement of physical as against perceptual gloss. It was not until an article published by Hunter (1937) that notions of additional perceptual gloss factors were expanded. This influential paper proposed a number of different aspects of perceptual gloss – and interestingly, did not focus on how gloss was to be measured objectively, but on determining the qualities that should be measured. Hunter outlined six types of perceptual gloss (see Fig. 1b–h):

(1) Specular gloss – this is defined as the perceived shininess, or the perceived brilliance of highlights. It is the most commonly measured parameter in experiments as an approximation for the physical measurement of perceptual gloss.
(2) Sheen at grazing angles – this is the perceived gloss at grazing angles of otherwise matte surfaces (for instance, very smooth, good quality matte paper can have a slight sheen when viewed at low grazing angles).
(3) Contrast gloss – identified by contrasts between specularities and the rest of a surface, this is associated with the observed contrast between specular highlights and otherwise diffusely reflecting surface areas.
(4) Haze – this is the presence of a hazy or milky appearance, adjacent to reflected highlights. An example of this might be the haze surrounding a reflected highlight on a brushed metal surface.
(5) Distinctness-of-reflected-image gloss – this is the perceived distinctness and sharpness of a pseudoimage seen reflected in a surface.
(6) Absence-of-surface-texture gloss – this is the perceived smoothness of a surface, where non-uniformities of surface texture such as blemishes are not visible.

Images illustrating these types of gloss can be found in Fig. 1. Hunter stipulated that the measurement of gloss should involve one or more of these types, to take into account the additional perceptual differences. He considered the perception of gloss in human vision to be a gestalt (corresponding to no single physical property of a surface, but formed by an appraisal of the whole scene); and that if there were indeed several types of gloss, no one device alone could measure it. In fact, two instruments commonly used to measure gloss in industrial or experimental settings were developed with the intention of measuring gloss in different ways – the glarimeter, or glossmeter, measures the ratio of specular to diffuse reflection, and the Dori-gon measures the distinctness of image – which correlate with two of Hunter's dimensions. By Hunter's description, gloss is more complex than Pfund originally proposed, but is still in some way measurable in objective physical terms.

Despite this, theories proposing a single objective measure persisted; perhaps influenced by pervasive hypotheses concerning the computations involved in human vision generally. The inherent problem in the study of vision is that the information available to the brain from perceptual input is insufficient to provide an adequate account of the surrounding environment – a full representation has to be constructed from the information available. The theory of inverse optics proposes that the brain essentially inverts the sequence of physical processes to reach a model of the environment. Applying this theory to the field of colour vision – the brain tries, according to inverse optics, to calculate the original surface reflectance functions by discounting the illuminant, using reverse physics to approximate intrinsic physical properties of the surroundings. However, this kind of computation would be highly complex and – critically – could hardly ever yield sufficient information to arrive at a solution. A computational model of inverse optics could, however, demand that the brain estimates a single physical objective measure of a property such as gloss, thus explaining the desire to encompass gloss with a single variable which corresponds and agrees with human perceptual judgements. One should not gain the impression that theories based in inverse optics have been completely discarded. In the 1990s Blake and Bülthoff concluded that the visual system 'seems to employ a physical model of the interaction of light with curved surfaces, a model based firmly on ray optics and differential geometry' (Blake & Bülthoff, 1990, p. 165). Their conclusions that the use of specular reflections and their geometry provide rich information concerning the three-dimensional structure of the object are still invaluable even when considered in alternative heuristics frameworks to inverse optics. Inverse optics retains attraction as a basis for theory, despite its intractability. Although clear differences between physical and perceptual conceptions of gloss were evident early in the study of gloss, these were not wholly acknowledged in the search for a perceptual measure of gloss that could be employed by the visual system to identify glossy surfaces and to compare relative gloss.

4. Emerging support for multiple factors

A gestalt concept of gloss was supported by the work of Harrison and Poulter (1951). This gestalt, they proposed, would include a combination of mainly specular reflection with contrast of specular and diffuse reflection, besides a number of other factors. Later papers developed this, coming from a wide range of research backgrounds. For example, snow was found to have a high contribution of specular reflection at higher angles of incidence, and yet at such angles does not appear shiny – at most, one sees a very bright glare reflected from the snow (Middleton & Mungall, 1952). This is because, considered as material, or 'stuff', the surface of fresh snow is made up of millions of uniquely shaped snowflakes, and the facets of these three-dimensional structures scatter light in all directions (some light is also transmitted through the layers of snow, and partially absorbed). It might be inferred from these results that the microstructure of the surface of the material is also important: the reflection of purely specular light alone does not produce perceptual glossiness. It seems we need a continuous area of the surface to be visible in order to assess the presence of gloss (e.g. smooth sheets of ice look very shiny). An informal paper from the Artificial Intelligence Laboratory of MIT concludes that the perception of glossiness arises as a result of at least two visual effects – that specular reflections from a surface producing mirror-like images of the surrounding environment lie in a different plane from the surface, and that highlights are 'abnormally bright' (Lavin, 1973). Beck and Prazdny (1981) studied such specular highlights more formally,

Fig. 1. (a) An advertisement for an Ingersoll Glarimeter, 1922. Reproduced under the Creative Commons license. (b–h) Illustrate examples of Hunter's six cues to gloss. (b) Shows sheen at grazing angles, on a piece of high quality matte paper. (c and d) Demonstrate both surface texture and distinctness-of-image gloss: (c) is focused on the fingerprint-blemished surface, whereas (d) is focused on the reflected image – the surface appears less glossy in (c) as the surface texture of the blemishes detracts from the surface gloss, and the distinctness of the reflected image is lower. (e) Shows the original photograph of a shiny surface with a strong highlight. In (f) all highlights have been removed, and the surface looks matte. In (g) the highlight has been reduced to demonstrate contrast shine, and in (h) all haze surrounding the highlight has been removed from the original image.

and found that not only are they important for the perception of gloss, but also the orientation and positioning of any highlights are crucial. The size, shape and position of the highlights should be consistent with the three dimensional structure of the object or material, and the supposed angle of illumination. However, the authors also conclude that specular highlights appear to have a purely local effect, that makes only the surrounding area of the surface or object appear glossy.

One of the first attempts to link perceptual gloss with physical parameters of materials was made by O'Donnell and Billmeyer Jr. (1986). This paper was a direct consequence of the work of Hunter; reiterating that visual observations led to the identification of six types of perceptual gloss (specular, sheen, contrast, haze, image distinctness, and surface texture). The interrelations between these six types were studied using a multidimensional scaling method, the results of which produced unidimensional interval scales of gloss. However, these scales only appear to apply to the very specific stimuli used, and the particular viewing and illumination conditions. An effect of extreme viewing angle on perceived gloss was acknowledged, but not incorporated into the multidimensional scaling analysis. The physical parameters of the stimuli were analysed using a conventional glossmeter (designed to measure specular contrast) and a Dori-gon instrument (designed to measure distinctness-of-image gloss); other types of gloss – explicitly discussed in the aims of the paper – were not fully considered. (It is worth pointing out here that whilst experiments prior to this refer to the instruments used as 'glarimeters', these are the same as glossmeters, and measure the ratio of specular to diffuse reflection.) Two sets of equations for perceptual gloss were produced: each mapped the analysed perceptual responses to the measurements obtained from only one of these instruments. If a glossmeter is used to capture the specularity contrast of the surface (one of Hunter's six dimensions of gloss), which was not found to be independent of lightness, and a Dori-gon instrument is used to capture distinctness-of-image (another of Hunter's dimensions) where the measurements are found to be lightness independent, then Hunter is clearly justified in arguing that specularity and distinctness-of-image are two separate dimensions, and that gloss is not unidimensional. For the glossmeter (but not for the Dori-gon), three linear equations were required to explain all the data (where each equation mapped the unidimensional solution for perceptual responses to a scaled instrument reading), depending on the lightness level of the stimuli. This suggests that unidimensionality is an unusual conclusion at which to arrive – lightness clearly affected the perception of one kind of gloss (as evidenced by the contrast effect, Pfund, 1930). Since the stimulus set, viewing and illumination conditions were highly specific, this suggests that even disregarding the problem of lightness, the equations would not generalise to alternative conditions – or even to natural scenes of broadband illumination. This is a particularly important aspect of the study of material properties – rather than searching for computations only useable under specific conditions, the solution needs to be applicable under a wide range of circumstances.

A separate paper by the same authors (Billmeyer & O'Donnell, 1987) used magnitude scaling to estimate perceptual differences between all possible pairs of stimuli (using the stimulus set from O'Donnell & Billmeyer Jr., 1986). This again produced unidimensional interval scales of perceptual gloss despite apparent consideration of all six dimensions proposed by Hunter. Data obtained correlated with instrumental gloss measurements made with standard glossmeters: but as glossmeters provide a simple ratio of two measures (specular and diffuse light), disregarding a great deal of information, this result is implausible. It seems that the range of information available in the set of stimuli was limited, and thus perceptual judgements of gloss were restricted to the use of specular information, forcing the decisions to be consistent with glossmeter predictions. This provides further support for the conclusion that methods of stimuli presentation and conditions of illumination and viewing were too specific. Bartleson highlighted the need to recognise the multidimensional nature of perceptual gloss in a report to CIE many years previously; yet this was largely overlooked in subsequent work (Bartleson 1974, as cited in Sève, 1993).

5. Persistent support for a single-measure approach

Further studies at around the same time persisted in the assumption that the measurement of gloss – as relating to perceptual experience – could be achieved using a single physical measure. Keane (1989) described in a patent paper the invention of an optical instrument, which could assess both the chromaticity of a surface, by measuring the wavelength reflectance function, and also gloss; the assumption being that colour perception is influenced by perceived surface gloss (U.S. Patent No. 4,886,355). Again, perceived gloss was considered to consist entirely of specular reflection. Considering that the invention was designed to provide a measure capable of compensating for additional factors in perceived colour, it is paradoxical that it neglects evidence in favour of the involvement of multiple factors in perceived gloss. Serikawa and Shimomura (1993), from the field of computer science, went as far as denying the idea that the specular reflection of images of the environment appearing on a different plane from the material surface corresponds with perceptual glossiness. Instead, they defined their measurements of perceptual gloss as involving a brightness function and the smoothness of an object's surface. It is a moot point whether the insistence of industrial research on a unidimensional approach to physical and perceptual gloss may have influenced research in the field of vision more generally. However, their conclusions regarding the measurement of perceptual gloss are in clear agreement – that a single objective scale is sufficient.

6. A return to multidimensionality

The tendency to cling on to a single-measure approach to perceptual gloss, in spite of the work by Hunter, was finally challenged in a critical review paper by Sève (1993). Many of the problems facing the study of gloss were addressed directly, and attention was drawn to a number of aspects previously neglected. Complications regarding the concept of gloss itself, by this point, were clearly evident. Although Schanda (1971, as cited in Sève, 1993) had outlined difficulties with defining and measuring gloss in a memorandum to CIE two decades earlier, this was evidently overlooked by most studies. Even the vocabulary of the CIE definition of gloss shifted from physical to perceptual, without noting explicitly the significance of this change (as cited in Sève, 1993). Terms for perceptual and physical concepts were being used interchangeably, so problems of terminology affecting the discussion were inevitable. In the field of colour vision, by contrast, a careful distinction is made between physical and perceptual terms or concepts, preventing such confusion (wavelength, luminance and purity characterise the physical dimensions of colour, whereas hue, brightness and saturation describe the perceptual qualities). In the interest of clarity, Sève adopted the term 'photometric gloss' for visual or perceptual gloss (Sève's term and the later-used 'psychometric gloss' are broadly equivalent).

An important point emphasised by Sève is that the choice of any physical gloss scale is arbitrary, as most instruments make some calculation of specular gloss alone. Yet it is not fully clear how these physical features will best correlate with judgements of perceptual gloss. Sève reiterates the importance of Hunter's multiple visual criteria for determining perceived gloss, and acknowledges that specular reflectance alone does not give a full explanation of perceptual gloss. Appraisal of gloss by the visual system is not dependent on one physical quantity, and does not try to measure or estimate a single physical quantity of the surface reflectance. This is the final nail in the coffin of a single estimated value of the physical world employed by the visual system to approximate gloss; and the theory of combined perceptual factors determining perceived gloss is reinforced.

One crucial point noted by Sève was that visual evaluation of gloss differs considerably from one observer to another. One observer attaches significance to certain characteristics of a scene that another does not, and so samples cannot be ordered linearly. From this fact alone, multidimensionality of perceptual gloss is intuitively inferred, with numerous contributions from different factors. Vision typically involves disentangling information obtained from the environment in the early stages of processing at the retina. For example, effective colour constancy requires the separation of illuminant and surface reflectance, which is further complicated by physiological limitations at the initial input stages of the visual system. All conundrums of vision involve a complex interplay between illumination, object or surface reflectance, and observer. Gloss as a percept is no different; observer, illumination conditions, lightness, contrast, specular reflectance, surface texture, highlights and their properties, specularly-reflected mirror images and binocularity all play a role in the perception of gloss.

Subsequent to this influential paper by Sève, published research on gloss appears to decline for several years. Then in the late 1990s and early 2000s, publications investigating gloss reappear. One such paper seems to signal a change of research tactic – moving from the study of objects, to the perception of materials and surface properties. Adelson (2001) points out that relatively little attention had been paid to the recognition of materials, as opposed to objects – the 'stuff' that makes up what we see is essential for judgements concerning the nature of the object; such as what it might feel like, or how it might be used. This emphasis on the study of textures and material appearance seemed to reignite the study of gloss as a surface property, and encouraged a change in approaches by sparking a variety of new methods (heavily influenced by developments in technology). More recently, studies on the representation of material properties such as texture and colour have also drawn attention to the study of gloss (Cavina-Pratesi et al., 2010a, 2010b; Fleming, Dror, & Adelson, 2003). In particular, these raise the question of whether the processing of gloss might be independent from the processing of texture, and other surface properties.

The clear assumption from Adelson's paper onwards is that gloss is a complex interaction of illumination, surface, environment and observer. This assumption gave rise to a new range of methods and approaches that take into account the multidimensionality of gloss. Since all problems of vision involve the interaction of illumination, surface, and observer, the findings are grouped accordingly – moving from illumination through surface to observer – including interactions between stages as appropriate. The main aims of the research – describing perceptually distinct dimensions of gloss, computation of perceived gloss from images, evaluation of gloss constancy, and the search for the specific cortical regions involved in gloss perception – are evident throughout the body of findings, and will be flagged as such.

7. Illumination

7.1. Real-world illumination

The importance of realistic illumination distributions in achieving a good level of perceptual constancy is evident in the study of colour vision, and it seems to play an equally important role in surface texture perception constancy. Natural illumination maps have characteristic non-Gaussian fluctuating statistical properties; and so Hartung and Kersten (2002) measured a number of natural illumination maps to investigate potential sources of information for perceiving objects as shiny. Consistencies between illumination of the background environment and the patterns of light reflected from objects were statistically correlated, and any step towards a non-natural map of illumination was immediately salient (a shiny object in an illumination map of white noise appeared matte). This indicates that the complexity of natural illumination maps is crucial for accurate and ecologically valid perception of surfaces, as the visual system takes advantage of this complexity – either through the explicit information available, or by means of correlations and similarities between the surroundings and objects within them.

These results corroborate the findings of Fleming, Dror, and Adelson (2003), obtained in matching experiments. An asymmetric matching task was used to measure perceived glossiness for spheres simulated in some comparisons under real world light fields, and in others with geometrically simple illuminants. Observers' matches were close to veridical under geometrically complex real world illuminations, but not under non-natural illuminations (that were not geometrically complex). This implies that complexity of illumination is necessary in the initial stages of surface material perception, and that compensation for a lack of this complexity is not possible later – although constancy is still not perfect under complex illumination. Dror, Willsky, and Adelson (2004) also provide support for the idea that the visual system takes advantage of characteristics of natural illumination maps, arguing that real world illumination is highly complex, and yet possesses a high degree of statistical regularity. If such statistical regularities could be assumed and utilised, this would marginally lessen the complex task of determining the properties of objects in the environment, and would also in part explain failures in perceptual constancy.

Olkkonen and Brainard (2010) found that changing the light field had a significant effect on perceived glossiness, as assessed with a matching paradigm, and concluded that the complexity of computing an estimate of glossiness is increased by a change of illumination. Two physical parameters determining surface properties, diffuse and specular reflectance, were manipulated by the observer across scenes illuminated with different light fields. Gloss constancy was not found across changes in illumination field. Importantly however, the effects of illumination changes on lightness and gloss were different and independent. The current consensus is that many pseudocues[1] are involved in the perception of gloss. Variation in the stimuli of multiple physical cues may well provide more than one pseudocue for glossiness; particularly considering that the stimuli were presented on a high-dynamic-range display, which provides more natural and physically accurate representations (and thus more accurate physical cues for gloss) than the more commonly used CRT screen. However, as the observer only manipulated one physical cue, analysis of the responses is based solely on adjustments along a scale of a single variable. Thus, while it may well be the case that a change of scene has a significant effect on perceived glossiness, it must be noted that the results of this particular paper quantified and calculated this effect using only a single observer-manipulated cue.

In the same year, Doerschner, Boyaci, and Maloney (2010) took a different approach to the same problem. Pairs of surfaces were compared for glossiness under two different real world light fields, and the data used to estimate transfer functions capturing the way in which perceived gloss was remapped from one field to the next. These remappings were best described linearly, and also exhibited transitivity. Some deviations from gloss constancy were shown; however it was found that the nonlinear scale of perceived gloss for one light field was the linear transformation of the nonlinear scale of perceived gloss for another light field. This is a significant discovery, as in many areas of perception the task to be accomplished is often approximated mathematically – which is an efficient and useful tool – however it is not assumed that the visual system might actually be employing a similar technique.

There is some reason to believe that the visual system is not capable of performing such calculations with the information available; yet other findings indicate that such tasks are somehow achievable. For example, in colour constancy, changes in illumination are computationally problematic, as a change in the illumination of a single surface alters the signals given by the L, M, and S-cones. In theory the proportional combinations of the signals given by these cones could differ wildly from those of the initial illuminant, as the proportions of the illuminant light at each wavelength might well be skewed in the opposite direction. However, Foster and Nascimento (1994) estimated L, M and S-cone values based on an illuminant change between two natural illumination maps (skylight and sunlight), and found that the change in L-, M-, and S-cone values could be explained well by multiplicative scaling of the signals, where the relative scaling value differs for each cone class and these values depend on the particular illuminant transition. On a similar note, the conclusion of the Doerschner, Boyaci, and Maloney (2010) paper found that a linear transformation can be made between perceptual parameters that are themselves nonlinear (the nonlinear relationship between the physical dimensions of gloss and the perception of gloss). Although such a relationship can be intuitively understood, there is no reason that this should be the case; for this reason it is an important finding.

Motoyoshi and Matoba (2012) carried out further studies of this nonlinear relationship between physical measurements and perceptual judgements of gloss, and found that varying the statistical characteristics of the illumination had systematic effects on perceived glossiness. Thus, while the relationship may not be linear, it is consistent to some extent. (The authors also concluded that

[1] For the purposes of this review, 'pseudocues' or 'perceptual cues' will refer to cues that the visual system extracts from the scene, and 'cues' will refer to physical properties such as specular reflectance.

judgements of gloss could be predicted by sub-band histograms of the images showing low level image properties – this was disputed, and will be discussed later in this review.)

In a more general study of material perception and the effect of illumination (rather than of gloss specifically), Pont & Pas (2006) found that material perception and light-field perception were essentially confounded in rendered images. However, when presented at a symposium (te Pas & Pont, 2005), these images were recreated with real-world stimuli, adding complex natural illumination. Subsequent judgements of materials were disambiguated, but less so for judgements of illumination. The addition of three-dimensional texture was most helpful in aiding material perception judgements; but this is a useful illustration of the importance of using complex real-world illuminants in obtaining veridical perceptual judgements.

7.2. Direction of illumination

The composition of illumination is not the only important component – it is also evident that its direction can have a significant effect on the perception of gloss and texture. Using the relatively new method of Maximum Likelihood Conjoint Measurement, Ho, Landy, and Maloney (2006) varied the illumination direction for surfaces of varying bumpiness. All participants perceived surfaces to be significantly bumpier with decreasing illuminant angle. This was not a failure of discrimination, and additional contextual cues to lighting direction did not improve roughness constancy. Thus it appeared that observers may be relying on features contained in the texture itself (such as highlights, shading and cast shadows) which change with the illumination. This was supported by a study by Nefs, Koenderink, and Kappers (2006), where differences in perceived surface relief were found to result from changes in illumination direction, but not from differing surface properties (glossy or matte). No evidence was found for glossiness influencing shape perception, however – so it seems to be the case that lighting direction influences the perception of texture and surface relief, and not vice versa. Leloup et al. (2010) also investigated whether the geometry of illumination – or luminance contrast – affected gloss perception, and although visual judgements of gloss did not correlate with instrumentally measured specular gloss (as might be expected, from previous discussion), psychometric gloss was a better correlate. However, illumination geometry was again found to be an important factor.

The importance of real-world illumination makes an appearance here, too – Pont and te Pas demonstrated that illumination complexity can manipulate judgements of lighting direction, as well as judgements of surface reflectance (2006). Using a discrimination paradigm, observers' abilities to discriminate between changes of illumination direction and changes in object surface reflectance were explored. This was first performed with computer rendered stimuli, and then with photographs of real objects. Discrimination was not supported with the rendered stimuli, while above chance performance was possible with photographed real-world objects. So again with certain types of rendered image, some cues important for perceptual judgements are evidently being omitted – the most salient being real-world illumination distribution.

8. Illumination and object/surface interaction

8.1. Specular reflectance

Specular reflectance does not consist of specular highlights alone; but all light reflected from a surface where the angle of incidence of the light and the angle of reflection are equal. This is one of the many cues that have been proposed as potentially informative in the perception of gloss, as glossy objects have a higher proportion of specular to diffuse reflection. There is support for this argument, as subjects can judge the specular reflectance of computer simulated glossy surfaces (Nishida & Shinya, 1998), and can also estimate particular properties of the surface reflectance without access to explicit information about the illuminant (Dror, Adelson, & Willsky, 2001). The solution for this, proposed by the authors, is that we rely on statistical regularities in the spatial structure of real-world illumination; and that these regularities are sufficiently predictable to allow us to estimate surface properties from statistical features of the image. This is consistent with both the gestalt view of perception, as well as the 'bag-of-tricks' computational approach (Ramachandran, 1985).

8.2. Specular highlights and their properties

As a result of numerous studies, it is now recognised that a number of properties of specular highlights must be present for gloss to be perceived convincingly. These properties include the relative brightness of the highlights, their contrast, position, orientation, and consistency relative to the object surface and shading.

An early paper on the properties of highlights found that increasing their size and brightness increases the area of the surface perceived to be shiny (Beck & Prazdny, 1981). The orientations of the highlights are also important – they must lie in the direction of minimal curvature, and the perceived gloss increases if they are consistent with the intensity gradient of the surface or of the surface contours (that is, the three dimensional shape information). This was supported by Hurlbert, Cumming, and Parker (1991), with the finding that increasing the brightness of the highlights increases the perceived level of gloss. Marlow and Anderson (2013) also showed that objects appear glossier if images are generated with a higher specular coverage; with increased sharpness and contrast.

Not only must highlights have certain properties in terms of relative brightness, sharpness and contrast, but they must also be consistent with the three dimensional shape of the object overall. For instance, the shading of an object should be congruous with the three dimensional shape in terms of the lines of contour; changes in illumination help to resolve any ambiguities in the solid shape of the object (Koenderink & van Doorn, 1980). Highlights placed on a two-dimensional image of a vase with shading consistent with the supposed three-dimensional geometry give a good impression of surface gloss if compatible with the lines of contour (Beck & Prazdny, 1981). Specular reflections also provide reliable and accurate constraints on the three dimensional shape, as there is a distinctive and characteristic way in which the reflected light (and the pseudoimage) is warped across the surface of the object, compatible with the three dimensional shape (Fleming, Torralba, & Adelson, 2004). These specularities can be distinguished from differences in texture, and remain consistent even with changes in environment. They can be extracted by populations of simple oriented filters. However, even when these conditions are met, the gloss ratings given by observers are not uniform across a surface with highlights (Berzhanskaya et al., 2005). Gloss ratings decrease as a function of the distance from a highlight, even when the distance is discounted from luminance values. This finding suggests that gloss constancy is restricted to a local level. The visual system does not appear to operate under the assumption that glossiness remains constant over a single object, unless there are similar reflections across the entire surface – which might be a possible flaw of gloss constancy. However, this would explain why objects rendered under realistic illuminations rather than single-point light sources look more glossy (Fleming, Dror, & Adelson, 2003), as the illumination geometry is more complex, giving a broader spatial distribution of light on the surface of the object. This means that more highlights, or local gloss percepts, are generated across the surface of the entire object.

Kim, Marlow, and Anderson (2011, 2012) supported the notion that multiple facets of specular highlights need to be considered. Besides concurring that highlights should be congruent with surface shading, they further suggested that the perception of gloss does not depend on the brightness of highlights alone; but that the locations of the specular reflections must correspond to the diffuse shading profile of the surface. This was demonstrated by adding lowlights – rather than highlights – to matte images, which gave as convincing a perceptual experience of a glossy surface as adding highlights. So it seems adding either highlights or lowlights can give the impression of gloss – combined with sharpness and contrast of highlights. Marlow, Kim, and Anderson (2011) also investigated the relationship between highlights and the diffuse shading profile, and varied highlight orientation relative to the diffuse shading of the surface by rotating the highlights. The distance of the highlights from the brightest region of diffuse shading was also varied, by transposing highlights in displays while also preserving the orientations of the highlights relative to their surrounds. Previously, highlight incongruence had been generated by simultaneously displacing the position and orientation of highlights in the image. It was therefore important to try and separate these two variables, to ascertain whether only one or both variables affected the judgments. Manipulating either variable in a non-natural direction reduced the perceived gloss; although rotations reduced perceived gloss more than transposed highlights, despite the fact that this displaced highlights into darker regions. Together, these findings provide further support for the view that the perception of surface gloss depends on highlight congruence with the structure of diffuse luminance variation in an image, and not just consistency with surface shape. While the highlights must be congruous with the diffuse shading profile of an object, the highlights themselves do not appear to influence perception of the diffuse shading profile. Todd, Norman, and Mingolla (2004) found that observers can discount the presence of specular highlights so that the relative lightness among different regions of the image is determined almost entirely by the diffuse component of surface reflectance.

However, while highlights do not seem to affect perception of the diffuse shading profile, the presence of specular highlights does bias judgements of ambiguously shaded objects towards a convex interpretation (Adams & Elder, 2014). This effect is likely to be an assumption based on illumination geometry, as highlights are less likely to appear on concave than convex surfaces. The effect decreases if the highlights are misaligned with regard to the surface shading, as they are more likely to be perceived as a feature of the surface rather than as a specular highlight.

Interactions of object surface and illumination play a significant role in the perception of gloss. Marlow, Kim, and Anderson (2012) proposed that changes in perceived gloss could be understood as a direct consequence of image properties that covary with surface geometry and illumination field. A change in either of these factors can generate different patterns of interaction with perceived gloss, and these interactions can be complex and variable. However, Marlow et al. argued that the successes and failures in the perception of gloss can be predicted by the way that each illumination field modulates the characteristics of the specular reflections. Such effects provide strong evidence for the modulation of perceived gloss occurring as a direct consequence of a systematic covariation of specular reflections with changes in the distal scene. However, to judge perceived gloss in this study, Marlow et al. used the variable with the largest apparent difference between stimuli – either the degree of coverage of specular reflections, sharpness, or contrast. This might suggest that the visual system makes a judgement based on a number of different types of information, where each does not contribute in a consistent way to the overall experience of gloss. This could provide an explanation for the supposed instabilities in perceived gloss when changes occur in surface geometry or viewing conditions. If the relations between physical parameters and perceived experience are nonlinear, perceptual features may vary in salience depending on the manipulations made, such that judgements would be made on the basis of different perceived variables each time.

9. Object properties

9.1. Surface texture and shape

The three dimensional shape of an object can affect perceived gloss alone, as well as through interaction with changes in the field illumination. Marlow, Kim, and Anderson (2012) showed that perceived gloss of a surface varied up to 80% as a function of the three dimensional surface relief alone, within a single illumination field.

Furthermore, there appears to be a significant influence of shape on the perception of material reflectance. Vangorp, Laurijssen, and Dutré (2007) found that when comparing two objects of identical material where the geometry of the two differs, accuracy of material perception decreases. The addition of edges significantly changes the perceptual judgement of the material; and two different materials presented in the same shape can look identical despite having very different reflectance properties. For example, two tessellated spheres rendered with two different types of blue plastic appear to be identical, and two objects rendered with identical materials but in different shapes (a smooth blob, and a tessellated sphere) are perceived very differently. The blob-shape appears to be very glossy, mainly as a result of the curved surface displaying a range of highlights, while the tessellated sphere mostly reflects diffusely and is perceived to be made of a matte material. (All images were rendered with real-world light probes, so specificity of a limited or unnatural illuminant did not affect judgements.) This finding is supported by a study by Nishida and Shinya (1998), where observers were found to have limited ability to recover surface reflectance properties under changes in surface shape – indicating that three-dimensional object shape can influence our perception of surface gloss. Olkkonen and Brainard (2011) found that both shape and illumination affected perceived glossiness, and that there were large interactions between illumination and object shape in their effects on perceived glossiness. Joint effects of the individual factors could not be predicted from the individual effects in a straightforward manner, and analysis of luminance histogram statistics could not account for the interactions. This can be related to the findings of Ho, Landy, and Maloney (2008) in terms of the use of 'pseudocues' – both shape and illumination field affect the pseudocues, yet the translation from physical measurements to pseudocues is not necessarily linear or even monotonic. The mechanisms may interact with each other in a nonlinear way in physical terms, or the perceptual pseudocues translate from the physical in a nonlinear manner. To date, these effects remain unexplained.

Surface properties other than the shape of the object itself play a further role in the perception of gloss. Ho, Landy, and Maloney (2008) demonstrated that variation in three dimensional surface texture significantly affects gloss constancy: – if a surface texture is bumpier, this results in an increase in perceived gloss. However, beyond a certain level of bumpiness (with a large difference between the high peaks and low troughs) the surface looks less glossy. This study was performed using a conjoint measurement paradigm, and Ho et al. suggested that the observed interactions between perception of gloss and bumpiness of surface texture are the results of imperfect cue learning (or use of pseudocues – that is, indirect use of the physical information available).

These conclusions were partially supported by Qi et al. (2012) who studied how mesoscale and microscale roughness affect perceived roughness. Mesoscale roughness is of a lower spatial frequency than microscale roughness – that is, the 'bumps' themselves are of larger size. (As an example, mesoscale is to microscale as pebbledash is to sandpaper.) Perceived gloss changed monotonically when varying the microscale roughness parameter, and non-monotonically when varying the mesoscale roughness parameter: that is, both parameters affected perceived gloss, yet an additive model was inadequate to describe the interactive and nonlinear influence. As in the study by Ho, Landy, and Maloney (2008), the effect of surface texture was non-linear, and changes in approximately mesoscale roughness did not produce a consistent effect on the perceived glossiness.

9.2. Surface lightness

Surface lightness, regardless of colour, also has a significant effect on perceived gloss – and there seems to be an effect in both directions. Harrison and Poulter (1951) observed that dark surfaces appear glossier in comparison to lighter surfaces. Glossier surfaces appear darker than their rough/matte counterparts, apparently due to increased contrast between the specular and diffuse components (Beck, 1964). However, this seems to conflict with Todd, Norman, and Mingolla (2004) findings that observers are able to discount the presence of specular highlights in determining relative lightness. Todd et al. concluded that observers were able to exclude specular highlights in making their judgements of relative lightness, which were subsequently determined largely by diffuse reflectance from the surface – although this apparent conflict is based on the assumption that glossiness is entirely determined by specular highlights.

9.3. Surface colour

Research to date has produced conflicting and uncertain results regarding the potential influence of surface colour on gloss perception. Initial studies seemed to show that there was little in the way of an interaction – Xiao and Brainard (2008) found little evidence to suggest that variation in surface gloss had a noticeable effect on the appearance of colour. In one condition, surface gloss and body colour of a sphere were varied, and in the second condition the point on the object at which the participant observed the colour was varied. The visual system seemed to compensate for the physical effect of varying gloss, but a small effect was still observed on the perceived colour appearance. An effect of patch location was also found, though smaller than the physical effect, but compensation of test patch location did also occur. However, later studies found some evidence in favour of colour information affecting gloss perception. Wendt et al. (2010) showed that the inclusion of colour information in stimuli improved gloss constancy performance (although gloss was classified using only specular highlights). Availability of colour information led to a significant improvement in consistency in glossiness matching (that is, fewer systematic errors) compared to greyscale surface trials. Some observers even gave priority to colour information over motion (discussed in the next section) as a cue to glossiness; although in general observers showed different levels of receptiveness to certain combinations of information to be used in making a judgement. This implies at least some basic input from colour processing, but again indicates that different observers prioritise different cues for gloss.

More recent investigation into the potential importance of colour processing for perceived gloss has focused on colour information obtained from the specular and diffuse components (Nishida et al., 2008). When wavelength compositions of specular highlights and diffuse light were changed, observers perceived naturalistic glossy surfaces only when the physical constraint of highlight constraint held. In other words, highlights comprise a wide range of wavelengths of light, including the surface reflectance and the illuminant. The diffuse component, however, cannot contain any wavelength absent from the reflected highlights, as this is composed of all wavelengths in the illuminant, and additional wavelengths cannot be added when reflected from a surface. Gloss perception was also reduced when there were no luminance increments between the diffuse reflectance and highlights. A subsequent paper (Nishida, Motoyoshi, & Maruya, 2011) found that multiple colour band analysis using raw cone-signal based images could not fully explain the luminance–colour interaction in gloss perception, as when an image synthesised from S, M, and L cone images violated the physical constraint it was still perceived to be naturally glossy. However, the authors concluded that this kind of multiple colour band analysis might be a promising hypothesis for observed colour and luminance interactions. In a similar study (Hanada, 2012), the colour coordinates of the objects and highlights were varied, while luminance was unchanged. Objects were perceived as glossier when the highlight and object colours were different, demonstrating the normal difference between purely specular reflection and surface reflectance. Unnatural combinations of colours were still perceived to be relatively glossier, when compared to stimuli with identical surface and highlight colours, even though the luminance of each pixel of the images was controlled.

10. Observer and object/surface interaction

10.1. Motion information

When we perceive objects in everyday life, we are not limited to viewing static objects. We are continually moving around our environments; and if not changing our physical position, we are constantly making eye saccades. This motion produces a steady stream of optic flow, which provides a rich source of perceptual information about our surroundings. When inspecting a new or interesting object, we might pick it up and rotate it by a window. Such inspection allows us to investigate the surface properties of the material, by observing the changes in surface reflection. Hurlbert, Cumming, and Parker (1991) noted that specular highlights appear to remain stationary on the surface of a rotating sphere when the observer is stationary: – the highlights appear to slide across the surface of the object, and thus remain stationary relative to the observer. It is evident that a great deal of information about surface properties such as gloss can be extracted – the movement of specular reflection across an object reveals a great deal about its three dimensional shape, and this movement is particularly revealing for glossy objects. Hartung and Kersten (2002) showed that the pattern of optic flow projected from a rotating shiny object is significantly different from that of a rotating matte object. A number of objects were 'painted' with the image of an illumination map, so that for any given static view it appeared shiny – but when it began to rotate, it appeared matte. Rather than staying stationary, the specular highlights moved with the surface of the object – thus producing a different pattern of optic flow.

These findings are well supported. Sakano and Ando (2008) investigated the effect of self-motion through a scene on gloss perception. Temporal changes in the scene caused by lateral motion of the observer enhanced the strength of perceived gloss; even though rendered stimuli were used. Stimuli on a screen moved in accordance with any movement of the observer's head, to simulate movement in a three-dimensional space. The stimuli luminance also changed temporally in terms of the spectral highlights as well as position, so that the object appeared to be stationary in 'three-dimensional' space, while a reference stimulus did not change on the monitor. Similarly, Wendt et al. (2010) found that motion information significantly improved gloss constancy performance – systematic errors were significantly smaller in gloss matches under dynamic conditions compared to static conditions, regardless of whether binocular information was available. (This is readily confirmed by real-life situations, when we rotate objects in our hands to see highlights move across the surface – while remaining stationary relative to the illuminant – to assess glossiness.) Doerschner et al. (2011) investigated whether there might be a characteristic way in which such features move during object motion or changes of viewpoint, which might act as a reliable source of information in judgements of gloss. For moving stimuli, subjects reported that objects with normal specular motion appeared shinier than those with static reflections (relative to the object). However, on trials where the object did not move, performance was at chance level – indicating that motion cues alone caused differences in appearance, rather than the way in which the motion stimuli had been created. Rather than just contributing to the perception of glossiness of an object, these motion cues could be used to distinguish between matte and shiny surfaces. Therefore the visual system appears to rely on characteristic optic flow patterns in determining glossiness. Lichtenauer, Schuetz, and Zolliker (2013) supported this further in a study where judgements of rough and glossy surfaces were compared, by either interacting or passive observers. Active exploration of the rendered stimuli gave significantly higher inter-observer agreement of perceptual judgements; supporting the conclusion that the motion of an object, whether facilitated by the observer or the object, reveals a characteristic optic flow which can inform perceptual judgements of gloss.

Ho, Maloney, and Landy (2007) also investigated the effect of viewpoint on perceived gloss, by carrying out an adjusted version of the earlier conjoint measurement study. Bumpiness and illumination were kept constant, and observers were asked to make judgements of the surface properties from two different viewpoints. Observers failed to achieve roughness ('bumpiness') constancy based on similar pseudocues to the previous study, suggesting that the human visual system does not always select the right cues for the visual task. This might seem to contradict the results discussed above. However in this study there was no explicit observation of the transition between viewpoints but rather a comparison of judgements from two locations. It seems to be the case that a change in viewpoint without observing optic flow confuses our roughness constancy, while the inclusion of motion improves it.

10.2. Viewing distance

To date, there has been little research into the effect of viewing distance on perception of gloss. However suggestions have been made regarding reasonable viewing distances when conducting empirical studies involving perceptual judgements of gloss. Czepluch (1976, as cited in Leloup et al., 2013) recommended that restrictions should be placed on relative distances between the illuminant, object, and observer in gloss scaling in particular, as 'any standard geometry for visual evaluation of gloss [was] lacking'. Such recommendations might be based purely on speculation that increased viewing distance affects perceptual acuity – for instance, Ho, Landy, and Maloney (2008) showed the increased bumpiness of a surface alters the perceived gloss. Viewing surfaces of reduced bumpiness, but at closer viewing distances, might mean that observers are better able to perceive a finer scale of texture, which would influence the gloss judgement (Qi et al., 2012). Little is known about this potential factor, but it is undeniably an important variable to control.

10.3. Binocular disparity

Even before any detailed study of the perception of gloss began, binocular disparity had already been identified as a potentially invaluable source of information. Kirschmann (1895, as cited in Wendt, Faul, & Mausfeld, 2008) proposed that the disparity of highlights on specularly reflecting surfaces usually differs from the disparity produced by points on the surface itself. Czepluch (1984, as cited in Sève, 1993) also emphasised the importance of binocular disparity. Highlights reflected from an object appear to be positioned differently to each eye; thus each receives different information about the position of the highlight on the surface, as specular reflection is always reflected – by definition – at an equal but opposite angle to that of the illuminant, and this angle will be slightly different for the two eyes are they are laterally displaced. Thus highlights can be correctly identified, rather than seen as differently coloured patches on the surface.

The importance of binocular disparity has been confirmed by a considerable number of more recent studies. Hurlbert, Cumming, and Parker (1991) found that binocular disparity of specular reflections can override brightness in judgements of gloss, and Obein, Knoblauch, and Viénot (2004) proposed that retinal disparity plays an important role in the perception of gloss – mainly in the judgement of high gloss values (i.e. in highlights). While the latter has yet to be investigated further there is substantial evidence for binocular disparity as a significant cue for the perception of gloss. When information from a disparity is available, it can signal that a surface is glossy (Formankiewicz & Mollon, 2009), and perceived gloss appears to be stronger and more authentic (Wendt, Faul, & Mausfeld, 2008). In the former study, the author underlined that as the illuminant is directional, not only is there a disparity in the position of the highlight, but the intensity of the reflected light is also slightly different. The angles of reflection to each eye are not identical, yet for light to be specularly reflected the angle of illuminant direction and angle of reflection must be the same. A patch which appears to be reflecting largely specular light to one eye will reflect slightly more diffuse light to the other. Thus, the visual system is exposed to discrepancies in the monocular luminance of highlights as well as their relative location when viewing a glossy surface. The ability of subjects to detect a binocular luminance disparity was measured, and the results were consistent with Weber's law,[2] Ricco's Law,[3] and Bloch's Law,[4] demonstrating that the visual system is more than capable of distinguishing these disparities.

Furthermore, Wendt et al. (2010) showed that the presence of disparity information significantly improved gloss constancy performance, both alone and in conjunction with additional information such as colour and motion. However, developing Formankiewicz and Mollons' earlier findings, Methven and Chantler (2012) found that while stereo disparity increased the perceived glossiness for rough surfaces, specular highlight disparity alone

[2] Weber's Law states that the Just Noticeable Difference (JND) between two stimuli is proportional to a constant ratio of the magnitude of the stimuli.

[3] Ricco's Law states that, for stimuli of less than one arc-minute in diameter (the resolution of the eye at the fovea, larger at the periphery), spatial summation applies – the threshold intensity multiplied by the area equates to a constant for a test patch to be detected (that is, a larger patch of lower luminance is just as detectable as a smaller patch of higher luminance).

[4] Bloch's Law describes temporal summation, and states that within a certain time limit (100 ms), the minimum number of quanta required to detect a test patch is constant, regardless of whether the patch was of high luminance and lower presentation time or low luminance and higher presentation time (that is, light intensity multiplied by time presented equals a constant for detection of a patch).

was not enough to ensure increased perceived glossiness. More naturalistic renders of objects and surfaces were used, and the conclusions further confirm the emerging picture of the need for a number of interacting factors. Naturalistic specular highlights are generally sufficient for gloss perception, as long as they are placed correctly, but the constancy of this perception is strengthened by the addition of information such as a disparity in specular highlights. While a single type of information may induce some level of perceived gloss, alone it does not ensure maximal perception of gloss. Evidence supporting binocular disparity by means of a performance based task was obtained by Muryy et al. (2013). Images of specular objects were binocularly presented, and observers were asked to adjust the positions of a number of 'probe dots' to indicate the level of depth that they perceived in the image. For simple surfaces, where there was no indication that the disparities presented were 'wrong', participants erroneously said that the virtual surface was real, by indicating a more realistic level of perceived depth. However, when surfaces were more complex, participants made fewer errors, and correctly identified surfaces with larger disparities in unexpected locations, by indicating much lower values of perceived depth. This suggests that the visual system assesses sensory signals for relevance and usefulness, based on intrinsic markers of reliability. These markers are in the disparity signals themselves, as errors were made at face value – this suggests that the brain interprets specular objects by applying a general strategy instead of implementing physical rules of specular reflections, which proves useful when the disparity signals are abnormal.

An additional study by Kerrigan and Adams (2013) tested observers' abilities to use specular information and binocular disparity to identify the curvature (convex or concave) of an object, to determine whether this might be invoked by knowledge of a geometric model of specular reflection. Binocular vision enables observers to distinguish specular highlights from other variations in luminance, as unlike surface markings, specular highlights 'float' on a plane above the surface if concave and below if convex. However, observers' performances were not consistent with a full geometric model of specular reflection – showing substantial errors particularly for concave surfaces. Kerrigan and Adams came to the same conclusion as Muryy et al.; that the visual system seems to invoke a general strategy, rather than responding based on an understanding of the physics of specular reflections. However, it is important to note that this is not the same as a 'bag-of-tricks' approach but instead halfway between this and a reverse optics/physics approach.

10.4. Physical interaction

Besides interaction with objects in the environment on a purely motion-based level, active handling also appears to improve our visual perception. This might not be limited to motion based information alone – for when we pick up an object to inspect it, we also make judgements of texture using our sense of touch. It is intuitive, but not necessary, that these tactile judgements might feed into visual perception. Bergmann Tiest & Kappers (2007) found that judgements of rough and glossy surfaces were slightly better and more consistent when observers also made haptic judgments, compared to judgements made on the basis of visual observation alone. Interestingly, participants ordered the samples according to different criteria – some ordering on high spatial frequencies, whereas others ordered on low spatial frequencies. This provides evidence not only for a holistic account of texture judgements in terms of the senses, but also evidence for a constellation approach for visual cues (pseudocues). Each observer may give different weightings to the types of information available in making these visual judgements – perhaps based on the kinds of surfaces they have previously experienced.

11. Observer

11.1. Linking the perceptual and physical dimensions

Perhaps the hardest task in this field is the problem of bridging the gap between existing knowledge of the physical dimensions, and perceptual judgements of the human observer. We have already seen that the relationship between the physical and perceptual dimensions cannot be described linearly, but that a linear change in the physical dimension can correlate to a linear change within the perceptual dimension (e.g. Doerschner, Boyaci, & Maloney, 2010). Despite our lack of knowledge of the relationship between the physical and the perceptual dimensions, there is evidently a great deal of consistency in the way in which the physical environment is interpreted by the visual system. This is evidenced by findings such as those of Doerschner et al., and also our general day-to-day experiences (visual constancy is sufficiently successful to the point that failures are unusual and interesting).

One of the first experiments to address the problem of linking perceptual and physical dimensions was by Ferwerda, Pellacini, and Greenberg (2001). Here, a psychophysically-based light reflection model of surface gloss perception was proposed; and experiments were conducted to explore how physical parameters describing reflectance properties of glossy surfaces might link to the perceptual dimensions of the appearance of gloss. Multidimensional scaling techniques were employed to incorporate the acknowledged multidimensional nature of gloss perception. As a result, Ferwerda et al. suggested that there were two 'perceptually meaningful' axes of perceptual gloss-space: the apparent contrast of a reflected image, and the apparent sharpness or distinctness of this reflected image. Magnitude estimation was then used to place quantitative scales on the axes proposed. However, some concerns about the method should be raised. Participants were asked to judge the apparent difference in gloss in a pair of stimuli by means of a sliding scale ranging from 0 to 100. Such a measure is less reliable in terms of consistency between participants, or indeed even within the judgements of a single participant. When considering a large number of comparisons between stimuli, any given scale needs an established reference point. Differences in pairs of stimuli should be compared directly with other stimuli; otherwise the judgements made cannot be reliably related to one another. A method involving a comparison of two pairs of stimuli, where all possible comparisons within the stimuli set are used, might be more suitable for such an investigation. Observers are asked to indicate which pair they perceive to have the larger difference in the required variable. This would allow the data to be interpreted and quantified in a valid way; and would thus be far more informative. In addition, the reliance on the two proposed axes alone does not allow for any interaction with factors previously acknowledged as influential in the perception of gloss; curiously limiting the scope of further multidimensionality after employing multidimensional scaling techniques.

More recently, Obein, Knoblauch, and Viénot (2004) used a maximum likelihood difference scaling paradigm to estimate gloss scales for a series of black coated stimuli. A nonlinear relation between gloss percept and instrumental specular gloss values was found, and sensitivity was higher at extreme scale values than in the middle. If a reverse optics method were being employed, one would expect to find a linear relationship between the percept and instrumental values, as the physical scales themselves would be estimated. Therefore, this nonlinear relationship supports a conclusion favouring a pseudocue- and interpretative-based approach. However, in line with the previous convention, judgements of gloss were reliant only on specular highlights. This shows a non-linear relationship between the physical and perceptual parameters of a single source of information, influential in the perception of gloss. Of course, these initial experiments necessarily manipulated a limited number of variables as they were the first of their kind. Expanding this to incorporate additional variables which factor into our perception of gloss would be a considerable and extremely complex task, yet it is important to note that the information available to observers in this particular case was constrained.

11.2. Gloss constancy

A number of different physical and perceptual cues which influence constancy of perceived gloss have already been discussed. Deviations from gloss constancy are evident under a number of different viewing conditions – strong interactions between object shape and illumination geometry produce failures in gloss constancy (Olkkonen & Brainard, 2011), perception of gloss is not independent of light field (Doerschner, Boyaci, & Maloney, 2010), and constancy is affected by viewpoint (Ho, Maloney, & Landy, 2007) and variation in surface texture (Ho, Landy, & Maloney, 2008). Constancy improves under natural illumination, although is not perfect (Dror, Willsky, & Adelson, 2004; Fleming, Dror, & Adelson, 2003), and also improves with the inclusion of colour, motion and disparity information (Wendt et al., 2010). It also seems that gloss constancy operates at a local level (Berzhanskaya et al., 2005). Considering the body of findings related above, it is evident that there are a number of failures of constancy and inconsistencies between physical measures and perceived gloss that are difficult to explain. If the function of perceived gloss is assumed to be identifying surface properties, then constancy of perception is important. There is some evidence for a less-than-perfect gloss constancy (such as consistency of judgements under different illuminants, Fleming, Dror, & Adelson, 2003), and findings suggest that it operates in a similar way to colour constancy. When more information is available to the visual system in the scene, and when the stimuli are more realistic and lifelike, observers show a greater degree of constancy (Kraft & Brainard, 1999).

A great deal of research has been done on colour constancy but comparisons of colour- and gloss-constancy are not straightforward. The measurement and quantification of gloss constancy involves problems that do not arise in work on colour constancy. In colour constancy both perfect constancy and perfect inconstancy can be objectively characterised (judgements with perfect inconstancy are determined purely by the spectral composition of light reaching the eyes rather than solely by the colour reflectance properties of surfaces). It is not clear what form of judgment would constitute perfect inconstancy for gloss perception; the lack of a 'low-end' to the gloss constancy scale makes it difficult to quantify and compare deviations in gloss constancy. While it can be clear that observers are not achieving perfect constancy in experiments, quantifying the degree of imperfection of judgements in a particular task or comparing deviations across tasks is not generally possible. Of course the *relative* degree of constancy found when a single factor is varied in an experiment can still be measured. However, as soon as two factors are varied making comparisons between their effects and quantifying their interaction is problematic. Evidence to date indicates that observers are capable of making relative judgements of gloss when comparing stimuli varied along a single dimension, but when multiple factors are jointly manipulated interactions occur and often result in a confound – although these are reduced when motion, complex illumination and colour information are available. It seems that perceived gloss is related to its physical determinants nonlinearly, or at best imperfectly.

11.3. Cortical processing of gloss and other surface properties

While much of the focus in gloss research has been directed at the perceptual cues involved by means of psychophysical experimentation, additional lines of enquiry have looked into the processing of perceptual information beyond the retina and into the cortex. Such investigation aims to discover the way in which perceptual information is processed in later stages of visual perception, in order to test theories of essential computations that might be performed; and whether this involves additional unknown factors or processes. This kind of knowledge might feed back into research at earlier stages of visual processing, by highlighting additional perceptual tasks that might contribute to other visual processes. Cant and Goodale (2007) carried out an fMRI experiment to investigate the cortical mechanisms underlying the roles of object form and surface properties in object recognition. The results suggested that there were different pathways in extrastriate cortex for the processing of form and surface-properties. It was also concluded that the extraction of surface colour seemed to occur relatively early in visual analysis, compared with the extraction of surface texture. A tentative inference from this might be that the extraction of surface texture requires further (and more complex) computation than colour.

In a more recent set of studies, Cavina-Pratesi et al. replicated these findings (2010a). By studying visual object agnosia patients, a behavioural double dissociation was found with a double dissociation in the damaged areas of cortex – one patient could distinguish object shape but not texture, and a second could distinguish texture but not shape. Separate processing of surface texture and form was found in the ventral stream; surface texture activated an area quite distinct from areas activated by shape and form. This is evidence that these areas play a causally necessary role in the discrimination of these features; and that the two tasks are to a great extent accomplished independently by the visual system. In a second paper, Cavina-Pratesi et al. (2010b) sought to determine whether there was a single region involved in the processing of surface properties, or whether there was a number of more specialised regions implicated; each dealing with a particular surface property. A double dissociation was found between two patients, in the processing of surface properties (texture and colour) and geometric (shape) properties. Separate foci were also found for colour and texture – areas selective for shape, texture, and colour were found to be distinct from areas responding to a combination of these features. Thus, it suggests that there are separate channels for processing form, texture, and colour; as well as the division between surface properties and object shape/form.

Kentridge, Thomson, and Heywood (2012) developed this line of enquiry further with an investigation into whether glossiness perception was mediated by the same processes as colour or surface texture. Gloss is conceptually distinct from texture and colour, but not necessarily distinct in visual processing – yet it was found that glossiness perception could be mediated independently of cortical processing of colour or texture. Patient MS displays a number of visual abnormalities, and is a cerebral achromatopsic – he is unable to discriminate colour and texture, as a result of a lack of these cortical areas. MS performed significantly better than chance on a gloss perception task, for real and rendered stimuli, though slightly worse than controls. This task could not have been solved on the basis of local feature comparisons, as lightness and texture were both randomised. Thus, it was concluded that the perception of gloss does not depend exclusively on processing in the same constellation of regions necessary for the perception of colour and texture.

12. Neural selectivity

A number of recent studies have investigated the neural correlates of perception of surfaces and their properties, with a small number focusing on the perception of gloss. Results from previous studies (Cavina-Pratesi et al. 2010a, 2010b) suggest that information concerning surface properties is processed in the ventral visual stream, and the results from the studies on gloss corroborate this.

Nishio, Goda, and Komatsu (2012) were the first to investigate neural selectivity for the perception of gloss. They examined the responses of neurons in the inferior temporal (IT) cortex of macaques while presenting stimuli of objects varying in specular reflection, diffuse reflection, and roughness. Neurons in the superior temporal sulcus selectively responded to specific types of gloss – this remained constant when the shape or illumination of the object was altered and perceived gloss was the same, but changed when the images were scrambled and perceived gloss was different. For instance, one cell responded selectively to stimuli with very sharp highlights, and did not respond at all to weak glossiness. A second responded strongly to shiny surfaces that had blurred highlights, and a third responded only to matte stimuli with very low specular reflectance. Nishio et al. concluded that there is a population of cells that represent different types of gloss, each cell having a different selectivity. They also proposed that mechanisms in the visual cortex integrate local features of the image to extract information about surface gloss, and that this information is systematically represented in the population of neurons in the IT cortex.

Shortly afterwards, Okazawa, Goda, and Komatsu (2012) investigated selective responses to glossiness using fMRI. Specular reflection alone was manipulated in generating images of specularly reflecting and matte objects. A set of scrambled images was also produced, and responses to the specular images were compared with responses to the matte and scrambled images. Activation was found throughout the visual pathway, from V1 to V4, and the posterior inferior temporal cortex (only slightly different to the superior temporal sulcus, as found in Nishio, Goda, & Komatsu, 2012). Contrasts of the images were subsequently manipulated, and the activations observed could not be explained by the use of global or local contrasts. Okazawa et al. concluded that processing of specular images occurs along the ventral visual pathway, to particular regions in the IT cortex. This is consistent with the findings of Nishio et al., and also with previous studies of the processing of surface properties in human fMRI – showing that even though specular reflection of the objects was the only variable manipulated by Okazawa et al., their results generally supported previous findings.

Wada, Sakano, and Ando (2014) performed the first human fMRI study on the areas involved in perception of gloss in the human cortex. Given this was a human study, a particular point of interest was that areas beyond the ventral visual cortex have been implicated in processing gloss. As described earlier, Kentridge, Thomson, and Heywood (2012) found that patient M.S., a visual agnosic with lesioned ventral visual cortex and intact dorsal visual cortex, was able to distinguish between glossy and matte objects at above chance levels. Furthermore, many visual features have been shown to influence human perception of gloss in psychophysical experiments, so plausibly a number of regions could be involved rather than a single localised area. First, they investigated which cortical regions might be involved more generally, by comparing responses to high and low gloss objects. All regions showed significant correlation with perceived levels of gloss, and were consistent with regions identified in the macaque studies apart from V3A/B in the dorsal visual pathway. It was proposed that the involvement of this region could be specific to the human visual system, supporting the findings of Kentridge et al. In a second experiment, visual areas modulated by selective attention to gloss were investigated. All regions showing activation were among those identified in the first experiment. Wada et al. concluded that a number of commonly identified regions of visual cortex may be involved in central processing of glossiness, with additional regions contributing to the processing of gloss cues; of which some may be specific to the human visual system.

13. Subsequent throwbacks to a single objective measure or approximation employed by the visual system

Despite the emerging consensus for a multidimensional account of the perception of gloss, the conclusions of a number of papers hark back to early research. However, the aims tend to the opposite end of the scale of solutions, as a number of 'bag of tricks' approaches are proposed – what might be seen as shortcuts 'that just work' – though in fact none of these have proved especially successful.

Perhaps the most prominent of these attempts was by Motoyoshi et al. (2007) who proposed that there were simple image statistics which could identify perceptual gloss in real-world surfaces. Images of glossy surfaces were analysed, and Motoyoshi et al. found that the skew of the luminance histogram and the skew of the sub-band filter output were correlated with perceived surface gloss – and inversely correlated with diffuse reflectance and a perceived matte surface (where a positive skew correlated with perceived gloss, and negative skew correlated with a matte surface). This was presented as evidence that human observers might estimate statistics such as the luminance histogram skew; in conjunction with evidence that a visual aftereffect was found based on this skewness. Adaptation to images with skewed statistics altered the apparent lightness and glossiness of subsequently viewed surfaces. This, Motoyoshi et al. proposed, suggested that a neural mechanism existed which was sensitive to such statistics of skewness.

This conclusion was shown to be flawed for a number of reasons. Landy (2007) published a response shortly after the original paper arguing that while these parameters of luminance histograms might be convenient mathematically, they did not correspond precisely to the computations used in perceptual judgements. Luminance histogram statistics are not the whole story for the perception of gloss or lightness, as a great deal also depends on the surrounding environment and surfaces. Perceived specular reflections such as highlights and pseudoimages are also necessary, and surroundings need a pattern of illumination consistent with statistics of natural scenes. Highlights must be positioned realistically, relative to the shading profile of the three dimensional surface. Glossy images may well have a skewed luminance histogram, but this is not a predictor of all images showing glossy objects – skew of the luminance histogram ignores all of the other cues (or pseudocues) accepted as being important to perceiving a glossy surface. Furthermore, Fleming (2014) made the point that this kind of diagnostic computation has the disadvantage of being fooled when the assumed statistics of the real world are violated; when in reality, gloss constancy is not flawed to this degree.

Anderson and Kim (2009) further criticised the proposals of Motoyoshi et al. (2007) by showing that the stimuli used in image analysis were not representative of the full range of possible stimuli encountered in the real world. The correlations only arose, they argue, because of the limited space of surface geometries, reflectance fields and illumination fields which Motoyoshi et al. evaluated. The authors emphasised that photometric statistics fail to be predictive as they are void of any structural information required in distinguishing different types of surface attributes. The perception of gloss depends critically on consistency in location and orientation of highlights, relative to the shading profile and the three dimensional surface geometry; and this cannot be deduced from skew computations, as all information regarding location is discarded. To illustrate this point, Anderson and Kim made a number of images of glossy surfaces that had a negative luminance histogram skew. They also showed that Motoyoshi's adaptation experiment gave the same results for any level of luminance contrast, demonstrating that this was not exclusive to gloss perception. Any proposed statistic of this kind would have to be capable of reliably discriminating between different contributions to an image. In a second paper (Kim & Anderson, 2010) the adaptation experiment of Motoyoshi et al. was replicated, and no consistent after-effect was found. Adaptation to zero-skew adaptors produced after-effects similar to positively skewed adaptors, and negatively skewed adaptors produced no reliable after-effects. Wijntjes and Pont (2010) investigated whether Ho et al.'s findings (2008) of relief height correlating with perceived gloss could be explained by Motoyoshi et al.'s gloss predictor. However skewness of luminance could not account for this effect.

Ultimately, all attempts to devise a single diagnostic statistic – not directly related to any physical parameter that generates a gloss percept – for the perception of gloss have failed, as have attempts to characterise the entirety of perceptual gloss using a single proposed mechanism. Many studies have successfully characterised perceptual gloss to some extent, but none encapsulate the wide range of characteristics which affect perceived glossiness. It is not as yet fully understood why the visual system interprets interactions of shape, illumination and specularity in certain ways. Additional confirmation of these conclusions can be seen in several other studies: Ji et al. (2006) showed that visually scaled gloss data do not correlate with conventional glossmeter measurements over the entire range, demonstrating that the measurement of a single physical attribute is insufficient to account for perceptual gloss. Lindstrand (2005) also argued that the nature of perceptual gloss is too complex to be characterised by a single instrument. An example of this in practice can be found in the study by Nefs, Koenderink, and Kappers (2006), investigating whether gloss influenced the perceived relief of a surface. Differences in illumination direction induced a change in perceived relief, but surprisingly, no systematic difference was found between matte and shiny surfaces. This seems to contradict the evidence discussed above. However, perceived gloss was assumed to be based entirely on specular highlights – therefore the 'surprising' findings were obtained as a result of neglecting to take multidimensionality into account.

14. In favour of a gestalt approach

Research on the perception of gloss has, to date, tended towards the conclusion that the visual system does not attempt to calculate or approximate the physical dimensions of surface reflectance or surface properties, but instead seems to analyse a constellation of cues and pseudocues in making these perceptual judgements. The sum of these object and scene cues forms tertiary properties of the perceived image. Fleming initially voiced support for this approach in his 2004 paper investigating the power of specular reflections in perceiving the three dimensional shape of an object; since then, a great deal of evidence and support in favour of this approach has emerged.

In 2010, Wendt et al. showed that observers used several different kinds of information available in making judgements of gloss, to varying degrees (motion, disparity, and colour). All types of cue investigated improved overall gloss constancy, both when used alone and in conjunction with other cues, but observers showed differences in their prioritisation of the various cues, when presented with multiple kinds of information. Leloup et al. (2012) uncovered similar responses – observers were asked to make pairwise comparisons of real life stimuli, which incorporated multiple perceptual cues for glossiness. These comparisons were used to derive an overall scale of perceptual gloss. Differences in both distinctness of image and luminance affected perceived gloss. However, different strategies of evaluation were found between observers, as they attributed varying levels of importance to the different cues.

Moreover, cue (and pseudocue) selection differs from task to task for all observers. In a study investigating the cues used for comparative judgements of gloss, observers relied on whichever most reliably distinguished the pair of stimuli (Marlow & Anderson, 2013). Images differed in specular coverage, sharpness and contrast – so if there was high variability in specular coverage, but low variability in sharpness and contrast, gloss judgements would be strongly predicted by specular coverage. Marlow et al. concluded that in static images presented monocularly, judgements of perceptual gloss rely on a heuristic weighting of cues for the characteristics of specular reflections. However, for this particular set of images it must be remembered that while weighted combinations of the variables used strongly accounted for observers' perceptual judgements, this was for a limited set of surfaces under very specific conditions (Fleming, 2014).

It is evident that we can recognise the physical nature of objects from information available in the key features of the appearance of gloss (Fleming, Wiebel, & Gegenfurtner, 2013; Ged et al., 2010). There is collective agreement that the brain does not, and could not, perform computations of inverse optics, as there is not enough information available to the visual system to invert the process of image formation and arrive at the base surface and illumination properties (Anderson, 2011). Fleming supported these conclusions in a recent review paper (2014), and argued that findings regarding the orientations and position of highlights imply that the goal of perception is not an inverse optics approach or a 'bag of tricks' method, but rather that it aims to characterise the overall 'look' typical of particular surfaces, and how this appearance tends to vary. Constellations of low- and mid-level image measurements convey the extent to which the surface manifests specular reflections; and statistically informative appearance characteristics can be measured which indicate the nature of underlying changes in material properties. These can be correlated between samples of related materials, to establish the typical appearance of a glossy surface. Fleming also proposed that such 'statistical appearance models' are more expressive (as a result of treating the image as a gestalt), and easier to compute than the physical parameters; and are therefore a powerful mid-point between a 'bag of tricks' and inverse optics.

A mid-point model has a considerable advantage over the more extreme models, Fleming continues, in that it has the capability of predicting what new, unseen surfaces of similar properties might look like. This is more efficient than the long-division inverse optics method, and more accurate and reliable than depending on a standalone diagnostic image statistic. There is a general assumption that salient features are likely to relate in some systematic way to the underlying properties of the materials, and it seems that observers use the most salient (in terms of variation) perceptual cues when making judgements of relative gloss. Furthermore, Fleming rightly points out that the visual system does not necessarily care about representing the physical dimensions in a way true to their physical organisation. For instance, hue is perceptually circular, in that a perceptually valid colour wheel can be produced with reds and blues blending into one another sequentially through purple, whereas in physical terms, wavelengths are linearly organised and purple light can only be composed of a mixture of multiple wavelengths. We have therefore no reason to assume that the visual system makes use of an internal scale that is wholly true to the physical scales of dimension.

15. Summary

Initial theories of gloss perception relied on the use of a single dimension on a physical scale. This was soon refuted, and attention turned to a multidimensional approach, as interactions with 'unexpected scene variables' indicated that the perception of gloss was far more complex than initially thought (Ho, Landy, & Maloney, 2008). Some shifted to the other extreme and proposed a diagnostic image statistic, but this was quickly overturned on the grounds that the proposed statistic was flawed and that such a statistic would not necessarily be reliable. Discussion returned to the consensus that perceptual gloss is reliant on multiple dimensions. This carries the implicit assumption that a solvable formula exists for the multiple dimensions, given sufficient investigations; yet recent results indicate that this assumption too may be oversimplified. Not only is there variability between the salience of different features from object to object; there is also fluctuating inter-observer agreement about the applicability or salience of different perceptual cues; and differences in the importance attached to these cues and their salience between observers. As if this was not enough, the judgements made by observers in response to real life stimuli are not easily replicated in experimental simulations, and this suggests that we have yet to identify the full extent of relevant information used in veridical perceptual judgements. When there is limited information available from stimuli, observers are forced to prioritize the most salient distinguishing factor, which results in great inter-observer disagreement. However when there is a broad spectrum of perceptual cues and a richness of information not normally present in simulated images (when the images are as close as possible to achieving a real life experience) so that observers are not forced to prioritize the information available – then there is much greater consistency in responses. This suggests that more work is required to identify the additional perceptual cues on which observers rely, and the nature of their interactions with established cues.

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