Perception and misperception of surface opacity

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A fundamental goal in extracting scene structure is distinguishing different physical sources of image structure. Light reflected by an opaque surface covaries with local surface orientation, whereas light transported through the body of a translucent material does not. This suggests the possibility that the visual system may use the covariation of local surface orientation and intensity as a cue to the opacity of surfaces. We tested this hypothesis by manipulating the contrast of luminance gradients and the surface geometries to which they belonged and assessed how these manipulations affected the perception of surface opacity/translucency. We show that (i) identical luminance gradients can appear either translucent or opaque depending on the relationship between luminance and perceived 3D surface orientation, (ii) illusory percepts of translucency can be induced by embedding opaque surfaces in diffuse light fields that eliminate the covariation between surface orientation and intensity, and (iii) illusory percepts of opacity can be generated when transparent materials are embedded in a light field that generates images where surface orientation and intensity covary. Our results provide insight into how the visual system distinguishes opaque surfaces and light-permeable materials and why discrepancies arise between the perception and physics of opacity and translucency. These results suggest that the most significant information used to compute the perceived opacity and translucency of surfaces arise at a level of representation where 3D shape is made explicit.

A fundamental goal of vision research is to understand how the brain derives the appearance of objects and materials from image structure. This problem is difficult because image structure arises from a number of distinct physical sources: 3D shape, reflectance, transmittance and/or subsurface scattering, and the light field. Our ability to perceive the color, lightness, gloss, translucency, and shape of materials implies that there must be information available to perform these computations, although such processes are just beginning to be understood.

Recent work on opaque surfaces has shown that the perception of reflectance depends on both physical (1–8) and perceived (9–12) 3D shape. The 3D shape of surfaces modulates the pattern of specular reflections projected to the eyes, which induces corresponding variations in the perception of gloss (1–8). Perceived 3D shape can also alter the apparent reflectance of identical luminance gradients (9–12). When a fixed image gradient appears to be generated by a shaded surface with a high curvature, it appears more matte than when the same gradient appears to be generated by a lower surface curvature (10–12). These results suggest that the reflectance properties of surfaces are derived at a level of representation where 3D shape is made explicit.

The physics characterizing the interaction of light and translucent materials is also affected by its 3D shape and is more complicated than the physics of surface reflectance. The light projected from a translucent material depends on its 3D surface geometry, reflectance properties, and how light is transported into and out of its volume. The amount, spectral content, and direction of the light crossing the surface of the material depend on its refractive indices, the viewing direction, and angle of incident light. The light scattered within a material depends on the density and reflectance of the particles suspended within its body (13–15). The amount of light transmitted through a translucent object also depends on its thickness, which may not be computable from the images because it requires information about surface geometry that is not in view. The complexity of light interactions with translucent materials has motivated the suggestion that the perception of translucency may depend entirely on heuristic “rules of thumb,” similar to those employed by artists to depict such attributes (16).

There may, however, be some general generative constraints that the visual system may use to compute the opacity of surfaces. One characteristic feature of opaque surfaces is that the intensity of light projected to the image covaries with surface orientation in light fields with a dominant illumination direction, which generates patterns of surface shading. The intensity of diffuse reflectance declines with increasing angle between the surface normal and illumination direction. Although this covariation can be reduced by cast shadows and interreflections, the covariation of intensity and surface orientation will not be completely eliminated, particularly for locally convex surface patches. In contradistinction, the sub-surface scattering that arises with translucent materials can produce smooth image gradients that completely eliminate the systematic covariation of intensity and surface orientation. This suggests that the covariation of intensity and surface orientation could provide information that the visual system uses to evaluate the opacity of surfaces: If intensity covaries smoothly with local surface orientation, it provides evidence that this light has been reflected by the surface (i.e., shading); however, if intensity varies smoothly but independently of locally convex surface orientation, then it could provide information that the light projected to a vantage point is generated by light–material interactions that occur within the body of an object.

One of the primary assumptions shaping the work described herein is that surface opacity constitutes a physical and perceptual dimension, rather than distinct categories of materials. The same assumption is embodied in models of transparency. The endpoints of this dimension can be illustrated by plotting intensity as a function of surface orientation for an opaque and translucent material with the same 3D shape (Fig. 1A). In this example, the translucent surface is illuminated by a punctate source

Significance

One of the most perplexing problems in vision science is to understand how the visual system computes the reflectance and transmittance properties of different materials despite variability in 3D shape and illumination. We show that 3D shape can play a decisive role in the perception of surface opacity and that gross misperceptions of surface opacity can arise for specific surface geometries and light fields. We argue that the perception of surface opacity depends on the relationship between intensity and 3D surface orientation and show that this relationship can play a decisive role in modulating the perception of surface opacity, independently of the true physical characteristics of materials.

Author contributions: P.J.M., J.K., and B.L.A. designed research; P.J.M. and B.L.A. performed research; P.J.M. analyzed data; and P.J.M. and B.L.A. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1711416115/-/DCSupplemental.

www.pnas.org/cgi/doi/10.1073/pnas.1711416115

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located inside the object, whereas the opaque (Lambertian) surface is illuminated externally by four rectangular area lamps. Local surface orientation is depicted by a circular base tangent to the surface and a line depicting the outward pointing surface normal (Fig. 1B). The intensity of each pixel is plotted as a function of the angular separation (slant) of surface normals with respect to the illumination direction that generates the strongest intensity-orientation covariation (see Methods). Note that the translucent object exhibits no clear dependence of intensity on surface orientation. In contradistinction, the opaque surface exhibits a low-dimensional (~1D) dependence of intensity on surface orientation. The specific shape of this “contour” depends primarily on the diffuse and specular reflectance of the surface as well as the locations of shadows. In this (Lambertian) example, intensity declines as a cosine function of the angular difference between the primary illumination direction until ~90° from the dominant overhead light source; orientations greater than 90° generate an attached shadow, and the intensities of these regions depend on illumination from the illuminants from below and to its sides. The “thickness” or spread along the contour depends on factors that weaken intensity-orientation covariation (here, the different directions and intensities of the multiple light sources).

The experiments described below were designed to assess whether the covariation of intensity with 3D surface orientation modulates the perception of surface opacity. Most previous studies (13–21) into the perception of translucency have attempted to identify cues that provide information about the relative opacity/translucency of a material by holding 3D shape fixed and either identifying or manipulating image properties that modulate perceived surface opacity (such as contrast). Here, we take the complementary approach and fix the luminance gradients in the images and vary the 3D shapes that appear to generate them. Thus, any differences in perceived translucency that arise from modulating 3D shape cannot be explained by differences in 2D image properties but must arise at a level of representation where 3D shape is made explicit.

Results

The Computation of Opacity and Translucency from 3D Intensity Gradients. In experiment 1, we rendered images of a translucent and opaque surface and generated an alternate shape interpretation for each. The alternate shape was designed to change the relationship between image intensity and surface orientation relative to that of the rendered surface. The physically translucent object had a shape resembling a bloated “snake” that varied in thickness along its medial axis. It was illuminated from behind (see Methods), which resulted in intensity maxima at the narrower regions and intensity minima at the thicker regions. The projected intensities of the gradients generated by the translucent snake do not exhibit any systematic covariation with surface orientation (Fig. 2, Upper Left). A second shape—a twisted “ribbon”—was constructed so that the intensities generated by the snake would be mapped onto a surface such that they covaried with local surface orientation (Fig. 2B, Upper Right). If the visual system uses this covariation to infer the opacity of a surface, the ribbon should appear opaque even though the image gradients were generated by an object that was translucent.

The second pair of surfaces was created by first generating a surface where intensity varies perfectly with surface orientation (a “bump”; Fig. 2B, Lower Right) and then mapping these gradients onto a second shape that eliminated this covariation (a “torus”; Fig. 2B, Lower Left). Note that neither of these surfaces/materials was rendered; the gradients were texture mapped onto each of the two surfaces to create the stimuli. The surfaces for both pairs of surfaces were covered in a black dot or grid texture superimposed over the luminance gradients, and the two 3D shape perceivers were generating using binocular disparity or structure from motion. The contrast of the luminance gradients of the two shapes was varied in seven steps by multiplicatively scaling the range of intensity images. Observers performed paired comparison experiments in which each combination of the two 3D shapes and seven different values of image contrast were presented, and observers selected the surface that appeared more translucent in each pair. Different groups of naïve observers (n ≥ 10 in each experiment; see Methods) were used for each pair of 3D shapes (snake versus ribbon or bump versus torus) and for each shape cue (binocular or structure from motion).

The effect of perceived shape on perceived material can be directly experienced by the reader by viewing Movies S1 and S2. Movies S1 and S2 are example stimuli used in the experiments shown in Fig. 2. Example stimuli for the stereoscopic experiments are shown in Fig. 3. The shape interpretations where surface orientation and intensity exhibit a low-dimensional covariation appear opaque (the bump and ribbon), whereas the shape interpretations that do not exhibit this covariation appear translucent (the torus and snake). Note also that the perception of illumination also differs for these two shapes. The shapes that appear translucent appear to transmit light from a source located behind or inside the object, whereas the shapes that appear opaque appear to reflect light from above. The results of experiment 1 are shown in Fig. 2A, which plots the proportion of trials that each stimulus was chosen as appearing more translucent than the other surfaces. The contrast of the luminance gradients increases from left to right in each graph. The large, vertical separation between the white and black data points demonstrates that observers are sensitive to the relationship between intensity and apparent surface orientation when judging translucency: The snake and torus appear more translucent than the ribbon and bump. Main and interaction effects of 3D shape and contrast were tested using planned within-subject contrasts. The effect of shape on perceived translucency is statistically significant for both sets of stimuli [counterclockwise from Fig. 2A, Top Left: F(1, 13) = 60; F(1, 13) = 18; F(1, 9) = 255; F(1, 10) = 18, P << 0.01, for each]. The 3D shape interpretation also influences the effect of image contrast on perceived translucency, producing a significant interaction between the main effects of shape and contrast [counterclockwise from Fig. 2A, Top Left: F(1, 9) = 12, P < 0.01; F(1, 10) = 12, P < 0.01; F(1, 13) = 60, P << 0.01; F(1, 13) = 18, P << 0.01]. Decreasing contrast increases perceived translucency for the bump surface, consistent with the view that low contrast is a cue to translucency (18–20). However, the torus, snake, and ribbon shapes appear most translucent for moderate contrast values. This interaction suggests that 3D shape can change the way that image contrast influences the perception of surface opacity.
The Misperception of Opacity. The intensity of an opaque surface will only covary with surface orientation in light fields that contain a predominant illumination direction. It is the variation in the 3D pose of a surface with respect to this illumination direction that is responsible for the coupling between surface orientation and intensity of shaded surfaces. Purely diffuse illumination (i.e., illumination in a Ganzfeld) eliminates intensity gradients due to shading and hence eliminates this source of covariation. The intensity variations of a uniform albedo surface embedded in a purely diffuse light field will depend on the pattern of interreflections and the area of the Ganzfeld that illuminates each point on a surface (“vignetting”). This area is smaller for deep concavities due to self-occlusion than protruding convexities, which are fully exposed to ambient lighting. Since interreflections and vignetting depend more on the direction and magnitudes of surface curvature than surface orientation, opaque surfaces in a Ganzfeld will exhibit inconsistencies between surface orientation and intensity. If the visual system interprets the inconsistency between surface orientation and intensity as a cue to translucency, then an opaque surface containing a distribution of convexities and deep concavities should appear translucent when rendered in a diffuse illumination. To test this prediction, Lambertian and translucent variants of a bumpy surface [similar to that of Kim et al. (23)] were rendered in either a Ganzfeld or natural illumination. Observers viewed the surfaces along the direction of surface relief in structure-from-motion displays similar to our previous experiments (Movies S3 and S4). Observers matched the material appearance of each surface by adjusting the material parameters of a cube rendered in a natural light field (Fig. 4). In one experiment, the cube was rendered without specular reflections, and observers only adjusted the density of subsurface scattering (Fig. S1A). In a second experiment, the cube was rendered with specular reflections, and observers adjusted both the density of subsurface scattering and intensity of specular reflections (Fig. S1B). The results of both experiments show the Lambertian surface rendered in a Ganzfeld appears translucent. The vertical axis represents the density of subsurface scattering particles; the correct match for a Lambertian surface is the highest density on the graph (256); the graphical settings for each surface is depicted in Fig. S1D. The results show that the Lambertian surface rendered in the natural light field appears opaque and matte, whereas the match for the same surface in the Ganzfeld is less translucent and glossy \( F(1, 4) = 1.00, P < 0.01 \) in Fig. S1A; \( F(1, 4) = 576, P < 0.01 \), in Fig. S1B; and \( F(1, 4) = 1,931, P < 0.01 \) for the specular parameter in Fig. S1B. This result implies that the visual system misattributes the diffuseness of the light field to the subsurface scattering of a translucent material in the absence of any covariation in surface orientation and intensity, presumably because such materials occur more generically in natural scenes than completely diffuse light fields.

Our hypothesis also predicts that translucent materials should fail to appear translucent if the light transported through the material accidentally preserves the covariation of intensity and surface orientation. Fig. 5 depicts two shapes designed to test this hypothesis, which are variants of the translucent snake from Fig. 3. In one shape, the diameter of the circular cross-section varies along the snake’s medial axis; for the other, the diameter of the cross-section remains constant and appears as a curved cylinder. For specific combinations of illumination and subsurface scattering density, the intensity of the light transported through the cylinder covaries with surface orientation. Both shapes were rendered as identical translucent materials and were embedded in a light field with a predominant direction of illumination from behind (see Methods). Seven different levels of physical translucency were rendered by varying the density of subsurface scattering particles. Lambertian variants of these objects were also rendered within the same light field rotated 180° so the predominant direction of illumination was along the line of sight. Seven albedos of the Lambertian surfaces were chosen to produce the same maximal luminance as that generated by the translucent surfaces. Nine observers ranked the surfaces from most to least translucent in a paired comparison experiment. Fig. S3B shows the proportion of trials that each surface was chosen as appearing more translucent than the other surfaces as a function of the maximal intensity in the image. The open symbols depict the translucent renders, and the small gray symbols depict the Lambertian renders. The results reveal a large discrepancy between perceived and physical translucency for the translucent cylinder. The cylinder appears less translucent than the snake even though they are physically the same material for all values of subsurface density, \( F(1, 8) = 30, P < 0.01 \). Moreover, perceived translucency varies with the density of subsurface particles differently for the snake and cylinder, \( F(1, 8) = 18.7, P < 0.01 \). The perceived translucency of the snake increases as density declines (and is hence physically more translucent), whereas the cylinder appears less translucent as physical translucency increases. The misperception of translucency for the cylinder is well predicted by the emergence of a spurious relationship between surface orientation and the intensity of light passing through the translucent volume (Fig. S3C). These results provide further support

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that appear translucent (i.e., that were either rendered as light transmitted through a light-permeable material or as light reflected from an opaque surface depending on perceived 3D surface geometry, (ii) illusory percepts of translucency can be induced by embedding opaque surfaces in diffuse light fields that eliminate the covariation between surface orientation and intensity, and (iii) illusory percepts of opacity can be generated when transparent materials are illuminated in a manner that generates images where surface orientation and intensity covary. Thus, opaque materials can appear translucent and translucent materials can appear opaque when they are embedded in light fields that either eliminate or generate systematic covariation in 3D surface orientation and intensity, respectively.

Our hypothesis can also provide insight into illusory percepts of translucency induced by depth map textures (18) and ramp shading (23), where image brightness is determined by the distance of the surface relative to some reference point. These illusory percepts of translucency also appear to depend on the relationship between intensity and local surface orientation. Images that exhibit stronger inconsistencies between intensity and surface normals appear more translucent (the left object in Fig. S4) than those that generate spurious correlations between intensity and surface normals (the sphere in Fig. S4).

The general insight shaping our theoretical approach is that the computation of surface opacity is derived by the way that light covaries with 3D surface geometry. The hypothesis explored herein only considers how intensity varies as a function of local 3D surface orientation because this is the primary generative source of intensity variations generated by opaque surfaces in a directional light field (“shading”). Our hypothesis does not exclude the possibility that higher order 3D shape variables may also be used to compute the opacity/translucency of surfaces or may be used to weight the extent to which the surface orientation/intensity covariation cue is used in such computations. Deep surface concavities can generate shadows, vignetting, and interreflections, all of which disrupt the relationship between surface orientation and intensity (23, 24). Surface convexities, by contrast, are much less subject to these influences and will generally preserve the surface orientation/intensity covariation characteristic of opaque surfaces. This suggests that the pattern of intensity variations across a surface may not all be weighted equally in the visual system’s computation of surface opacity. This can be seen in Fig. S2, which depicts surface normal-intensity plots for a bumpy Lambertian surface in natural illumination. Despite the presence of extensive cast shadows and interreflections present in many regions of the surface, intensity covaries with surface normals on locally convex surface patches where cast shadows and interreflections are less likely. In contradistinction, this covariation is not observed in the same regions for the variants of the surface in Fig. S2 that appear translucent (i.e., that were either rendered as opacity/translucency of surfaces or may be used to weight the extent to which the surface orientation/intensity covariation cue is used in such computations.

Fig. 3. A and B show two possible stereoscopic shape interpretations for the same luminance gradients. The upper shape interpretation in each panel (i.e., the snake and torus) appears as a translucent volume illuminated from within, whereas the lower shape interpretation (ribbon and bump) appears as an opaque surface reflecting light from above. The two eyes' views are arranged for crossed free fusion.

Discussion

The goal of the work presented herein was to gain insight into how the visual system distinguishes luminance gradients generated by surface shading from gradients generated by subsurface scattering. This problem is computationally difficult because shading and subsurface scattering can generate similar luminance gradients if illumination and 3D shape are free to vary. We hypothesized that the covariation of intensity with surface orientation is a source of information that links projected light to 3D surface geometry and therefore can be used to distinguish image structure generated by optical interactions with surfaces from optical structure generated by subsurface scattering. In support of this hypothesis, we showed that (i) identical luminance gradients can appear either as light transmitted through a light-permeable material or as light reflected from an opaque surface depending on perceived 3D surface geometry, for the hypothesis that the perception of translucency requires inconsistencies between intensity and 3D surface orientation.

Fig. 4. Misperception of surface opacity in diffuse illumination. Two images of the same bumpy, opaque (lambertian) surface rendered in either a natural light field (Left) or diffuse illumination (Right). The diffuse illumination elicits an illusory percept of gloss and translucency. The cubes show the appearance of the match surface at PSE in subsurface scattering and specular reflectance (Fig. S1).
translucent or rendered as opaque in a diffuse light field). A promising line of future work will be to assess how well material properties are predicted by different regions of surfaces characterized by higher order shape descriptors (such as convexities, concavities, or saddles), in conjunction with the surface orientation–intensity analysis proposed herein.

Previous studies (13–21) that have investigated cues to perceived translucency have held 3D shape fixed and either varied material properties (or statistics) do not provide inputs needed for these computations; it simply implies that such inputs do not acquire perceptual meaning in specifying the opacity/translucency of a material until they are linked to a representation of 3D shape. There are a number of outstanding issues raised by the studies reported herein. First, our orientation–intensity plots were derived using the ground truth surface orientations and intensities rather than any direct measurements of perceived shape. Although the orientation/intensity computations must be derived from perceived 3D shape, any distortions in perceived shape relative to ground truth in our stimuli would likely be related by a monotonic transformation of surface orientation and illumination direction [e.g., affine distortions (25, 26)], and hence do not affect our main arguments. Second, although vivid percepts of 3D shape and opacity/translucency can arise from static monocular images, there is currently no explanation of how 3D shape can be computed from such images. The stimuli and analyses described herein exploited parallax cues to elicit a particular 3D shape percept, and hence offer no insight into how the visual system solves this problem. Lastly, our experiments—like all previous studies into the perception of opacity/translucency—have only investigated uniform albedo surfaces, so it is unclear
whether our results generalize to stimuli containing densely varying surface albedo. We therefore performed additional experiments using stimuli containing variations in surface pigmentation, and observed the same dramatic effect of 3D shape on perceived surface opacity/translucency (Fig. S7). It is clear from viewing these stimuli that the visual system successfully segments the contributions of texture from the smooth gradients generated by shading or subsurface scattering, although it remains unknown how the visual system performs this decomposition. Thus, the same orientation/intensity analysis proposed herein can account for these textured stimuli under the proviso that the intensity variations caused by albedo (texture) are correctly identified as texture.

The results presented herein and elsewhere indicate that the perception of surface opacity/translucency, like the perception of specular and diffuse reflectance, depends on the apparent 3D structure of images (9–12, 23, 27–29). Indeed, we have argued the concept of a surface, both conceptually and perceptually, entails a notion of shape, which in our environment is 3D. If this is correct, it suggests that the representations used to derive properties such as opacity/translucency occur at a level where 3D shape is made explicit. Future research is required to develop a more complete understanding of precisely how computations of 3D shape and material properties are coupled, i.e., how the visual system uses 3D shape to derive material properties, and how material properties influence the computation of 3D shape.

**Methods**

The experiments were approved by the University of Sydney and participants provided written informed consent and were debriefed about the aims in adherence with the Declaration of Helsinki. The three inputs to the surface orientation-intensity analysis were a RADIANCE high dynamic range (HDR) image of the surface, its depth map, and a list of illumination directions to be analyzed, which covered the spherical space of possible illumination directions. For each illumination direction, the image intensities were plotted against the angular separation of the surface normals relative to that direction. The plot shown for each surface was selected because it exhibits the strongest negative correlation between intensity and surface orientation of all of the illumination directions analyzed. See Fig. S8 and Supporting Information for the full methods.

**ACKNOWLEDGMENTS.** This research was supported by grants awarded (to B.L.A.) from the Australian Research Council.