

The role of natural lighting diffuseness in human visual perception

Yaniv Morgenstern¹, Wilson S. Geisler², and Richard F. Murray³

¹Department of Psychology, University of Minnesota, Minneapolis, MN, USA

²Department of Psychology and Center for Perceptual Systems,
University of Texas at Austin, Austin, TX, USA

³Department of Psychology and Centre for Vision Research,
York University, Toronto, ON, Canada

ABSTRACT

The pattern of the light that falls on the retina is a conflation of real-world sources such as illumination and reflectance. Human observers often contend with the inherent ambiguity of the underlying sources by making assumptions about what real-world sources are most likely. Here we examine whether the visual system's assumptions about illumination match the statistical regularities of the real world. We used a custom-built multidirectional photometer to capture lighting relevant to the shading of Lambertian surfaces in hundreds of real-world scenes. We quantify the diffuseness of these lighting measurements, and compare them to previous biases in human visual perception. We find that (1) natural lighting diffuseness falls over the same range as previous psychophysical estimates of the visual system's assumptions on diffuseness, and (2) natural lighting almost always provides lighting direction cues that are strong enough to override the human visual system's well known assumption that light tends to come from above. A consequence of these findings is that what seem to be errors in visual perception are often actually byproducts of the visual system knowing about and using reliable properties of real-world lighting when contending with ambiguous retinal images.

Keywords: lightness perception, illumination statistics, Bayesian modeling, inverse optics

1. INTRODUCTION

Visual perception is a computationally difficult task largely because images are highly ambiguous; different patterns of light can specify the same real-world object (Figure 1A) while the same pattern can specify a different object (Figure 1B). To estimate an object's

physical properties from an ambiguous image, the human visual system must rely on assumptions about what interpretation of images is most likely to be correct. It is well known that in order to assign 3-D shape to 2-D shaded images, the human visual system relies in part on an assumption that light comes from overhead, as it does in most real world scenes [1-3]. Given the importance of lighting in image formation, recent work has focused on what additional statistical regularities are present in natural lighting [4-9], and what assumptions the human visual system makes about lighting [10-18].

One important property of natural illumination that the visual system may rely on is diffuseness. Lighting can range from very diffuse to very direct. By diffuse light, we mean light that comes from a broad range of directions. In contrast, direct light comes from a single direction; it is caused by a single, small or distant source such as the sun. The level of a scene's lighting diffuseness can drastically change the appearance of an object in an image (Figure 1A). Thus, when the visual system is challenged with increased ambiguity (e.g., when viewing stimuli under reduced scene context or visibility), its assumptions about lighting diffuseness are critical for generating percepts that successfully contend with the inherent ambiguity in natural images. In this paper, our interest is in whether human observers' assumptions about lighting diffuseness arise from a strategy that is most likely lead to successful behaviors in the real world. To this end, we compare the human visual system's assumptions about lighting diffuseness to the diffuseness of natural illumination (see also [9]).



Figure 1. Luminance values in retinal stimuli are highly ambiguous. (A) Photographs showing the influence of lighting direction and diffuseness on object appearance. (B) In this rendered scene, the diamond patches on the surface of the cubes have the same luminance (based on a demonstration from [29]). Nonetheless, the diamond patches on each cube are perceived to be different in their lightness. Depending on illumination and a host of other factors, the same object in (A) can underlie different luminance patterns, while an object that is different in (B) can arise from the same luminance value.

2. NATURAL LIGHTING DIFFUSENESS

Surprisingly, despite the great variation in natural lighting, previous studies have shown that real-world illumination nevertheless has a high degree of statistical regularity [4-7]. These studies have described light in terms of the pattern of illumination arriving at one point in space $P = (x, y, z)$ from every direction (θ, ϕ) , where the polar angle θ ranges from 0 to π radians (rad), and azimuth ϕ ranges from 0 to 2π rad. Here we will refer to this pattern of light, followingDebevec [19], as the light probe (Figure 2A). The light probe can be visualized as a collection of light rays originating from all directions and arriving at point P .

Dror et al. [4] and Mury et al. [5] analyzed high dynamic range light probes that were produced by combining photographs, sometimes of mirrored balls, taken in different directions and at different exposures. Light probes produced with photographic methods are time consuming to produce, but capture both high and low spatial frequency patterns, faithfully representing sharp features such as edges and specularities. However, for some purposes, such as understanding the shading of Lambertian objects, a much coarser sample of the light probe is adequate, since a Lambertian surface acts as a low-pass filter on a light probe [20, 21]. With this in mind, Mury, Pont, and Koenderink [6, 7] built a 12 photodiode multidirectional photometer (which they call the plenopter) that can quickly measure low-pass components of light probes. We expanded on this earlier work. We collected a large number of low-resolution light probes in a range of environments using a custom-built multidirectional photometer (sections 2.1 and 2.2), developed independently of Mury et al. We characterized the diffuseness of light in these environments (section 2.3), and related the diffuseness of natural lighting to human psychophysics (sections 3 and 4).

2.1 The multidirectional photometer

We used a multidirectional photometer that makes fast and accurate measurements of real-world lighting relevant to Lambertian surfaces. The multidirectional photometer is a 20 cm diameter aluminum sphere, mounted with 64 approximately evenly spaced photodiodes (Figure 2B). Each photodiode is filtered to match the photopic spectral sensitivity of the human visual system (V_λ), and fitted with an aperture that reduces its directional selectivity so as to provide the sharpest image possible with 64 sensors. The device measures light ranging from low-lit indoor scenes to direct sunlight, and makes several complete measurements per second.

2.2 Measurements of lighting in the real-world

We report two types of multidirectional photometer measurements. The first type was taken at or around the area of York University from 12:00 pm to 1:30 pm through the months of August to October, 2010. These months correspond to late summer and early autumn. Each new measurement site was selected so that the previous measurement sites

could not be seen from the new spot. For these measurements, the centre of the photometer was 122 cm above the ground and was held in place by a microphone stand. We made 570 measurements in several environments, listed in the legend of Figure 3. The other 52 lighting measurements were taken over the course of a day. The photometer was always in the same location and light probe measurements were made approximately every 20 minutes, from sunrise to sunset. These measurements were taken on the roof of the Lassonde building at York University on November 20, 2010 where the sky conditions varied from sunny to slightly overcast to completely overcast. For these measurements, the centre of the photometer was placed at a lower position (104 cm above the ground) to ensure greater physical stability. All measurements are available online (purl.org/NET/rfm/joy2014).

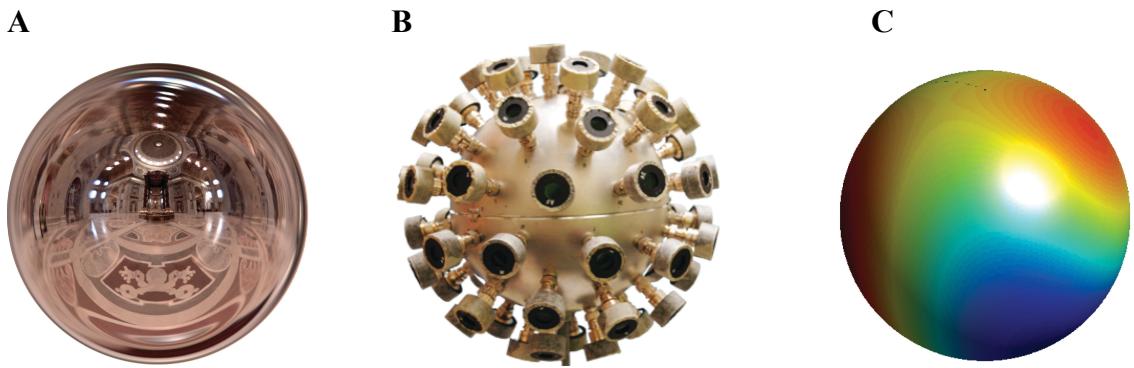


Figure 2. Capturing coarse samples of natural illumination. (A) An example of a high-resolution light probe from Debevec’s gallery [19]. The light probe is a spherical representation of illumination coming from all directions and arriving at a single point in space. (B) The multidirectional photometer was used to capture low-resolution light probes (e.g., (C)) that capture the lighting relevant to shading of Lambertian surfaces. *White* regions in (C) indicates high luminance, and *black* indicates low luminance.

2.3 Diffuseness of natural illumination

We quantified the diffuseness of the low-resolution light probes captured by the photometer (Figure 2C) in terms of its illuminance contrast energy (*ICE*). As described in Morgenstern, Geisler and Murray [9], the *ICE* of a light probe is the mean contrast energy of the illuminance distribution $E(\theta, \phi)$ over the surface of a sphere illuminated by the probe:

$$\lambda = \left(\frac{1}{4\pi} \int_0^{\pi} \int_0^{2\pi} \left(\frac{E(\theta, \phi) - \bar{E}}{\bar{E}} \right)^2 \sin \theta d\phi d\theta \right)^{1/2} \quad (1)$$

where \bar{E} is the mean illuminance over the sphere. The *ICE* of the light probe is the coefficient of variation of the illuminance over the sphere (i.e., its standard deviation

divided by its mean). Low values of *ICE* correspond to diffuse light (i.e., a roughly constant illuminance pattern), and high values correspond to direct light (i.e., illuminance pattern depends on orientation relative to a dominant light source). Thus, the terms “diffuseness” or “directness” of a light probe are simply opposites.

Figure 3A shows the *ICE* values of our lighting measurement from several types of environments. The histogram for each environment was scaled to a peak of 1.0. Figure 3A also shows two reference points based on simple lighting models in computer graphics; one dotted line represents the *ICE* for a distant point light source (an *ICE* value of 1.29), and another dotted line represents the default diffuseness level used in OpenGL, a point plus diffuse model where the ambient light is 1/5 as strong as the point light. Most environments have relatively diffuse lighting, with mean *ICE* at 0.54.

3. HUMAN OBSERVERS’ ASSUMPTIONS ABOUT LIGHTING DIFFUSENESS

The world is not random; it has much structure. As an example, Figure 3A shows that there is regularity in lighting diffuseness in natural scenes. In the face of ambiguity, observers who rely on these regularities, statistically speaking, are most likely to form successful behaviours in the world. In this section, we explore whether human observers rely on the diffuseness of natural illumination.

3.1 Lightness perception and the equivalent illuminant model

Luminance is a conflation of surface reflectance and illumination. Thus, there are many combinations of surface reflectance and illumination that underlie a particular luminance value. To behave successfully in the face of inherently ambiguous luminance patterns, human vision is challenged to estimate lightness, the perceived reflectance value.

Recent studies have measured the lightness of a surface as a function of its slant [10-14]. In these studies, observers’ lightness constancy was poor: observers estimated lightness accurately for near-frontoparallel patch orientations, but underestimated lightness when the patch was highly oblique relative to the light source. A simple normative model, an *equivalent illuminant model* [15], fit to the human data estimated the relative magnitude between a diffuse and direct light. The fitted parameters of this model showed that the pattern of human results is, qualitatively, what one would expect if observers followed a strategy that estimated scene variables such as reflectance, orientation, and lighting (an inverse-optics strategy), but overestimated the diffuseness of the lighting.

Figure 3B shows the level of diffuseness estimated from the model that is needed to explain each observer’s lightness judgments. Human observer biases in real scenes match the diffuseness of natural illumination [10, 11]. On the other hand, human observer diffuseness biases in Boyaci et al.’s computer rendered scenes (i.e., shown on a computer monitor) are much lower than the diffuseness of natural illumination [12-14]. One

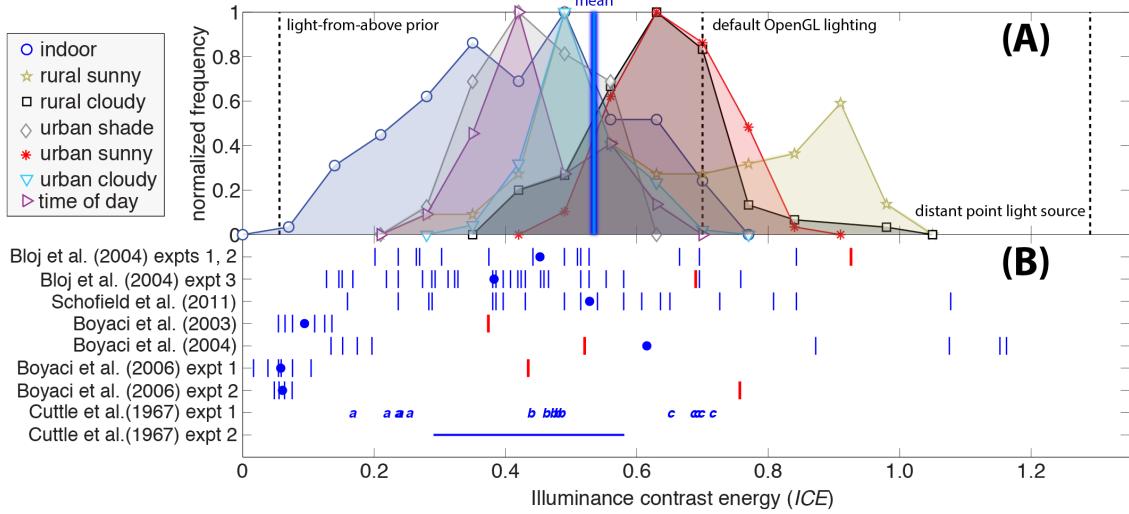


Figure 3. Comparing the diffuseness of natural illumination and human observers' assumptions about lighting diffuseness. (A) Histograms of the diffuseness of natural light in terms of ICE . The “time of day” histogram shows the measurements made over the course of a day. The dashed vertical lines show the diffuseness of a light source matched to Morgenstern et al.’s [28] “weak cue” condition (the line labeled “light-from-above prior”), the default OpenGL lighting, and a distant point light source. The thick vertical blue line shows the mean diffuseness level across all measurements. (B) Psychophysical estimates of observers’ assumptions about diffuseness. Small vertical blue lines show the ICE assumptions of individual observers. Blue dots show averages across observers. In Bloj et al. and Boyaci et al., the red lines show the ICE of the actual illuminants in the experiments. Schofield et al. ran their experiments in the dark and Cuttle et al. had observers change the diffuseness of the lighting in their scenes, so we do not show a red line indicating an ICE value for their lighting. Except for Cuttle et al. (1967), the y-axis label refers to the experiment number in the corresponding published papers. We refer to “Cuttle et al. (1967) expt 1” as the experiment that reports human observers’ light settings under changing levels of the overall magnitude of the ambient light (their Figure 12). The light setting of ‘a’ refers to the condition when observers set scene lighting so that they could not adequately see the experimenter’s facial features. The light setting of ‘b’ is when observers set scene lighting so that they adequately see the facial features. The light setting of ‘c’ was lighting that was too harsh to reveal the facial features. Each letter corresponds to the average of 40 results from 20 observers in different levels of ambient light. We refer to “Cuttle et al. (1967) expt 2” as their measurements showing the range of preferred lighting across altitude and azimuth changes in the direction of the dominant lighting source (their Figure 17).

potential reason for this poorer correspondence with the average diffuseness in natural scenes is that observers may not have seen these computer-generated scenes as completely realistic. Consistent with this view, previous work has found that lightness constancy is weaker in computer-generated scenes [22], and scenes with dark backgrounds, small frameworks, and lower articulation [23], which are factors that may contribute to the weaker constancy in Boyaci et al.’s scenes.

3.2 Lighting diffuseness assumption when interpreting shape-from-shading

The perception of 3-D shape from 2-D shading is inherently ambiguous; any given 2-D image could have been generated from any of an infinite number of 3-D scenes (Figure 4A; See also: [24, 25]). To investigate the assumptions human observers use to resolve this ambiguity, Schofield, Rock and Georgeson [16] measured human observers' 3-D shape interpretation for 2-D images of sinusoidal modulating surfaces. They found that observers' shape percept changed as a function of grating orientation, which is what one would expect if observers' assumed a particular ratio of diffuse to direct lighting. Figure 3B shows that their human observers' assumed diffuseness levels that overlap with the range of diffuseness found in natural illumination.

3.3 Preferred lighting diffuseness in architectural spaces

With the purpose of designing architectural spaces that enhance visual experience of objects in space, Cuttle, Valentine, Lynes and Burt [26] measured a human observer's preferred level of lighting diffuseness. In their study, observers sat in an enclosed room in which a wide variety of possible lighting conditions could be simulated. The observers sat across the room from the experimenter and used a gauge to set the level of lighting diffuseness so that the features on the experimenter's face were (*a*) too soft to adequately see, (*b*) preferred, or (*c*) too harsh to be acceptable. In one experiment (their Figure 12), Cuttle et al. manipulated the magnitude of the diffuse light. Regardless of the magnitude, observers set the preferred level of lighting diffuseness to be about constant. When we convert their measurements in terms of the scalar-vector ratio [27] to *ICE* (see Appendix F in [9] for conversion), the preferred lighting (criterion *b*) falls just under the mean diffuseness level for natural illumination, while lighting too soft (criterion *a*) or strong (criterion *c*) falls on inner and outer limits of the diffuseness values found in indoor scenes (Figure 3), such as those in which Cuttle et al.'s measurements were made. In another experiment from Cuttle et al. (their Figure 17), observers judged their preferred diffuseness levels under directional lighting with different azimuth and altitude angles. Regardless of the direction of maximum light energy, the preferred level of lighting diffuseness fell within the range of natural lighting diffuseness (Figure 3). These results suggest that humans have some quantitative sense of the typical levels of diffuseness that occur in natural scenes.

4. ESTIMATING THE DIFFUSENESS OF THE LIGHT FROM ABOVE PRIOR

One of the most well known regularities in the natural world is that light usually comes from overhead. Human observers make this assumption when interpreting ambiguous visual input. Take, for example, the shaded disks in Figure 4A. Each shaded disk could be an image of a bump illuminated from one direction, or a dent illuminated from the opposite direction. Human observers reliably see the disks as whichever shape, bump or dent, is consistent with illumination from above. If the figure is turned upside down, the

perceived shape of each disk changes from bump to dent and vice versa, preserving the impression of illumination from above.

Recent work shows that even barely perceptible lighting direction cues override the overhead light assumption [28]. However this does not necessarily mean that in everyday scenes the assumption plays a minor role in shape perception. Whether the assumption’s role is minor depends on how strong are directional lighting cues in natural scenes. If typically the lighting at each point in natural scenes is highly directional and provides strong lighting direction cues, then the light-from-above assumption will have a minor role. On the other hand, if natural lighting is highly diffuse, and provides only weak lighting direction cues, then the assumption’s role in shape perception may be more significant.

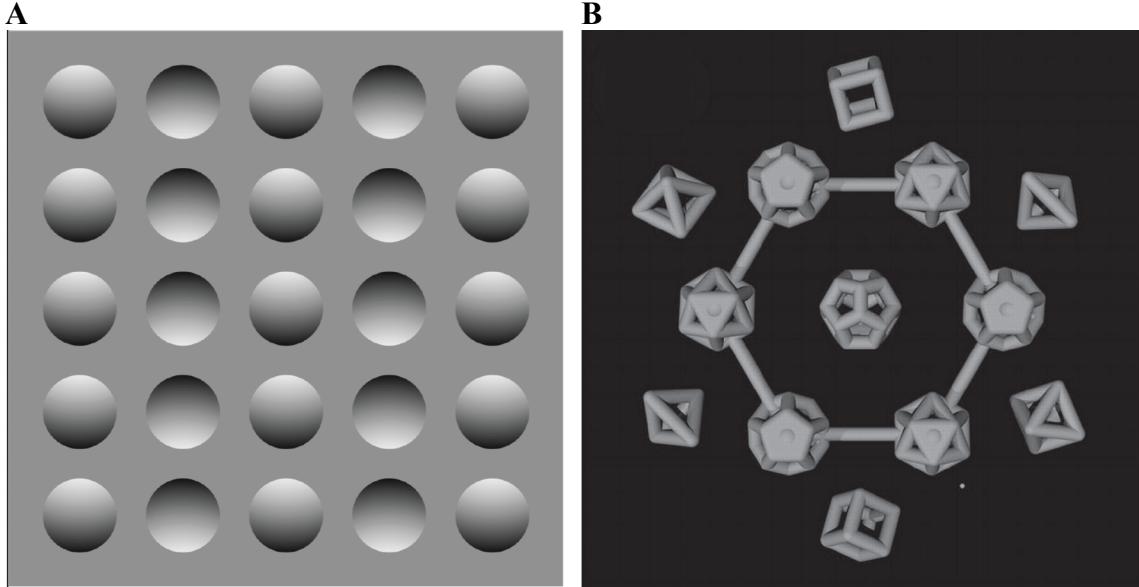


Figure 4. The light from above assumption is weak. (A) Except for a 180° rotation, the shading of the circular patches in the odd and even columns is identical. Human observers tend to interpret the shape of the images in the odd columns as bumps and even columns as dents, consistent with an overhead lighting assumption. (B) Example of “weak cue” condition from Morgenstern et al. [28] that matches the strength of the light-from-above prior. The diffuseness of the weak cue condition is on the low end of natural lighting diffuseness (shown as a reference line called ‘light-from-above prior’ in Figure 3A).

One way to evaluate the assumption’s role in everyday scenes is to compare the strength of the prior to the strength of lighting direction cues in natural scenes. Morgenstern et al. [28] found that their “weak cue” condition (Figure 4B) is matched to the light-from-above assumption: Lighting conditions that provide stronger lighting direction cues than this matched condition override the prior, and lighting conditions that provide weaker

cues do not. We compared the directness of the illumination in the weak cue stimulus to the directness of natural illumination, to see whether we can expect lighting cues in natural scenes to usually override the light-from-above prior. As shown by the “light-from-above prior” reference line in Figure 3A, lighting conditions matched to the overhead assumption have much lower *ICE* value than almost any of the natural illuminants that we measured with the multidirectional photometer. This suggests that natural lighting almost always provides lighting direction cues that are stronger than the light-from-above assumption, and hence that the prior plays a minor role in shape perception in everyday scenes.

There is a strong relationship between image shading and the underlying object shape and the lighting position in a scene. Thus, relying on a weak overhead lighting assumption is a rational strategy for estimating an object’s properties (such as its shape) in a world where successful behavior towards shapes from image shading requires knowing the current lighting direction.

5. CONCLUSIONS

A fundamental problem in visual perception is how human observers resolve ambiguity. In the present work, we measured regularities in the diffuseness of natural illumination and examined how these measurements overlap with human observers’ biases. Using this approach, we found that lighting regularities can explain some otherwise mysterious properties of visual perception (e.g., lightness constancy errors, weak overhead lighting assumptions, preferred lighting for viewing objects). This suggests that the visual system uses an efficient evolutionary strategy to estimate an object’s properties from ambiguous images.

ACKNOWLEDGEMENTS

We thank Andrew Schofield for helpful discussions and clarifications of his work, and Christopher Cuttle for digitizing his work originally published in 1967. This work was supported by an Ontario Graduate Scholarship in Science and Technology to Yaniv Morgenstern, a Canada Foundation for Innovation and Natural Sciences and Engineering Research Council of Canada grants to Richard Murray, and NIH grant EY11747 to Wilson Geisler.

REFERENCES

- [1] Metzger, W. (2006). *Laws of seeing*. (L. Spillmann, S. Lehar, M. Stromeier, & M. Wertheimer, Trans.). Cambridge, MA: MIT Press. (Original work published 1936).
- [2] Ramachandran, V. S. (1988a). “Perception of shape from shading”. *Nature*, 331, 163-166.
- [3] Ramachandran, V. S. (1988b). “Perceiving shape from shading”. *Scientific American*, 256, 76-83.
- [4] Dror, R. O., Willsky, A. S., & Adelson, E. H. (2004). “Statistical characterization of real-world illumination”. *Journal of Vision*, 4, 821-837.

- [5] Mury, A. A., Pont, S. C., & Koenderink, J.J. (2007). "Light field constancy within natural scenes". *Applied Optics*. 46(29), 7308-7316.
- [6] Mury, A. A., Pont, S. C., & Koenderink, J.J. (2009a). "Representing the light field in finite three-dimensional spaces from sparse discrete samples". *Applied Optics*. 48(3), 450-457.
- [7] Mury, A. A., Pont, S. C., & Koenderink, J.J. (2009b). "Structure of light fields in natural scenes". *Applied Optics*. 48(28), 5386-5395.
- [8] Morgenstern, Y. (2011). The role of low-pass natural lighting regularities in human visual perception. (Doctoral dissertation, York University, Toronto).
- [9] Morgenstern, Y., Murray, R.F., & Geisler, W.S. (2014). "Human vision is attuned to the diffuseness of natural illumination". *Journal of Vision*. 14(9):15, 1-18.
- [10] Ripamonti, C., Bloj, M., Hauck, R., Kiran, K., Greenwald, S., Maloney, S. I., & Brainard, D. (2004). "Measurements of the effect of surface slant on perceived lightness". *Journal of Vision*, 4, 747–763.
- [11] Bloj, M., Ripamonti, C., Mitha, K., Hauck, R., Greenwald, S., & Brainard, D.H. (2004). "An equivalent illuminant model for the effect of surface slant on perceived lightness". *Journal of Vision*, 4(9), 735–746.
- [12] Boyaci, H., Maloney, L. T., & Hersh, S. (2003). "The effect of perceived surface orientation on perceived surface albedo in binocularly-viewed scenes". *Journal of Vision*, 3, 541–553.
- [13] Boyaci, H., Doerschner, K. and Maloney, L. T. (2004). "Perceived surface color in binocularly-viewed scenes with two light sources differing in chromaticity". *Journal of Vision*, 4, 664–679.
- [14] Boyaci, H., Doerschner, K., & Maloney, L. T. (2006). "Cues to an equivalent lighting model. *Journal of Vision*", 6(2):2, 106–118, <http://www.journalofvision.org/content/6/2/2>, doi:10.1167/6.2.
- [15] Brainard, D. H. & Maloney, L. T. (2011). "Surface color perception and equivalent illumination models". *Journal of Vision*, 11(5), 1, 1-18.
- [16] Schofield, A. J., Rock, P. B., & Georgeson, M. A. (2011). "Sun and sky: Does human vision assume a mixture of point and diffuse illumination when interpreting shape from shading?" *Vision Research*, 51, 2317–2330.
- [17] Murray, R. F. (2013a). "The Statistics of Shape, Reflectance, and Lighting in Real-World Scenes". In *Shape Perception in Human and Computer Vision* (pp. 225-235). Springer London.
- [18] Murray, R. F. (2013b). "Human lightness perception is guided by simple assumptions about reflectance and lighting". In *IS&T/SPIE Electronic Imaging* (pp. 865106-865106). International Society for Optics and Photonics.
- [19] Debevec, P. (1998). "Rendering synthetic objects into real scenes: Bridging traditional and image-based graphics with global illumination and high dynamic range photography". In Proc. ACM SIGGRAPH 98, M. Cohen, Ed., 189–198.
- [20] Basri, R., & Jacobs, D. (2001). "Lambertian reflectance and linear subspaces". In: International Conference on Computer Vision II, 383–390.
- [21] Ramamoorthi, R., & Hanrahan, P., (2001). "An efficient representation for irradiance environment maps". SIGGRAPH 01. New York: ACM Press, pp. 497–500.
- [22] Lee, T. Y., & Brainard, D. H. (2014). "The effect of photometric and geometric context on photometric and geometric lightness effects". *Journal of Vision*, 14(1):24, 1–17, <http://www.journalofvision.org/content/14/1/24>, doi:10.1167/14.1.24.
- [23] Gilchrist A.L. (2006). [Seeing Black & White]. Oxford University Press.
- [24] Belhumeur, P. N., Kriegman, D. J., & Yuille, A. L. (1999). "The bas-relief ambiguity." *International Journal of Computer Vision*, 35, 33-44.
- [25] Kersten, D., Mamassian, P., & Yuille, A. (2004). "Object perception as Bayesian

- inference. "Annu. Rev. Psychol., 55, 271-304.
- [26] Cuttle, C., Valentine, W.B., Lynes, J.A. and Burt, W. (1967). "Beyond the Working Plane." Proc. 16th. CIE Session, Washington DC, P67-12, 12pp
 - [27] Cuttle, C. (2003). [Lighting by design]. New York:Architectural Press.
 - [28] Morgenstern, Y., Murray, R. F., & Harris, L. T. (2011). "The human visual system's assumption that light comes from above is weak". Proceedings of the National Academy of Sciences, USA, 108, 12551–12553.
 - [29] Williams S.M., McCoy A.N., Purves D.(1998). "An empirical explanation of brightness," Proceedings of the National Academy of Sciences, 95, 13301-13306.