The effect of photometric and geometric context on photometric and geometric lightness effects

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We measured the lightness of probe tabs embedded at different orientations in various contextual images presented on a computer-controlled stereo display. Two background context planes met along a horizontal roof-like ridge. Each plane was a graphic rendering of a set of achromatic surfaces with the simulated illumination for each plane controlled independently. Photometric context was varied by changing the difference in simulated illumination intensity between the two background planes. Geometric context was varied by changing the angle between them. We parsed the data into separate photometric effects and geometric effects. For fixed geometry, varying photometric context led to linear changes in both the photometric and geometric effects. Varying geometric context did not produce a statistically reliable change in either the photometric or geometric effects.

Introduction

The visual system extracts information about the properties of surfaces in the visual scene. More specifically, from the light reaching the eye (the image), the visual system produces percepts such as color, texture, and glossiness. For these percepts to be informative about surfaces, visual processing must disentangle the effects of surface properties on the image from the confounding effects of the illumination.

The relevant physical property for a matte achromatic surface is its surface reflectance, a single number that represents the proportion of incident light reflected from the surface. The amount of light reaching the eye is the reflected luminance and is (if we neglect geometry) the product of the illuminant intensity and surface reflectance. The visual system represents achromatic surface reflectance through a perceptual quantity called lightness. For lightness to be a reliable indicator of surface reflectance, visual processing must stabilize lightness against variation in the reflected luminance caused by scene factors other than the intrinsic reflectance of the surface itself. The ability of the visual system to do so, at least approximately, is known as lightness constancy.

In natural scenes, a number of surface-extrinsic factors can affect the luminance reflected from a surface. The most widely considered factor is variation in the intensity of the sources of illumination themselves as can occur over the course of a day. Lightness constancy (as well as the closely related phenomenon of color constancy) has been extensively studied across changes in the overall illuminant intensity (and spectrum) for geometrically simple scenes (typically consisting of flat matte surfaces under a single diffuse illuminant). Given this simple geometry, the primary information available to support constancy in these scenes is photometric—the distribution of luminances in the image surrounding a probe surface of interest. For this special case, the photometric information can support good constancy, with performance consistent with the action of early visual mechanisms such as light adaptation and contrast coding. Performance is also consistent with predictions from ideal observer (Bayesian) models constructed for correspondingly simple imaging models (for reviews from both the lightness and color literature, see A. Gilchrist, 2006; Brainard, 2009; Kingdom, 2010; Brainard & Maloney, 2011; Foster, 2011; Brainard & Radonić, 2014).

There is also geometric structure to natural illumination, so the intensity of the illuminant can vary from one location in a scene to another, e.g., when comparing direct sunlight to shadow. Illumination can also be directional, so simply rotating a surface with respect to the dominant illuminant direction can affect the luminance of the reflected light. It is known that the visual system achieves some degree of lightness...
constancy with respect to each of these types of variation (Hochberg & Beck, 1954; Beck, 1965; Mershon, 1972; A. L. Gilchrist, 1977, 1980; Arend & Goldstein, 1987; Arend & Spehar, 1993a, 1993b; Boyaci, Maloney, & Hersh, 2003; Ripamonti et al., 2004; Kitazaki, Kobiki, & Maloney, 2008). Not well understood is what information in the retinal images enables such constancy and how this information is used by the visual system (for reviews see A. Gilchrist, 2006; Shevell & Kingdom, 2008; Kingdom, 2010; Brainard & Maloney, 2011; Brainard & Radonić, 2014).

It would be desirable to make progress on understanding constancy for geometrically complex scenes by building on what is known about constancy for geometrically simple scenes. The extent to which this will be possible, however, depends on how the effects of geometric manipulations on lightness interact with manipulations of photometric information of the sort that have been well studied for geometrically simple scenes. If there are no interactions or if the interactions are easily characterized, then it should be possible to leverage our knowledge from simple scenes to build theories that incorporate geometry. If there are complex interactions, however, they will need to be understood to ascertain whether it is sensible to generalize by building on what we know about lightness for simple scenes.

In this paper, we report the results of an initial set of experiments designed to explore interactions between photometric and geometric information on perceived lightness. We measured the lightness of probe tabs embedded in various contextual images. The stimuli were patterned on those used by A. L. Gilchrist (1980). We chose this configuration because it elicited large geometric effects on lightness in the previous studies but is simple enough to allow for independent manipulation of photometric and geometric information. To provide ready control over both photometric and geometric stimulus attributes, the stimuli were presented on a stereoscopic computer display system rather than as the real illuminated papers used in previous work. Two background context planes met along a horizontal roof-like ridge (Figure 1). Each plane was a graphics rendering of a set of achromatic surfaces, with the simulated illumination for each plane controlled independently. Photometric context was varied by changing the difference in simulated illumination intensity between the two background planes. Geometric context was varied by changing the angle between the two background planes. We measured the lightness of probe tabs rendered at different angles relative to the two background planes by asking observers to match each tab to a grayscale palette. We parsed the matching data into separate photometric effects and geometric effects, and we examined how changes in photometric and geometric context modulate these effects.

**Experiment 1**

**Methods**

**Observers**

Five observers (one male, four female, mean age = 23.4; labeled Observers 1–5) participated in this experiment. Each observer came to the lab for three to five sessions and was compensated for his or her time. The observers all had Snellen acuity of at least 20/40 (corrected) and scored at least 36/38 correct on the Ishihara color plates (Ishihara, 1977). In addition, the observers were all screened for stereopsis. This test was performed using the same apparatus used in the experiment (described below). By means of binocular disparity, a 2.62° × 2.62° square patch appeared either in front or in back of a fixed background plane. Observers were asked to indicate whether the patch appeared in “front” or in “back” of this plane. The background plane was rendered to be 764 mm away from the observer. The rendered distance of the patch from the background plane was adjusted via a two-down one-up staircase procedure (Levitt, 1971) to estimate 71% performance accuracy. All observers’ depth-discrimination thresholds were below 20 mm of rendered depth relative to the background plane (see below for description of the rendering procedure). The experimental protocol was approved by the University of Pennsylvania’s Institutional Review Board, and the procedures adhered to the tenets of the Declaration of Helsinki.

**Setup**

The stimuli were presented on a stereo apparatus. Two calibrated NEC PA241W LCD monitors were controlled by a single Macintosh OS/X computer, using MATLAB together with routines from the Psychophysics (Brainard, 1997; Pelli, 1997) and mgl (http://gru.brain.riken.jp/doku.php/mgl/overview) toolboxes. Observers sat with their heads stabilized via a chin rest in front of a black anodized metal faceplate. They viewed the stimuli through two 25 mm × 27 mm openings in the plate. The horizontal distance between the centers of these openings was 64 mm. A black cardboard divider sat perpendicular to the faceplate, preventing visual input intended for one eye from reaching the other.

Each eye received input from one monitor. The optical distance from each monitor to its respective eye was approximately 764 mm. The apparatus was aligned
Figure 1. Stimulus. (A) Schematic of stimuli, viewed from the side. The upper background context plane (lighter solid line) joined the lower background context plane (darker solid line), forming a horizontal ridge. The angle between the two context planes was 90° (as shown) in Experiment 1. In Experiment 2, it took on values of 45°, 90°, and 180°. A probe tab (dark dashed lines) extended from the ridge. An imaginary line extending from the center of the display toward the observer (light gray dashed line) was defined as 0° tab orientation. Negative tab angles denote tabs seen against the upper background context plane; positive tab angles denote tabs seen against the lower background context plane. (B) Front view of stimuli, 90° context angle for three illuminant change conditions with the difference between upper and lower simulated illuminants increasing from left to right. Illumination pair intensities: 78.96, 26.15; 137.20, 15.05; and 238.39, 8.66 cd/m². The three conditions shown are common to Experiments 1 and 2. For Experiment 1, an additional condition was included in which the upper and lower simulated illuminants were identical. The white surface shown in the center of each image illustrates one position of the probe tab. Each image is the right-eye view. (C) Geometric context manipulation. The upper panel shows a front view (right-eye image), and the lower panel shows a side-view schematic. The probe tab is in front of the lower context plane in the leftmost two images and in front of the upper context plane in the rightmost image. Three angles between the context planes were used: from left to right, 45°, 90°, and 180°.
by replacing the mirrors with beam splitters and aligning a grid image on each monitor to a physical grid located 764 mm from the eyes. The alignment information was used to warp the images presented on each monitor during the experiment to bring them into the geometry defined by the physical grid.

For the matching experiments, observers viewed a palette of Munsell papers that sat inside a plywood chamber (400 mm long × 405 mm wide × 405 mm deep). The chamber was painted matte gray and was illuminated by a fluorescent bulb. Inside the chamber, an additional LCD screen was placed on the back wall. The Munsell palette had values between 0.5 and 9.5 at 0.5-value intervals. These values corresponded to reflectance values ranging between 0.9% and 91% (details of the reflectance measurement procedure can be found in Allred, Radonjić, Gilchrist, & Brainard, 2012). The LCD screen in the chamber was used during experimental trials to display a number corresponding to one of the palette chip values.

Stimuli

The geometric structure of the stimulus scenes was specified in a three-dimensional scene space, and left- and right-eye two-dimensional images were then generated by using OpenGL graphics routines (http://www.opengl.org; routines accessed from MATLAB) to render the scene. The rendering was done assuming an interocular distance of 60 mm and that the eyes were converged on a distance of 764 mm (the approximate optical distance from the eyes to the monitors). To avoid introducing vertical parallax (which increases stereo vision stress), stereo pair images were rendered using the parallel (“off-axis”) method in which the camera’s view direction is normal to the vergence plane for both the left and right viewpoints, and perspective projections are done via asymmetric frusta. The rendering procedure ensured that perspective, occlusion, and binocular disparity cues to distance were properly represented in the images when the observer fixated at a location in the scene that was at a specified distance of 764 mm. Cues provided by convergence, accommodation, and a limited amount of motion parallax, on the other hand, were in conflict with the specified three-dimensional scene structure and indicated that the scene was flat. The subjective impression of three-dimensionality of our stimuli was nonetheless quite vivid, and an orientation-matching experiment (described in the Supplementary Material) confirmed this impression.

The stimuli consisted of two background context planes, specified as being 200 mm × 200 mm square in the three-dimensional scene space. The two planes were rendered at a 90° angle with respect to each other, and the horizontal ridge where they met was specified to be 764 mm from the observer in the three-dimensional scene space (Figure 1A, schematic of stimuli viewed from the side; B, pictorial representation of front view of stimuli as seen by observer). The context planes each contained 100 individual polygons—a selection of squares, rectangles, and L-shapes. The arrangement of these polygons was the same for both context planes. A dark gray background (350 mm × 550 mm in scene space) was rendered behind the contexts at a simulated distance of 984 mm from the observer. Its luminance was 0.78 cd/m².

The 100 polygons in each context were simulations of reflectance values between 0.07 and 1.00 chosen in equal log reflectance steps. Within each block of trials, the 100 reflectance values were randomly assigned to the 100 polygons in each context plane. This randomization occurred independently in each experimental block. The luminances for each polygon in each context plane were then calculated by multiplying all the reflectances by a simulated illuminant.

The simulated illuminants for the two contexts were different for most conditions. This manipulation changed the mean luminance of each of the two contexts and provided a photometric cue that would allow segregation of the two context planes. There were four illuminant change conditions in which the following four upper/lower simulated illuminant pairs were used: 45.44, 45.44; 78.96, 26.15; 137.20, 15.05; and 238.39, 8.66 cd/m².² The stimuli resulting from three of these pairs are illustrated in Figure 1B. The illuminant intensities were chosen so that each increment/decrement in illuminant intensity was an equal log step. Not illustrated by the figure is a condition in which the illuminant change was zero.

The simulated surfaces bordering the ridge joining the two background context planes were adjusted so that their simulated surface reflectance was the same on the two sides of the ridge. This was done to maximize the information available to the visual system that the two context planes were separate regions of illumination when the simulated illuminants were different and provided an additional segmentation cue that was held constant throughout the experiments reported in this paper (Adelson, 2000; A. Gilchrist, 2006). The continuity of simulated surface reflectance was achieved by two additional manipulations. First, the polygons along the upper and lower sides of the ridge were arranged such that their edges along the ridge aligned with each other. For example, in the right panel of Figure 1B, the L-shape in the lower right-hand corner of the upper context is aligned with a rectangle in the upper right-hand corner of the lower context. The edge they share along the ridge is the same for both polygons. This alignment was done for all the polygons across the ridge. Second, after the initial random assignment of reflectances, the reflectances for these
polygons were adjusted so that corresponding polygons across the ridge had the same reflectances. This was done by swapping reflectances with other polygons within each plane.

A quadrilateral probe tab was rendered near the center of the stimulus. The base of the tab lay along the ridge connecting the two context planes. The tab could be rendered in each of four orientations. In the two in-plane orientations, the tab was rendered flat within one or the other context plane. In the two out-plane orientations, the tab was rotated 90° from its corresponding in-plane position. Rotating each in-plane tab 90° preserved the local surround information of the tab but changed its orientation to be coplanar with the opposite context. We specify the tab orientation using the angular conventions shown in Figure 1, so the upper in-plane tab was specified by an orientation of −135° and the lower in-plane tab by an orientation of 135°.

The tab was specified as a 35 mm × 35 mm square in the three-dimensional scene space for the in-plane orientations. The precise shape of the tab in scene space for the out-plane orientations was adjusted so that each pair of in-plane and out-plane tabs had the same retinal size and shape for the right eye, using the following procedure. First, we rendered two context planes as in the experiment but with each containing a regular checkerboard of surfaces. When the tab was rendered at the in-plane orientation, it overlaid one of the squares on the checkerboard exactly. We then rendered the tab at the out-plane orientation. While viewing this out-plane tab with the right eye alone, we adjusted the vertices of the tab in the three-dimensional scene space, under the constraint that the rendered tab orientation remained fixed, until the tab projection overlaid the same square on the checkerboard. This procedure produced right- and left-eye images corresponding to a rendered quadrilateral at the out-plane orientation whose retinal projection for the right eye matched that of the rendered in-plane square (in scene space). The retinal left-eye images of the tab did not match; it is not possible to match the retinal images of a rendered surface for both the right and left eyes simultaneously while varying the rendered three-dimensional orientation of the surface, even if one allows a change in the shape of rendered surface across orientations.

The probe tab could take on any of nine luminance values between 0.58 and 238.39 cd/m² with equal log spacing (0.58, 1.23, 2.60, 5.53, 11.73, 24.91, 52.89, 112.28, and 238.39 cd/m²).

Procedure

Observers indicated in each trial which palette chip most closely matched the probe tab, using a slider that changed the number appearing on the LCD screen in the matching chamber. Observers were given instructions to match the lightness of the tab; specifically, they were told to match “what color paint the [tab] is coated with.” There were three special values that could appear on the LCD screen for judgments of values outside the range of the palette. The first was a value for surfaces “darker than 0.5.” Observers chose this value if the probe tab appeared to be a surface darker than the darkest palette chip. The second was a value for surfaces “lighter than 9.5” but that still appeared to be surfaces. Observers chose this value if the probe tab appeared to be lighter than the lightest palette chip but still appeared to be an illuminated surface. Finally, the third was a value for surfaces that appeared to be “glowing.” If the probe tab no longer resembled an illuminated surface but rather appeared to be generating light, observers chose this value.

There were three viewing conditions: binocular, left-eye monocular, and right-eye monocular. In the monocular conditions, the stimuli were rendered as for the binocular conditions, but a piece of opaque felt was placed over the left- or the right-eye opening of the faceplate. This prevented light from one of the monitors from reaching the eye. In these conditions, the absence of binocular disparity cues was expected to reduce (left eye) or eliminate (right eye) the percept that the probe tab was oriented differently from its surrounding context plane.

The pair of simulated illuminants was held constant within each block and varied across blocks. Within each block, observers saw each probe tab luminance at each of the four orientations three times in random order, resulting in a total of 108 trials. For each observer, the 12 blocks (three viewing conditions × four illuminant change conditions) were presented in random order.

Results

Binocular conditions

Basic features of the data: Figure 2 plots the mean \( \log_{10} \) reflectance of the matches, taken across replications and observers, as a function of probe tab luminance. Each panel shows the data for one illuminant change condition. Each curve represents the data for one probe tab orientation as indicated by the color and symbol. The data are highly regular, and the key qualitative features of the data may be seen in the plots.

First, as is expected, the matches increase monotonically as a function of tab luminance.

Second, the data do not differ with tab orientation for the 0 cd/m² illuminant change condition (no illuminant change). This is again expected although it is conceivable that there could have been an asymmetry between tabs presented against the upper and lower context plane or a difference between matches for in-
plane versus out-plane tab orientations for this condition.

Third, there is a clear effect of varying the simulated illuminant on matched lightness. The red points in each panel represent data for tabs whose immediate surround is provided primarily by the upper context plane, and the blue points represent data for tabs whose immediate surround is provided primarily by the lower context plane. The data separate by color in the plots with the separation increasing with the difference between upper and lower plane context illuminant. We refer to this as a photometric effect because, across illuminant context conditions, the geometry is held constant. These photometric effects may be thought of as a type of simultaneous contrast effect (Heinemann, 1955) and, for this reason, are expected.

Finally, there is a geometric effect: The lightness of the probe tab changes as it is moved from the in-plane to the out-plane orientation. This effect is seen most clearly in the 230 cd/m² illuminant change condition but is visible in each of the conditions in which there was an illumination intensity difference between upper and lower context planes. The in-plane/out-plane manipulation within each background planar context (upper versus lower) is represented by the change in symbols from circles to triangles. This change has the effect of reducing the photometric effect. That is, the triangles lie closer together than the circles. The geometric effect in our data replicates qualitatively the results obtained by A. L. Gilchrist (1980; see also Radonjić, Todorović, & Gilchrist, 2010). Our results generalize Gilchrist’s in that we demonstrate that the
effects may be obtained using simulations presented on computer-controlled displays for multiple tab luminances and for multiple illuminant context changes. Quantitatively, the magnitude of the effect shown in our data is smaller than obtained by Gilchrist, a point we return to in the Discussion.

**Dependence of effects on the illuminant context change:**
To examine how the photometric and geometric effects depend on the illuminant context change, we averaged the data shown in Figure 2 over probe tab luminance for each illuminant context change and probe tab orientation. Figure 3 shows the results averaged over observers with the mean lightness match plotted against probe tab angle for each illuminant context change.

We quantified the photometric effect for each illuminant change condition as the mean difference between the matches for all probe tabs whose immediate surround was primarily the lower context plane and all matches whose immediate surround was primarily the upper context plane. We quantified the geometric effect for each illuminant change condition as follows. First, we found the slope of the line connecting the pair of data points for each background plane and illuminant change condition (the slopes of the red lines shown in Figure 3; slopes represented in units of change in log10 match reflectance per 90° of tab angle rotation). We then took as a measure of the geometric effect for each illuminant change condition the average of the upper and lower context plane.

Figure 3. Experiment 1, mean matches as a function of probe tab angle. Each panel shows the mean matches, taken over observers, for one illuminant context change condition. The illuminant change condition for each panel is indicated in the panel’s title. Data for each observer were averaged over probe tab luminance and plotted as a function of probe tab angle. Error bars indicate ±1 SEM. Red lines join data whose immediate background is the same. Probe tab angles less than zero correspond to the upper (more intense illuminant) context plane, and probe tab angles greater than zero correspond to the lower (less intense illuminant) context plane. Individual observer plots in the same format are provided in the online Supplementary Material available at http://color.psych.upenn.edu/supplements/lightness_photo_geo/.
slopes. Figure 4 plots the photometric and geometric effects so obtained as a function of the context illuminant change. Both effects increase close to linearly with the magnitude of the illuminant change.

Because the dependence of both photometric and geometric effects on the magnitude of the illuminant change is close to linear, we can quantify the overall magnitude of these effects across all of our illuminant changes by the slope of the best-fitting line. This slope is 0.0012 (in units of log reflectance per cd/m²) for the photometric effect and 0.0006 (in units of log reflectance per 90°) for the geometric effect. These overall effects are indicated by the dark blue bars in the two panels in Figure 5. For our conditions and measurement conventions, the overall geometric effect is about half as large as the overall photometric effect (ratio of photometric to geometric effect: 2.1).5

**Monocular conditions**

To separate the role of photometric and geometric factors in the stimulus on inducing photometric and geometric effects, we analyzed the monocular control data in the same manner as with the binocular data to obtain photometric and geometric effects for these data. The overall effects are shown in Figure 5 (yellow panel).
and maroon bars in each panel). For the monocular data, there was an additional luminance with which the lightness was judged out of range for each observer, so we only averaged over tab luminances 5.53, 11.73, 24.91, and 52.89 cd/m² when analyzing these data. We also reanalyzed the binocular data for this subset of tab luminances (effects shown by light blue bars in each panel of Figure 5, referred to as the binocular matched condition).

The overall photometric effect does not vary systematically with viewing condition (Figure 5A). A two-way ANOVA on the overall photometric effect with viewing condition as a fixed factor and observer as a random factor (two levels for viewing condition: binocular matched vs. left-/right-eye monocular; main effects only modeled) revealed no significant main effect of viewing condition \((p = 0.14)\). There was a significant main effect of observer \((p < 0.05)\).

The overall geometric effect is essentially abolished for monocular viewing (Figure 5B). A two-way ANOVA on the overall geometric effect (same design as ANOVA for photometric effects reported above) revealed a significant main effect of viewing condition \((p < 0.001)\) but no main effect of observer \((p = 0.07)\). Matched pairs \(t\) tests indicated that the mean overall geometric effect for left- and right-eye viewing is significantly below that for binocular viewing with matched tab luminances \((p < 0.01\) in both cases). These results indicate that the geometric effects found in Experiment 1 result from binocular viewing and thus presumably have their origins in the change in perceived geometry provided by binocular disparity rather than from small changes present in the left-eye monocular image.

**Intermediate discussion**

The results of Experiment 1 establish that the effect of the photometric contextual cues on lightness perception could be reliably measured using our stereoscopic display and that there are both photometric and geometric effects on lightness for our stimulus conditions. Lightness matches to a given probe tab luminance depended on the tab’s orientation as well as on which context background plane it was seen against.

The effects of the photometric cues were independent of viewing condition; the overall photometric effects were comparable across binocular and monocular conditions. On the other hand, the overall geometric effects were driven by manipulations of binocular disparity rather than information available to either eye alone. This finding is in agreement with the conclusions from earlier studies (A. L. Gilchrist, 1977, 1980; Schirillo, Reeves, & Arend, 1990; Radonić et al, 2010).

Interestingly, the magnitudes of the photometric and geometric effects covaried with the changes in photometric context as revealed by the fact that both scaled linearly with the magnitude of the illuminant change. This is a form of independence: We only need to know the slope of each line to predict the sizes of the photometric and geometric effects for any illuminant change. To put it another way, the relationship between photometric and geometric effects is independent of the size of the illuminant change.

**Experiment 2**

**Overview**

Although there was three-dimensional geometric structure to the contexts employed in Experiment 1 (the fact that the two background context planes were not coplanar with each other), this structure was not varied. The purpose of Experiment 2 was to replicate the results of Experiment 1 and to explore the effect of varying the geometric information carried by the background context planes. In Experiment 2, we varied both the intensity of the illuminations as well as the angle between the two background context planes. We also rendered the probe tab at a larger number of orientations and omitted the illuminant change condition in which there was no difference in illuminant intensities.

**Methods**

The methods were the same as in Experiment 1 except for the following differences.

**Observers**

Five observers (one male, four female, mean age = 22.6) who did not participate in Experiment 1 participated in this experiment. Each observer came to the lab for five to six sessions and was compensated for his or her time. The observers all had Snellen acuity of at least 20/40 (corrected) and scored at least 36/38 correct on the Ishihara color plates (Ishihara, 1977). In addition, the observers were all screened for stereopsis as in Experiment 1. All observers’ depth-discrimination thresholds were below 20 mm of rendered depth.

**Stimuli and procedure**

We omitted the illuminant pair 45.44, 45.44 cd/m² (no difference). Thus, the following upper/lower
illuminant pairs were used: 78.96, 26.15; 137.20, 15.05; and 238.39, 8.66 cd/m².

We rendered the background context planes at three context angles relative to each other: 45°, 90°, and 180° (coplanar; see Figure 1). In all cases, each background context plane was rendered as a 200 mm × 200 mm square in the three-dimensional scene space. Thus, the size and shape of the retinal projection of the context planes varied with context angle. Note that, although the difference in illumination between the upper and lower context planes for the 45° and 90° context angles might naturally arise from a combination of directional illumination from above and some amount of ambient illumination, the illumination difference for the 180° coplanar condition models an illumination difference caused by a cast shadow.

For the 45° context angles, the tab angles were: ±157.5°, ±135.0°, ±90.0°, ±45.0°, and ±22.5°. The tab angles used in the 90° context condition were the same as those in the 45° context condition except for the exclusion of the ±157.5° tab angles, as these would have been behind the context plane. For the same reason, the tab angles used in the 180° context condition were those used in the 90° context condition except for the exclusion of the ±135.0° angles. The probe tab could take on any of five luminance values: 1.23, 3.79, 11.73, 36.30, and 112.28 cd/m². Tab luminances that elicited out-of-range responses from any observer were removed from the analysis for all observers. These were the highest and lowest tab luminances, leaving the data for three out of five tab angles for analysis.

In Experiment 2, the probe tab was 35 mm × 35 mm in three-dimensional scene space when it was in-plane with the background context planes in the 45° context angle condition. Its shape was adjusted for other probe tab angles using the procedure described in Experiment 1 so as to hold its right-eye projection constant across tab angles.

Observers viewed the stimuli under binocular and monocular conditions. For the monocular conditions, we studied only a subset of the probe tab angles and context angles. Only the 45° and 180° context angles were used. For the 45° context angle, only the ±157.5° and ±22.5° tab angles were used; for the 180° context angle, only the ±90° and ±22.5° tab angles were used.

The intensities of the pair of simulated illuminants and the angle between the context planes were held constant within each block but varied across blocks. Within each block, observers saw each target luminance at each orientation three times in a random order. For each observer, the 21 blocks (three context angles × three illuminant pair conditions for binocular viewing + two context angles × two eyes × three illuminant pair conditions for monocular viewing) were presented in random order. The number of trials per condition varied between 60 and 150, depending on how many different tab angles were presented.

Intermixed with the blocks of this experiment were blocks of orientation matches performed by the same observers. The orientation-matching experiment is described in the Supplementary Material.

Results

Figure 6 plots the data from Experiment 2 in the same general format as Figure 3. There is one panel for each combination of illuminant change and context angle. The magnitude of the illuminant change increases across each row, and the context angle increases down each column. The panels in the middle row thus represent the same context angle as was used in Experiment 1, and the data may be compared with those shown in Figure 3. The photometric and geometric effects that were found in Experiment 1 were also seen in Experiment 2: The matches for tabs seen against the lower context plane are higher than those for the upper context plane (photometric effect), and the data for each context plane generally increase with probe tab angle.

We quantified the photometric and geometric effects from Experiment 2 in the same way as we did for Experiment 1. The results are plotted in Figure 7, which may be compared with Figure 4. As with Experiment 1, both photometric and geometric effects increase close to linearly with the context illuminant change, and we can quantify the overall photometric and geometric effects by the slopes of the best-fit lines. Figure 8 shows the overall photometric and geometric effects for each background context angle in the same general format as Figure 5. For the 90° context (panels C and D), the effects are slightly smaller than those obtained in Experiment 1 (the photometric effect in Experiment 2 was 0.0009 compared with 0.0012 in Experiment 1; the geometric effect in Experiment 2 was 0.0004 compared with 0.0006 in Experiment 1). The ratio of photometric to geometric effect for the 90° context angle in Experiment 2 was 2.3, compared to a value of 2.1 obtained in Experiment 1.

The photometric effects do not vary with context angle. A two-way ANOVA on the overall photometric effect with geometric context as a fixed factor and observer as a random factor (three levels for geometric context; main effects only modeled) revealed no significant main effect of geometric context (p = 0.14). There was a significant main effect of observer (p < 0.005). A subtlety to this analysis is that a different set of context angles was used for the three different geometric contexts. For this reason, we reran the analysis using only the probe tab angles common to all three geometric contexts. The resulting slopes are also
shown in Figure 8A (binocular reduced bars). These reveal somewhat smaller photometric effects for the 45° and 90° contexts than are revealed by the analysis of the full data sets and are the same for the 180° context by construction. An ANOVA on the binocular reduced photometric effect slopes leads to the same conclusion as the ANOVA on the slopes obtained from the full data set (effect of geometric context, \( p = 0.23 \); effect of observer, \( p < 0.01 \)). Because the retinal size of the background context planes changed with the angle between these planes, the fact that the photometric effect does not vary with context angle indicates that this areal change is not a large factor with respect to the photometric effect.

An ANOVA on the geometric effect with the full data set (all tab angles analyzed for each geometric context) reveals that geometric context does have a significant effect on the geometric effect (effect of geometric context, \( p < 0.05 \); effect of observer \( p < 0.01 \)). When the same analysis is run using the reduced tab angles (Figure 8B, binocular reduced bars), however, the effect of geometric context is not significant (\( p = 0.31 \); effect of observer \( p = 0.05 \)). Because the reliability of the effect of geometric context on the geometric effect is sensitive to this subtle change in data analysis, we think the appropriate view is that our data do not have enough power for us to assert that such an effect exists. To the extent that there is a trend in the data, it is that the...
geometric effect is larger for the 90° geometric context than for the 45° or 180° contexts. *T* tests indicate that the geometric effect is significantly different from zero for the 45° and 90° contexts (\(p < 0.05\)) but not for the 180° context (\(p = 0.13\)).

**Monocular controls**

The data from the monocular control conditions for Experiment 2 are also plotted in Figure 8. The overall photometric effect does not vary systematically with viewing condition (Figure 8A, E; compare binocular matched, left-eye, and right-eye bars; the binocular matched effects were computed using the set of tab angles that were used for the monocular conditions). A three-way ANOVA on the overall photometric effect with viewing condition and geometric context as fixed factors and observer as a random factor (two levels for viewing condition: binocular matched versus left-/right-eye monocular; two levels for geometric context; main effects only modeled) revealed no significant main effect of viewing condition (\(p = 0.17\)) or geometric context (\(p = 0.15\)). There was a significant main effect of observer (\(p < 0.001\)).

The overall geometric effect is reduced for both the left and right eyes (Figure 8B, F). A three-way ANOVA on the overall geometric effect (same design as ANOVA for photometric effects reported just above)
revealed a significant main effect of viewing condition ($p < 0.05$) but no main effect of geometric context ($p = 0.53$) or observer ($p = 0.51$). Matched pairs $t$ tests, however, indicate that none of the four individual monocular effects (left and right eye, 45° and 180° contexts) are significantly different from the corresponding binocular effect. The fact that many of the ANOVAs run for Experiment 2 revealed significant observer differences, combined with the trend toward a smaller geometric effect for the 45° and 180° geometric contexts relative to the 90° context, may be the cause of the marginal statistical significance of the reduction in geometric effects for the monocular conditions in Experiment 2.

**Discussion**

Our study is among the first to measure how variation in both photometric and geometric context affect perceived lightness and perhaps the first of such studies to manipulate these two aspects of context using a factorial design. We measured the lightness of probe tabs rendered at different three-dimensional orientations, in the context of background planes rendered at different orientations (geometric context) and consisting of simulations of surfaces under illuminants of varying intensity (photometric context). For each geometric/photometric context pairing, we parsed the

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**Figure 8. Overall photometric and geometric effects, Experiment 2.** (A, C, and E) Overall photometric effects (slopes from Figure 7) obtained in Experiment 2 for each viewing condition. Dark blue: binocular; light blue: binocular reduced (only tab angles used in all three geometric contexts analyzed); green: binocular matched (tab angle luminances used matched the subset used in the monocular conditions); orange: left eye; maroon: right eye. Data are mean overall effect slope taken over observers. Error bars show $\pm 1$ SEM. The dashed horizontal line shows the binocular effect obtained in Experiment 1. Each panel shows data for a different context angle. (B, D, and E) Overall geometric effects obtained in Experiment 2. Same format as (A, C, and E).
lightness-matching data into separate photometric and geometric effects.

Our finding that the lightness of the probe tab is affected by its orientation adds to the body of evidence that the pose of a surface can affect its perceived lightness (Mach, 1886; Hochberg & Beck, 1954; A. L. Gilchrist, 1980; Knill & Kersten, 1991; Boyaci et al., 2003; Ripamonti et al., 2004; Radonjić et al., 2010). Importantly, we find that both photometric and geometric effects depend linearly on the difference in simulated illuminant intensity between the upper and lower background context planes, establishing an independence between photometric context manipulations and geometric effects (see also the Intermediate discussion). This independence was found in both Experiments 1 and 2 for each geometric context studied. This independence is the main experimental finding of this paper and is important because, if it generalizes to more complex configurations, it means that we can use measurements obtained for one set of illuminant changes to predict both photometric and geometric effects for other sets of illuminant changes.

It is clear our stimuli were simple, so that indeed additional work will be required to probe the generality of the independence we observe. One obvious generalization is to test what happens with our geometric configurations when the illuminant changes are not symmetric around a fixed mean level. A second is to study what happens for scenes with more than two background context planes. Finally, as we discuss in more detail below in the context of a comparison of our data with those of Radonjić et al. (2010), obtaining a better understanding of how the results of experiments conducted using computer simulations relate to those conducted using real illuminated surfaces is a priority.

Our experiments were designed to study the interaction between photometric and geometric contextual information on surface lightness and not to distinguish between specific theoretical approaches. Indeed, our finding of independence is qualitatively consistent with a number of such approaches. Gilchrist’s anchoring theory (A. Gilchrist et al., 1999; A. Gilchrist, 2006; see also Adelson, 2000), for example, posits that the lightness of a surface is computed separately with respect to distinct frameworks, using primarily photometric information within each framework. The separately computed lightnesses are then combined across frameworks via a weighted average with information that affects the segregation of the frameworks determining the weights. Such an account will lead to the type of independence we observe as long as changes in photometric information do not have a substantial effect on the cross-framework weights. This seems plausible for our experiments, given that the nonzero illuminant changes were clearly visible.

Equivalent illuminant theories (in the present context, see Boyaci et al., 2003; Bloj et al., 2004; Brainard & Maloney, 2011), which posit that the visual system computes the lightness of a surface by (in effect) discounting an estimate of the illumination (called the equivalent illuminant) impinging upon it, should be able to account for the observed independence as well as the variation in matches with tab angle, if the information provided by each context surface is used to estimate the intensities and positions of two separate directional light sources with the geometry of the light sources unaffected by changes in photometric information. This seems plausible for our stimulus configurations. We have not explicitly fit such models because once one posits that two directional light sources comprise the equivalent illuminant, we believe the explanatory power of the model exceeds the power of the current data set to reject it. It is also worth noting that the jump in matches that occurs on either side of the 0° tab angle position is difficult to reconcile with an equivalent illuminant model that posits an equivalent illuminant arising from the combination of only a single directional source together with an ambient illuminant.

We have two negative experimental findings. Our geometric context manipulation did not affect the photometric effects, and it did not affect the geometric effects. We hesitate to make much of these findings because the negative results may be a consequence of insufficient experimental power to reveal a small underlying effect. That said, the lack of an effect of geometric context on the photometric effects would represent a second type of independence. If it holds more generally, it means that an understanding of photometric effects obtained for one geometric context can be used to predict photometric effects in other geometric contexts. This conclusion would be more compelling if the data had revealed an effect of geometric context on the geometric effects at the same time as it failed to show an effect of geometric context on the photometric effects. It will be of interest to find stimulus manipulations that allow sharper tests of this type of independence.6

One possibility for the lack of geometric context would be if observers failed to accurately perceive the angle between the two background context planes. Although this seems unlikely given that we do find an effect of probe tab angle, we conducted an orientation-matching experiment, which confirmed that observers’ perception of the angle between the background context planes was reasonably accurate and varied with our geometric context manipulations. The orientation-matching experiment is reported in the Supplementary Material and also confirms that observers perceived the intended variation in probe tab angle.

We used a palette-matching paradigm. In a pilot experiment, we verified that we could also obtain
geometric effects with our stimulus configuration using a two-alternative forced-choice paradigm (2AFC, details provided in the Supplementary Material). The geometric effects obtained using 2AFC were slightly smaller than those obtained using matching with the same observers.

We studied a relatively simple stimulus configuration, patterned after the one introduced by A. L. Gilchrist (1980). This stimulus configuration was of interest because it can lead to large geometric effects (A. L. Gilchrist, 1980; Radonjić et al., 2010) when the stimuli consist of real illuminated surfaces but is simple enough that key parameters can be varied parametrically. To facilitate our stimulus manipulations, we presented the stimuli as simulations on a computer-controlled stereo display. For reasons that are not clear, the size of the geometric effects in our experiments is smaller than found in the original A. L. Gilchrist (1980) study and in its more recent replication (Radonjić et al., 2010). Figure 9 replots our data from Experiment 1 for the largest illuminant change condition (Figure 3D) along with data from two experiments from Radonjić et al. (2010, data from their experiment 2, figure 6 and experiment 3, figure 8). Their experiment 2 (their figure 6, blue triangles in our Figure 9) was similar to ours in design but was conducted with real illuminated papers. In addition, their background context planes were spatially homogeneous rather than articulated, they used a between-subjects rather than a within-subjects design, two probe tabs were visible in their stimuli in each trial, and they studied only one tab luminance. There are two salient differences between their data and ours. First, their geometric effect is considerably larger than ours. Second, their photometric effect goes in the opposite direction from ours. The fact that our stimuli were articulated and theirs were not does not explain these differences as articulation increases rather than decreases the geometric effect when the stimuli consist of real illuminated papers (Radonjić & Gilchrist, 2013). In their experiment 3, the probe tabs were spatially separated from the background context planes (see their figure 7). The data from this second experiment are much more similar to ours. Relative to their condition in which the probe tabs are adjacent to the background context planes, the geometric effect is reduced, and the photometric effect switches sign. Although the processes that mediate the differences between these experiments are not known, the similarity in the effect of changing from real to simulated surfaces and the effect of changing from adjacent to separated probe tabs is intriguing, as it suggests that both effects could be mediated by a common process that regulates the influence of the coplanar context surface on the lightness of the probe tabs. If so, the principles our experiments reveal may apply to this underlying process even if the stimulus factors that lead it to govern performance differ between stimuli consisting of real versus simulated surfaces. Understanding this more fully is an interesting direction for future research, not in small measure because it may provide clues as to why the effects we find here using computer simulations differ from those found previously using real illuminated surfaces for a fairly well-matched stimulus configuration. In turn, a better understanding of the key factors that must be incorporated into simulated scenes to have them evoke the same performance as scenes consisting of real illuminated surfaces would facilitate the study of larger effects using the parametric/computer display approach we have developed here and allow more powerful tests of the interaction between photometric and geometric context than we were able to obtain with our current methods.

Keywords: lightness, constancy, geometry

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Footnotes

1Convention for specification of physical dimensions is vertical then horizontal.
2We use improper units for illuminant intensity for convenience. By a simulated illuminant intensity of X cd/m², we mean that the luminance of a perfectly reflecting diffuser rendered under the simulated illuminant would be X cd/m².
3The full instructions for this and other experiments reported in this paper are available in the Supplemental Material available online at http://color.psych.upenn.edu/supplements/lightness_photo_geo/.
4Data are shown only for tab luminances for which no out-of-range responses were given by any observer for any of the binocular conditions. These are the middle five tab luminances (2.60, 5.53, 11.73, 24.91, and 52.89 cd/m²). Because it is not clear how to average data when there are any out-of-range responses, we excluded tab luminances for which any out-of-range responses were given by any observer from the analyses. The full individual observer data for this and other experiments reported in this paper are tabulated in the Supplementary Material available online at http://color.psych.upenn.edu/supplements/lightness_photo_geo/.
5Note that one could adopt different conventions for quantifying the effects so that the ratio is a definition-dependent quantity. For example, one could take the photometric effect as the difference between the upper and lower context measurements for the in-plane probe tabs rather than the difference in mean matches between probe tabs for the upper and lower contexts. Doing so would change the magnitude of the obtained photometric effect. It is not clear that any particular choice of convention in this regard is privileged. Some care, however, must be taken in comparing photometric effects across conditions in which different sets of probe tab angles are used, a subtlety that will come up for Experiment 2 of this paper. Similarly, our choice of expressing the geometric effect with respect to a 90° tab angle change is arbitrary.
6Note that there are studies in which geometric manipulations of a scene do change geometric effects. For example, Ripamonti et al. (2004) found that moving the location of a light source within a scene changed the pattern of how lightness varied with the slant of a probe surface. That manipulation, however, did not hold the photometric context even close to constant.

References


