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Effects of scene content and layout on the perceived light direction in 3D spaces

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The lighting and furnishing of an interior space (i.e., the reflectance of its materials, the geometries of the furnishings, and their arrangement) determine the appearance of this space. Conversely, human observers infer lighting properties from the space's appearance. We conducted two psychophysical experiments to investigate how the perception of the light direction is influenced by a scene's objects and their layout using real scenes. In the first experiment, we confirmed that the shape of the objects in the scene and the scene layout influence the perceived light direction. In the second experiment, we systematically investigated how specific shape properties influenced the estimation of the light direction. The results showed that increasing the number of visible faces of an object, ultimately using globally spherical shapes in the scene, supported the veridicality of the estimated light direction. Furthermore, symmetric arrangements in the scene improved the estimation of the tilt direction. Thus, human perception of light should integrally consider materials, scene content, and layout.

Introduction

Light makes objects visible without being visible itself in empty space. The combination of the spatial and spectral characteristics of the light source(s) and the materials, scene content, and layout determines the appearance of a space (the so-called “forward problem” of computer graphics). As such, the space's appearance is the main cue for the perception of its

lighting and materials, scene content, and layout. However, there is no unique solution to the so-called inverse problem (i.e., inferring the physical scene properties from the scene's appearance) because of basic image ambiguities. Therefore, light, material, and scene content and layout perception are expected to be confounded. Several studies addressed perceptual interactions between light and material perception (Dror, Willsky, & Adelson, 2004; Khang, Koenderink, & Kappers, 2003, 2006). Here we present a first systematic exploration of the effect of scene content and layout on the perceived light direction in a space.

In the past years, research on light direction detection from images of surfaces has drawn a lot of attention both in computer vision and psychophysics. In computer vision, the light direction is one of the key elements that determine the shading patterns on an illuminated object, and therefore its estimation is used in shape-from-shading algorithms. In psychophysics, understanding how human beings account for the variations in light field properties (i.e., light direction, intensity, and diffuseness) is essential for research on color/lightness constancy (Brainard, 1998; Brainard, Brunt, & Speigle, 1997; Gilchrist et al., 1999; Maloney, Gerhard, Boyaci, & Doerschner, 2010), human perception of “illuminance flow” (Koenderink, Van Doorn, & Pont, 2007; Koenderink, Van Doorn, Kappers, te Pas, & Pont, 2003; Pont & Koenderink, 2004), and to understand how human beings estimate 3D shape from shading (Khang, Koenderink, & Kappers, 2007; Mingolla & Todd, 1986).

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However, every biological or artificial visual system faces the problem that images are ambiguous, in the sense that every image can be the result of an infinite number of possible combinations of shapes, surface materials, and lighting conditions. Thus, to recover the light direction from the appearance of an image is challenging because there is no unique solution. Pentland (1982) investigated how well humans could estimate the illumination direction from an image. He provided a sheet with a series of disks with varying surface normals. The observers were asked to select from these disks the one with its surface normal closest to the illumination direction in test pictures of natural objects. The results showed that the observers could estimate both tilt and slant of the illuminant direction with an average deviation of 6° from the veridical direction and a standard deviation less than 12° .

Koenderink et al. (2003) conducted a study on estimating the illumination orientation from textures in images. The participants were asked to match the illumination direction of a probe (i.e., a hemispherical boss on a plane) to the illumination direction of the textures. They found that participants were generally quite good at estimating the illumination orientation with a standard deviation of 13.6° but not its direction, because 180° flips happened quite frequently because of the “convex/concave ambiguity” (Brewster, 1826; Gregory, 1970; Ramachandran, 1988). Connected with this finding, they confirmed the “light-from-above bias” (Hoffman & Marshall, 1998; Ramachandran, 1988; Rittenhouse, 1786), which means that participants almost invariably judged the illumination to be from above rather than from below. Moreover, they found that participants were much worse at estimating the elevation of the illumination than the orientation, as the “bas-relief ambiguity” theory predicts (Belhumeur, Kriegman, & Yuille, 1999). The lower performance for estimating elevation than for azimuth was confirmed in an experiment done by Pont and Koenderink (2007) in which artificial Lambertian spheres and images of real rough spherical objects with various surface textures were used. They varied the diffuseness of the illumination in addition to the direction of the illumination. They found that illumination direction estimates interacted with illumination diffuseness estimates, because more frontal lighting or more diffuse lighting resulted in quite similar changes in object appearance (i.e., diffuseness-direction ambiguity).

It is already known that human beings can detect the light direction on an illuminated object from the shading, shadowing, and highlight at the level of significant global surface curvature on the macroscale (Boyaci, Doerschner, & Maloney, 2006; O’Shea, Agrawala, & Banks, 2010). For objects with rough surfaces, there is an additional source of optical information named “surface illumination flow,” which

is the variation of the surface texture over the object surface due to illuminated corrugations on the meso-scale. Koenderink et al. (2003) found that observers could estimate the illumination orientation of isotropic rough surfaces rather precisely but that for anisotropic rough surfaces, observers made very systematic errors depending on the level of anisotropy, causing specific deformations of the surface illumination flow (Koenderink et al., 2007). Also, Khang et al. (2006) found that the estimated illumination direction in images of three-dimensional (3D) convex shapes differed for different types of reflectances, causing different types of shading variations. Thus, shading, shadowing, and 3D texture patterns are important cues for light direction estimation, and systematic deformations of those patterns may result in specific deviations in the estimates.

The studies mentioned above were all performed using images on screens. In real scenes, observations may be less ambiguous for several reasons: (a) Observers can move their eyes, head, and body, which results in many extra cues (e.g., motion parallax and multiple views), and (b) observers may rely on stereoscopic vision and a higher dynamic range. We used an optical mixture setup to test human observers’ sensitivity for the low-order lighting properties, such as intensity, direction, and diffuseness in real scenes (Xia, Pont, & Heynderickx, 2014b). The observers were asked to adjust the lighting on a probe to make it appear like it fit the scene. The scene consisted of five small different geometrical shapes (a bowling pin, a pentagon body, a disk body, a cross body, and a star body), which were arbitrarily selected and scattered in the space. The results showed that humans were quite sensitive to variations in light intensity in the scene and that they could also infer the light diffuseness, albeit with a bigger variance. However, one interesting phenomenon found in this study caught our attention and impelled the study described in this article. The results showed that although observers’ estimations of the light direction correlated well with the veridical light direction, they showed a significant deviation near a pentagon body and not near a bowling pin (Xia, Pont, & Heynderickx, 2014a).

We noticed that, both in psychophysical research and interior design, it appears to be neglected that objects placed within a 3D space might influence the perception of light—and, more particularly, the perception of the light direction—in this space. Empirical evidence for the influence of the shape and arrangement of objects in real scenes on the perceived light direction is still missing.

The experiments in this article were designed to investigate the following two research questions:

1. Whether the shape and layout of objects in a real scene influence the perceived light direction

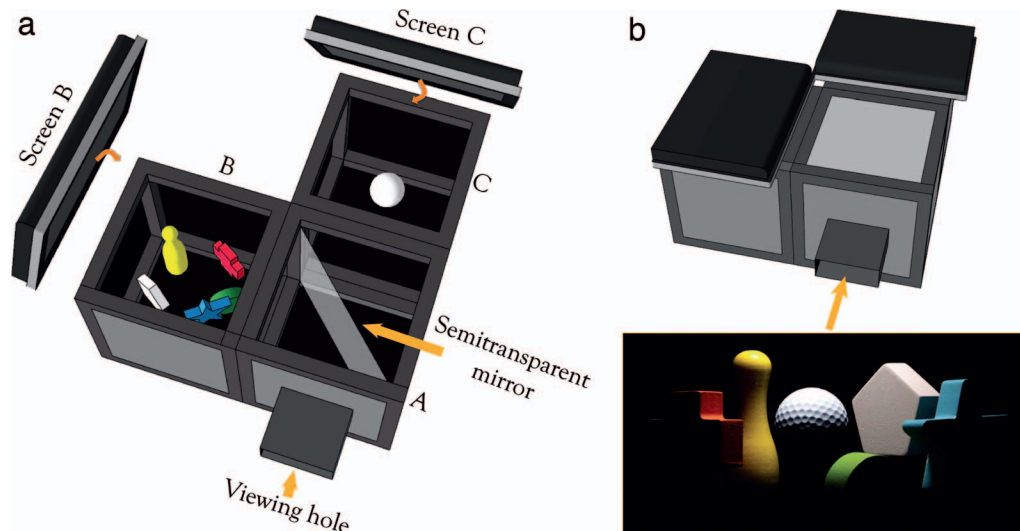


Figure 1. Illustration of the setup. (a) The setup consists of three $30\text{ cm} \times 30\text{ cm} \times 30\text{ cm}$ cubes, of which the inside is covered with black velvet paper (the inner width of the cubes was 25 cm excluding the width of the frames). In Cube B, we made a simple scene with five geometrical shapes. In Cube C, we placed a white painted golf ball, which served as the probe. A semitransparent mirror was placed vertically at the diagonal of box A. Two LCD screens covering the top of cube B and cube C provided the lighting, which could thus be varied independently for the scene and the probe. (b) The setup and an optical mixture of the scene and the probe photographed through the viewing hole.

2. If the answer to the first question is yes, how the shape properties and light direction estimation are related

General methods

We conducted an adjustment task based on the generic notion of a “gauge object.” We used an experimental setup in which a real gauge object was optically introduced into a real scene (Xia et al., 2014b; Xia, Pont, & Heynderickx, 2013). Our setup is illustrated in Figure 1a. The scene consisted of five colorful painted matte wooden geometrical shapes and was located in cube B. A painted matte white golf ball, serving as the probe, was put in the center of cube C. Because a white object has a higher albedo than an object with any other color, one of the shapes in the scene was also painted white to provide an anchor (Gilchrist et al., 1999). The scene and probe were optically mixed together by a semitransparent mirror put in cube A at 45° with respect to the viewing direction. The observers saw the optical mixture of the scene and probe through a viewing hole as if they were put together, as illustrated in Figure 1b. The lighting on the scene and probe was provided by an LCD screen on top of cube B and cube C, respectively. Independent images were displayed on the two screens to provide individual lighting for the scene and for the probe. We

refer to Xia et al. (2013, 2014b) for more information on the experimental setup.

The width of the cubes was 30 cm , and the top of cube B and cube C was covered with a $930\text{ pixels} \times 930\text{ pixels}$ squared area on the screens. The average light direction as defined by the light vector (Gershun, 1939; Mury, 2009) was varied by displaying a white disk with a diameter of 7 cm (i.e., 264 pixels) at different positions on the LCD screen. In the sections explaining the experimental setup, analysis, and results, we will describe these variations in terms of position, but it should be remembered that this is just a convenient parameterization of the direction in this specific setup. When illuminating the scene, the white disk was displayed at one out of nine fixed positions on the LCD screen. The bird’s-eye view of these nine positions is depicted in Figure 2, and the positions are labeled from P1 to P9. Their location on the LCD screen is marked using x - and y -coordinates. These positions of the disks were selected within a certain distance from the edges of the cube to make sure that there was enough space to adjust the light direction.

The direction of the light source on the scene can be converted into two angles, that is, the slant and tilt angle, as listed in Table 1. As Figure 3 shows, the slant of the light source is the angle θ between the viewing direction and the vector from the center of the probe to the center of the light source (PS ; using a light source in P3 as an example). The tilt of the light source is the angle φ between the positive x -axis and the projection of PS onto an eye-centered reference frame (i.e., the surface XPZ). The light sources in the same row of

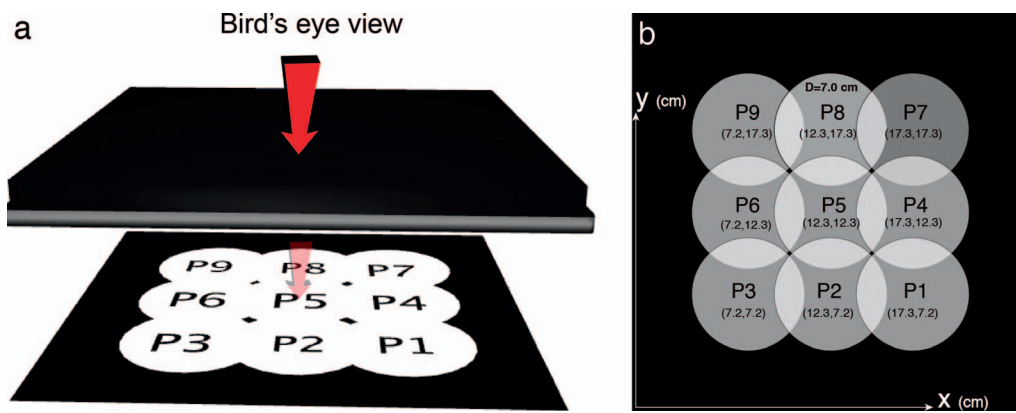


Figure 2. (a) Illustration of the bird’s-eye view of the stimuli on the scene. Variation in direction was achieved by changing the position of a displayed white disk. Nine positions from P1 to P9 were used, as shown in the figure. The diameter of the disk was 264 pixels, and the width of the full window was 930 pixels (25 cm). (b) Detailed information of the disk’s positions.

Figure 2 have the same slant angle, being 74° for the front row (P1, P2, P3), 90° for the second row (P4, P5, P6), and 106° for the back row (P7, P8, P9). Similarly, the light sources in the same column have the same tilt angle, being 73° for the right column (P1, P4, P7), 90° for the middle column (P2, P5, P8), and 107° for the left column (P3, P6, P9).

On the probe side, a disk with the same diameter was displayed in a random position serving as the light source that had to be adjusted.

The experiments were performed in a dark room. The observers looked at the optical mixture of the scene and the probe through the viewing hole and were asked to adjust the light direction on the probe to fit the light direction on the scene. The four arrow keys on a

keyboard were used to adjust the light direction. The observers could choose to take small steps or big steps by pressing corresponding keys on the keyboard when performing the adjustment. Once the “big step” was selected, each time the arrow key was pressed, the center of the light source moved 30 pixels (approximately 0.8 cm) in the selected direction. Otherwise, if “small step” was used, the center of the light source moved 10 pixels for each push on the key. If the position of the adjusted light source reached one of the boundaries, the computer gave a warning sound.

Experiment 1: Is the perceived light direction in real scenes influenced by the shapes and scene layout?

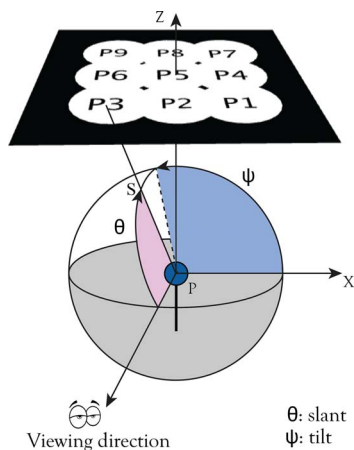


Figure 3. Illustration of slant and tilt for the light source located in P3. The blue spot shows where the probe is located. The slant θ is defined as the angle between the viewing direction and the vector from the center of the probe to the center of the light source (\vec{PS}). Tilt φ is defined as the angle between the positive x-axis and the projection of \vec{PS} into eye-centered reference frame (i.e., surface XPZ).

In a former study by Xia et al. (2014a), the observers were asked to adjust the light direction of a probe to fit the light direction on a scene. The results showed that the estimated light direction correlated well with the veridical light direction but with a significant contraction near a pentagon body and not near a bowling pin. These results suggested that a human’s perception of light direction might be influenced by the shape and layout of the objects in the scene. To test this conjecture, the first experiment was designed.

Position	P1	P2	P3	P4	P5	P6	P7	P8	P9
Slant θ	74°	73°	74°	90°	90°	90°	106°	107°	106°
Tilt φ	73°	90°	107°	73°	90°	107°	73°	90°	107°

Table 1. Slant and tilt angles for the nine positions of the light source on the scene.

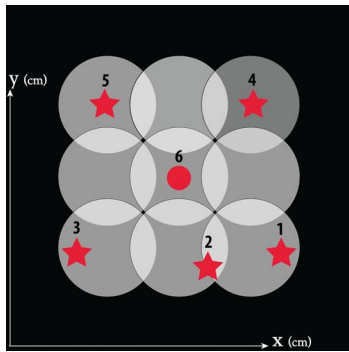


Figure 4. Illustration of the projected positions of the five shapes in Scene A. Number “1” represents the star body, number “2” the cylinder, number “3” the cross body, number “4” the pentagon body, and number “5” the bowling pin. The red disk in the center represents the position of the probe.

Experimental design

Four scenes were created with five shapes in each scene: a bowling pin, a cylinder, a pentagon body, a star body, and a cross body, as Figure 1 shows. Scene A was originally used in the experiment by Xia et al. (2013, 2014b). The bird’s-eye view of the projected position for each of the five shapes in Scene A is illustrated in Figure 4 with a red star. The probe was in the center of the box, marked in Figure 4 with a red disk. In Scene B, the position of the shapes was horizontally mirrored with respect to Scene A to test whether the layout caused the systematic contraction in estimated light position (see Figure 5). If so, the pattern of the estimated light positions should be mirrored as well. In Scene C, the bowling pin of Scene B was replaced by another pentagon body to test whether the contraction in estimated light position occurred because of the pentagon body. In Scene D, both pentagon bodies of Scene C were replaced by bowling pins to test whether the use of bowling pins could result in a more veridical estimation of the light position than the use of pentagon bodies.

This experiment was based on a between-subject design. It was divided into four sessions with a different scene per session. In each session, the light source was

displayed three times in each of the nine positions (see Figure 2), resulting in 27 trials.

There were 15 participants in each session. All participants had normal or corrected-to-normal vision. They all gave written, informed consent. All experiments were done in agreement with the local ethical guidelines, Dutch Law, and the Declaration of Helsinki and were approved by the TUDelft Human Research Ethics Committee (HREC).

Results

Figure 6 shows the average estimated position of the light source above the probe (pink disks) for the nine different positions of the light source above the scene (white disks). The error bars on the pink disks show the 95% confidence intervals. We also show the raw data in Figure 7 as scatter plots of the estimated positions of the light source in each scene, including the 50% prediction ellipses for each light source position. The results show that the pattern of the estimated light positions was indeed mirrored when the scene was mirrored (compare Scene A and Scene B). Scene C, replacing the bowling pin with another pentagon body, resulted in a systematic contraction of the estimated light position along the y-axis (slant angle) near both pentagon bodies. Scene D, replacing both pentagon bodies with bowling pins, finally resulted in estimated light positions close to veridical ones. Furthermore, we found that the variance of the estimated light position along the y-axis was always larger than along the x-axis (as evidenced by the error bars in Figure 6 and the shape of the ellipses in Figure 7).

Two 3 (row) \times 3 (column) repeated-measures analyses of variance (ANOVAs) were performed: one for the estimated distances along the x-axis and one for the estimated distances along the y-axis (hereafter referred as X-position and Y-position) of the light on the probe, for each of the four scenes separately. We found that in all four scenes, the estimated X-position was significantly influenced by the column, in which the light source on the scene was located: Scene A, $F(2, 88) = 420$, $p < 0.001$; Scene B, $F(2, 88) = 300$, $p < 0.001$; Scene C, $F(2, 88) = 423$, $p < 0.001$; Scene D, $F(2, 88) =$

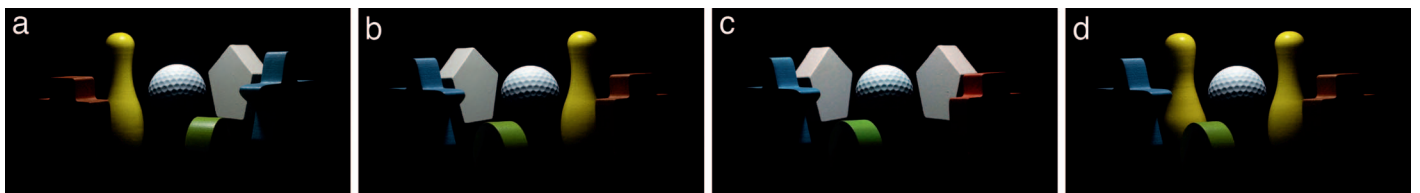


Figure 5. Four scenes, each consisting of five shapes (bowling pin, cylinder, pentagon body, star body, and cross body). (a) Scene A: original scene. (b) Scene B: horizontally mirrored version of Scene A. (c) Scene C: the bowling pin in Scene B was replaced by another pentagon body. (d) Scene D: both pentagon bodies in Scene C were replaced by bowling pins.

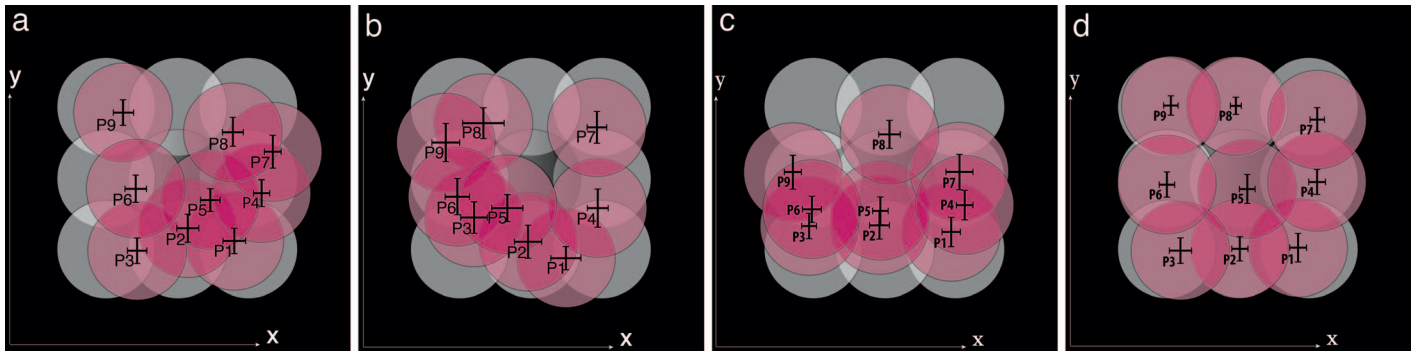


Figure 6. Illustration of the nine positions of the light source on the scene (white disks) and the corresponding average estimated position of the light source on the probe (pink disks) for (a) Scene A, (b) Scene B, (c) Scene C, and (d) Scene D. The error bars on the pink disks show the 95% confidence intervals (for $N = 45$ measurements).

629, $p < 0.001$. Similarly, the estimated Y-position was significantly influenced by the row: Scene A, $F(2, 88) = 164$, $p < 0.001$; Scene B, $F(2, 88) = 116$, $p < 0.001$; Scene C, $F(2, 88) = 69$, $p < 0.001$; Scene D, $F(2, 88) = 232$, $p < 0.001$. These results suggest that, generally, the observers were able to distinguish different light directions in all four scenes.

Nevertheless, the estimated light source positions were closer to the veridical ones in Scene D with the two bowling pins than in the other scenes, as shown in Figure 6 and Figure 7. Together with the finding that the average estimated light position was often contracted around the position of the pentagon body, we assumed that the globally spherical smoothly curved bowling pins, in comparison with the faceted pentagon shapes, helped the observers to perceive the veridical light direction.

Both Scenes C and D had a pair of the same objects (i.e., pentagon bodies and bowling pins) standing side by side in the scenes. The estimated light position along the x-axis in these two scenes was much closer to the veridical value than in Scenes A and B. According to a post hoc analysis, the absolute difference (AD) between the estimated light position and the veridical value (expressed in terms of distance in X for the position of

the light disk on the LCD screen) was significantly smaller for Scene C ($M = 1.81$, $SE = 0.08$) and Scene D ($M = 1.56$, $SE = 0.07$) than for Scene A ($M = 2.58$, $SE = 0.09$) and Scene B ($M = 2.90$, $SE = 0.11$). Thus, we conclude that symmetric arrangements within a scene improve the estimation of the tilt direction of the light source.

The results above showed that human perception of the light direction in a real scene was systematically dependent on scene layout and content.

Experiment 2: Which properties of shapes influence light direction estimation?

In Experiment 1, we have shown that the estimated light direction was influenced by the scene content and the scene layout. Furthermore, we found that scenes with a globally spherical smoothly curved bowling pin resulted in a more veridical estimation of the light direction than scenes with a faceted pentagon shape. This suggests that the bowling pin provides more

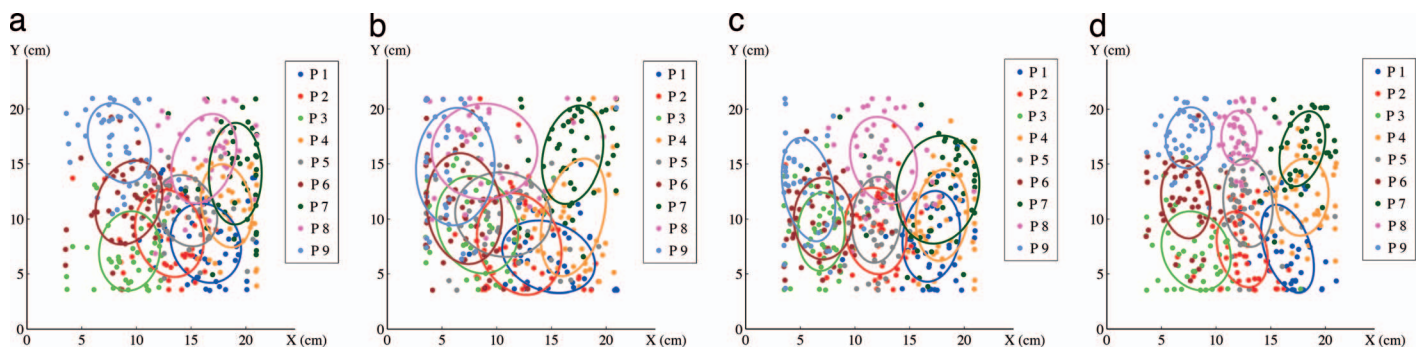


Figure 7. Scatter plots of the estimated position of the light source for 45 measurements in Scene A (a), Scene B (b), Scene C (c), and Scene D (d). Different colors represent the different light positions on the scene from P1 to P9 (as depicted in Figure 2). The 50% prediction ellipses for each light source position on the scene are given in the corresponding color.

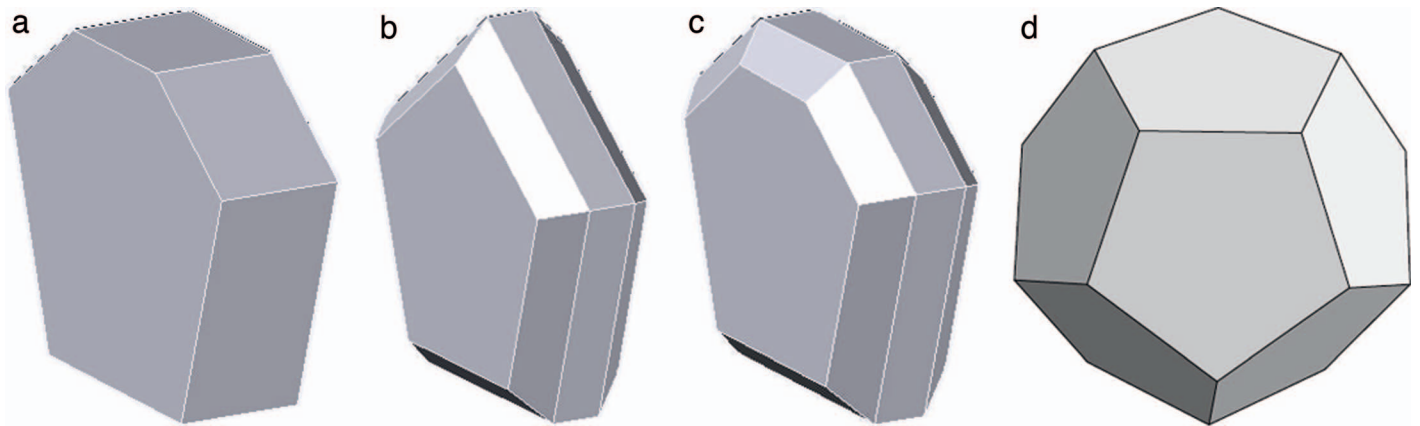


Figure 8. The four shapes used in Experiment 2. Shape I, II, and III were developed starting from the pentagon body by (a) cutting its top, (b) cutting its edges, (c) first cutting its top and then its edges, (d) Shape IV, a pentagonal dodecahedron with a globally spherical shape.

information about the light direction than the pentagon body. The bowling pin differs from the pentagon body in two ways. First, the bowling pin has a smoothly curved surface, which generates gradual shading gradients under our lighting, whereas the pentagon body has facets that generate stepwise shading variations. The second difference is that the bowling pin has a close to spherical shaped top, whereas the pentagon body is globally flattened. *Globally spherical* in this study refers to a convex geometry that has symmetrical shape variations approaching or subsampling a sphere, like the top part of the bowling pin. Otherwise, if a shape is wider and taller than deep (along the line of sight), we call it globally flattened, like the pentagon body. For a global spherical geometry, the surface normals are usually rather uniformly distributed across all directions.

As a consequence, two questions arise:

1. Will the estimation of the light direction become more veridical if the shape of the pentagon body remains globally flattened but the number of visible facets increases?
2. Will the estimation of the light direction become more veridical if another globally spherical shape is used but with a limited number of facets?

We designed Experiment 2 to answer these two questions.

Experimental design

We designed four new scenes in a systematic way. We kept the three shapes (i.e., the cylinder, star body, and cross body) in the front of the scene at the same position but added a pair of new matte and white painted wooden shapes in each of the four new scenes (see Figure 8). Shape I, Shape II, and Shape III were made starting from the pentagon body in Experiment 1, while cutting its top for Shape I, or its edges for Shape II, or both its top and its edges for Shape III. The number of perceivable facets gradually increased from Shape I, to Shape II, and to Shape III. Shape IV was a pentagonal dodecahedron with a globally spherical shape but a low number of visible facets as compared with Shape II and Shape III. As in Scene C and Scene D of Experiment 1, the new shapes were put side by side in the back of the scene, as shown in Figure 9.

Similar to Experiment 1, this experiment consisted of four sessions with a different scene per session. The light source on the scene was displayed three times in each of the nine positions (see Figure 2), resulting in 27 trials per session. The task of the participant was to adjust the direction of the light source on the probe to fit the light direction on the scene. This experiment was based on a within-subject design. The trials were randomly given in each session, and the order of the four sessions was also randomized for each observer.

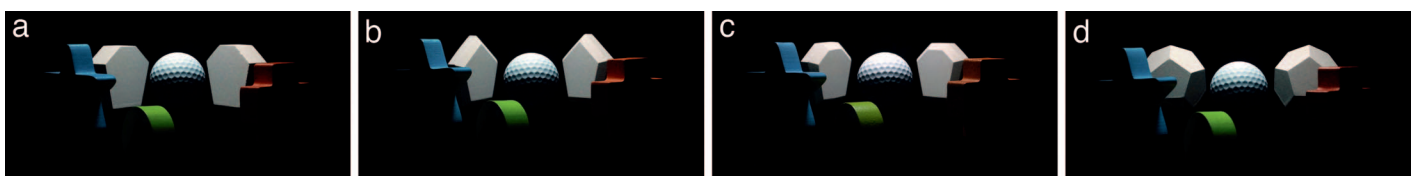


Figure 9. The four scenes used in Experiment 2. Within each scene, a pair of shapes put side by side in the scene: (a) Shape I in Scene E, (b) Shape II in Scene F, (c) Shape III in Scene G, and (d) Shape IV in Scene H.

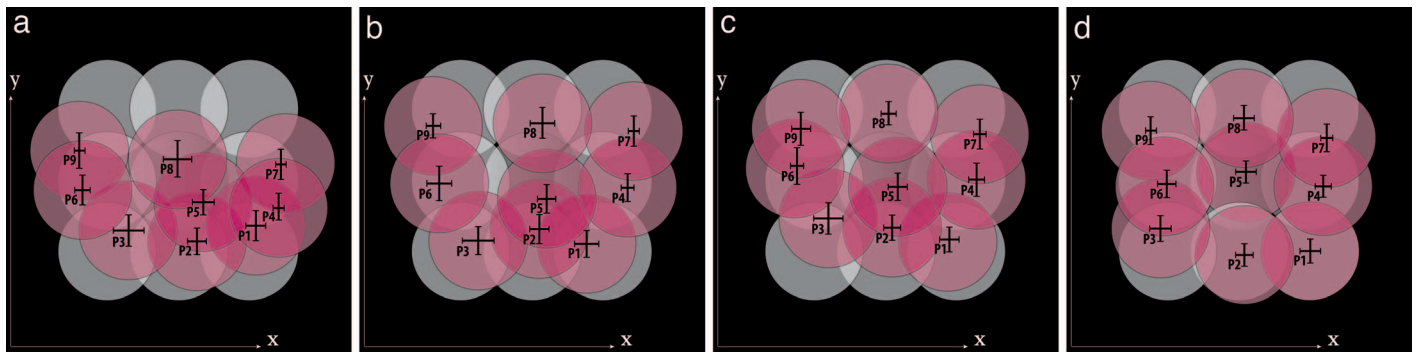


Figure 10. Illustration of the nine positions of the light source on the scene (white disks) and the corresponding average estimated position of the light source on the probe (pink disks) for (a) Scene E, (b) Scene F, (c) Scene G, and (d) Scene H. The error bars on the pink disks show the 95% confidence interval (for $N = 45$ measurements).

The observers could have a break between sessions. After all four sessions were completed, the participant was asked to rank the sessions from 1 to 4 based on the difficulty they experienced when doing the direction estimation, where 1 stands for the most difficult session and 4 for the easiest one.

Fifteen observers participated in this experiment. All participants had normal or corrected-to-normal vision. They all gave written, informed consent. The experiment was done in agreement with the local ethical guidelines, Dutch Law, and the Declaration of Helsinki and was approved by the TUDelft HREC.

Results

Figure 10 shows the average estimated light position on the probe side (pink disks) for the nine different positions of the light source on the scene side (white disks). The error bars on the pink disks show the 95% confidence intervals. The scatter plots of all raw data of the estimated light position on the probe are shown in Figure 11, together with the 50% prediction ellipses for each light source position in the scene. The results show

that, generally, the estimated position along the y-axis in Scene F, Scene G, and Scene H was closer to the veridical value than in Scene E. Furthermore, in general, the position along the x-axis in Scene H was closer to the veridical value than in the other three scenes, especially when the light source in the scene was in Position 1 and Position 3. The shape of the ellipses with more variance along the y-axis than along the x-axis indicates that the estimated slant angles spread wider than the estimated tilt angles.

Analysis on the estimated light positions

Two 3 (row) \times 3 (column) repeated-measures ANOVAs were performed, one for the estimated X-position and one for the estimated Y-position, for each of the four scenes separately. In all four scenes, the estimated X-position was significantly influenced by the column in which the light source on the scene was located: Scene E, $F(2, 88) = 855$, $p < 0.001$; Scene F, $F(2, 88) = 706$, $p < 0.001$; Scene G, $F(2, 88) = 598$, $p < 0.001$; Scene H, $F(2, 88) = 612$, $p < 0.001$. Similarly, the estimated Y-position was significantly influenced by the row in which the light source on the scene was located:

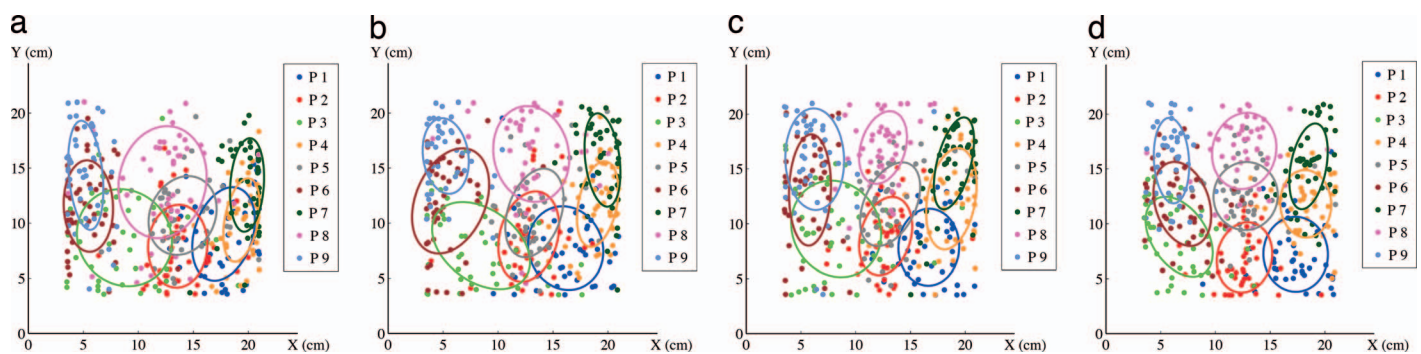


Figure 11. Scatter plots of the estimated position of the light source for 45 measurements in Scene E (a), Scene F (b), Scene G (c), and Scene H (d). Different colors represent the different light positions on the scene from P1 to P9 (as depicted in Figure 2). The 50% prediction ellipses for each light source position on the scene are given in the corresponding color.

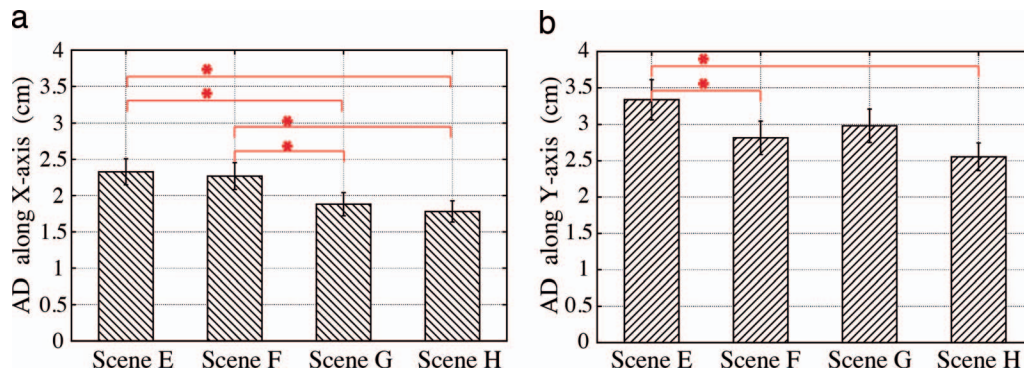


Figure 12. The average absolute difference (AD) between the estimated light position and the veridical one, as expressed in distance along (a) the x-axis (tilt angle) and (b) the y-axis (slant angle) of the light disk on the LCD screen. The paired bars marked with a red star were significantly different from each other according to the post hoc tests. The error bars show the 95% confidence intervals (for $n = 15$ observers \times 3 repeats \times 9 positions = 405 measurements).

Scene E, $F(2, 88) = 70$, $p < 0.001$; Scene F: $F(2, 88) = 139$, $p < 0.001$; Scene G, $F(2, 88) = 108$, $p < 0.001$; Scene H, $F(2, 88) = 236$, $p < 0.001$. Again, these results indicate that, overall, the observers were able to distinguish different light directions in our scenes. However, we also found an interaction between the row and column of the position of the light source on the scene for the estimated X-position in all four scenes: Scene E: $F(4, 176) = 24$, $p < 0.001$; Scene F, $F(4, 176) = 28$, $p < 0.001$; Scene G, $F(4, 176) = 17$, $p < 0.001$; Scene H, $F(4, 176) = 4$, $p = 0.004$. As already illustrated in Figure 10 and Figure 11, the estimated light position seems shifted more to the middle column in the front row than in the other rows.

To investigate the influence of the shape type on the estimated light direction, we calculated the AD between the estimated light position and the veridical one (expressed in terms of distance in X and Y for the position of the light disk on the LCD screen). Two 4 (scenes) \times 3 (row) \times 3 (column) repeated-measures ANOVAs were performed using the AD of the X-position and Y-position as a dependent variable. Figure 12 shows the average AD of the X-position and Y-position for each scene. The paired combinations marked with a red star were significantly different from each other according to the post hoc tests. The results show that the shape type significantly affected the AD of the X-position, $F(3, 132) = 9.33$, $p < 0.001$. The post hoc test revealed that the ADs in X-position of Scene G ($M = 1.88$, $SE = 0.081$) and Scene H ($M = 1.78$, $SE = 0.074$) were significantly smaller than that of Scene E ($M = 2.27$, $SE = 0.094$) and Scene F ($M = 2.33$, $SE = 0.091$). This indicates that the estimated direction was significantly improved in Scene G and Scene H. The results also show that the column in which the light source on the scene was located had a significant effect on the AD in X-position, $F(2, 88) = 8.73$, $p < 0.001$, such that the AD in the middle column ($M = 1.77$, $SE = 0.084$) was significantly smaller than in the left ($M =$

2.13, $SE = 0.057$) and right ($M = 2.29$, $SE = 0.079$) columns. In other words, the estimated tilt angle in the middle column was closer to the veridical tilt angle than the estimated tilt angle in the other two columns. Also, the AD of the Y-position was significantly influenced by the shape type, $F(3, 132) = 5.71$, $p = 0.001$, such that the AD in Scene E ($M = 3.34$, $SE = 0.139$) was significantly larger than in Scene F ($M = 2.82$, $SE = 0.117$) and Scene H ($M = 2.55$, $SE = 0.097$). This indicates that the observers had the worst performance, inferring the slant angle in Scene E, characterized by the object with the smallest number of faces. We also found a significant influence of the column on the AD of the Y-position, $F(2, 88) = 5.84$, $p = 0.004$. The middle column had a significantly smaller AD in the Y-position ($M = 2.72$, $SE = 0.101$) than the left column ($M = 3.18$, $SE = 0.103$), which implies that the estimated slant angle in the middle column was significantly closer to the veridical slant angle than the estimated slant angle in the left column.

Thus, altogether we found that the estimated direction became more veridical from Scene E and Scene F to Scene G (i.e., as the number of perceived faces on the object increased). Scene H, with two globally spherical pentagonal dodecahedrons, gave the most veridical estimation of the light direction. The globally spherical pentagonal dodecahedron in Scene H had five visible faces, which was more than that of Shape I in Scene E but less than Shape II and Shape III in Scene F and Scene H. This indicates that, apart from increasing the number of the perceivable faces, the global sphericity resulted in a more veridical estimated light direction as well.

Analysis on variance between estimations

Besides comparing the estimated light direction with the veridical one, we here analyze the spread in the estimated light direction (again expressed as X- or Y-

Scenes	Ranked as 1 (most difficult)	Ranked as 2	Ranked as 3	Ranked as 4 (easiest)
Scene E	12	1	0	2
Scene F	0	7	6	2
Scene G	2	6	7	0
Scene H	1	1	2	11

Table 2. Ranking order of the experienced difficulty in estimating the light directions for Scene E, F, G, and H over 15 observers. *Notes:* The smaller the ranking order, the more difficulty the observers encountered.

position) between the participants. The standard deviation of the estimated light position was calculated for each scene and each position of the light source on the scene separately. The scenes were mutually compared using paired-samples *t* tests. For the estimated X-position (i.e., the tilt angle), no statistically significant difference in standard deviation was found between any of the two scenes. For the estimated Y-position (i.e., the slant angle), we found that the standard deviation of Scene H ($M = 3.05$, $SE = 0.10$), compared with Scene E ($M = 3.69$, $SE = 0.15$), Scene F ($M = 3.53$, $SE = 0.11$), and Scene G ($M = 3.58$, $SE = 0.18$), was in all cases significantly smaller: Scene H-E, $t(8) = -5.46$, $p = 0.001$; Scene H-F, $t(8) = -3.56$, $p = 0.007$; Scene H-G, $t(8) = -3.422$, $p = 0.009$, but no significant difference in standard deviation was found between Scene E, Scene F, and Scene G. This result indicates that the globally spherical shape used in Scene H significantly decreased the variation in estimated slant angle compared with the faceted pentagon body used in the other scenes.

Subjective reports on the experienced difficulty

The observers were asked to rank the scenes from 1 (most difficult) to 4 (easiest) according to the difficulty they experienced when doing the task. Table 2 shows the ranking order of the four scenes over all observers. Scene E was reported as the most difficult scene more frequently than the other three scenes. Scene H was reported as the easiest among all four scenes. In general, this result was consistent with the observers' performance (in terms of veridicality) on estimating the light direction in the four scenes.

Discussion and conclusions

The aim of this study was to investigate the potential effects of scene content and layout on the perceived light direction in an interior space. It should be noted that this research was performed using a viewing box. If the observers would be able to really enter the scenes, they might get more information about the light

direction from, for instance, thermal effects of infrared radiation or intraocular light scattering (Van den Berg, 1986). In this study, two experiments were designed, with the first one studying whether this kind of influence exists and the second one studying which properties of the objects in the scene influence the light direction estimation in a systematic way.

We found that observers were sensitive to the light direction (the light direction was parameterized as light source position in our specific experimental setup), but its veridicality was dependent on the scene content and layout. Generally speaking, both increasing the number of visible faces of the objects and using globally spherical shapes in the scene resulted in more veridical estimations of the light direction. Furthermore, arranging scenes symmetrically improved the observer's inference of the light tilt direction.

We see two candidates for cues that help the estimation of the light direction. The first cue is the shading variation over the objects' surfaces, and the second cue is the "illuminance flow" over the scene (i.e., the spatial variation in brightness over the scene due to illumination). The number of visible faces of the objects increased from Shape I to Shape II and Shape III, generating more steps in the shading pattern over the objects, which resulted in a more veridical estimation of the light direction. Khang et al. (2003) found that increasing numbers of faces on 3D shapes was helpful for the interpretation of the surface reflectance variations on the shapes. To discriminate the reflectance variations, the shading effect derived from the interaction between the geometry and lighting should be taken into account. Our results directly showed that the light direction estimation could benefit from increasing the number of faces. Furthermore, we found that a globally spherical shape resulted in a more veridical estimation of the light direction than more flattened shapes. Because our probe was also globally spherical, a reason might be the fact that the shading patterns were more comparable for this case than for the flattened shapes. Alternatively, estimation of the light direction from a shape can be expected to depend on that shape, similar to the finding of Koenderink et al. (2007) that observers' detection of light direction was systematically confounded with surface structure (e.g., comparing light direction estimation for isotropic rough surfaces with that for anisotropic rough surfaces). Let's take as an example an extreme case of a flattened shape, like a piece of paper. In such a case, observers can detect whether the light source is in front of the paper or behind the paper but not from which direction the light comes exactly. The surface normals of a globally spherical shape are sampled rather homogeneously across all directions. In combination with a prior for global convexity (Langer & Bulthoff, 2001) this could result in more veridical estimates.

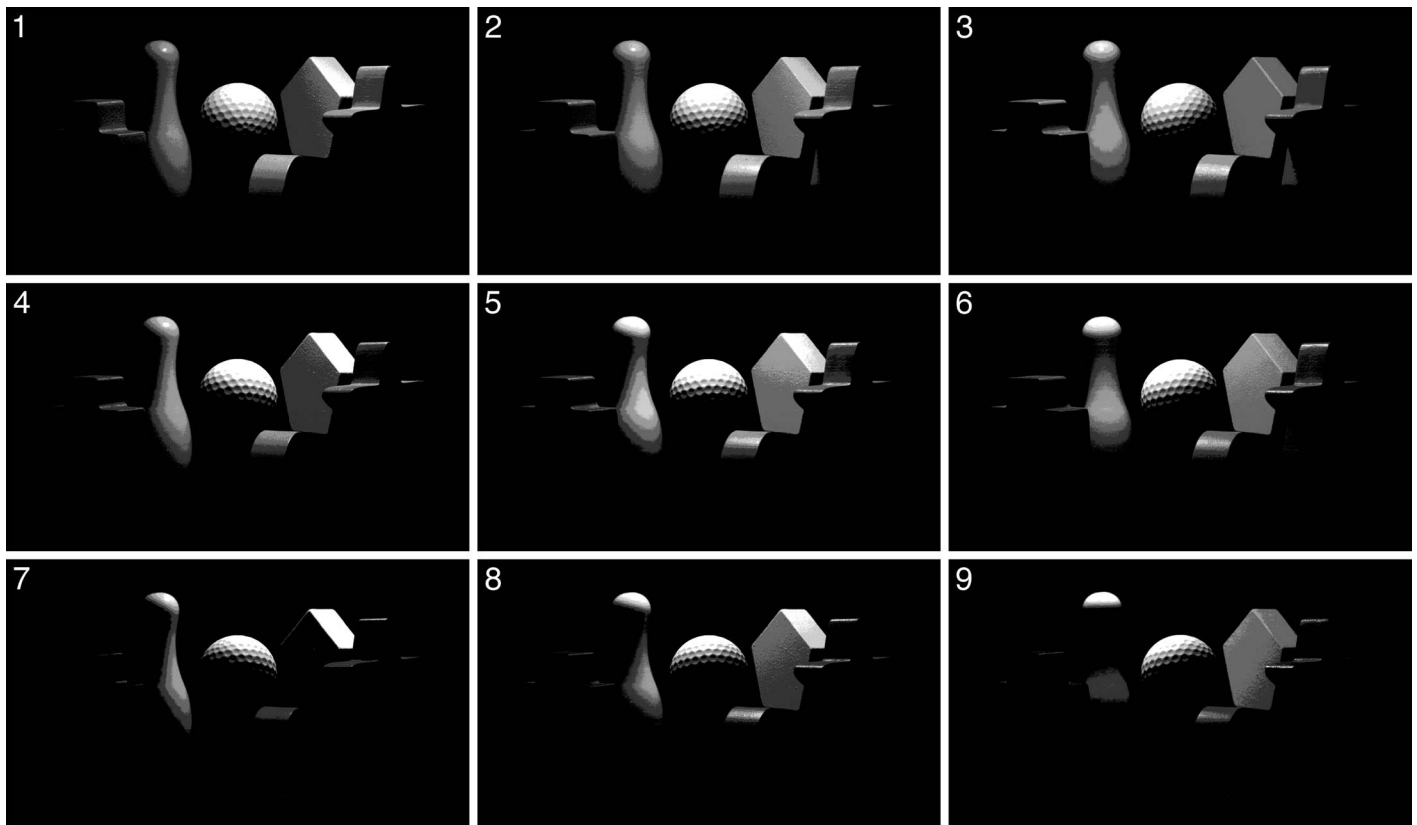


Figure 13. Photographs of the optical mixtures of Scene A with the probe under nine light directions from P1 to P9 (shown in Figure 2). Note that the image was converted to grayscale and posterized from 255 to 6 gray levels.

The second candidate cue concerns the “illuminance flow” over the scene (Koenderink et al., 2007; Pont & Koenderink, 2004). The variation of illuminance on the macroscale is usually denoted as “shading.” The illuminance flow provides additional cues about the light direction to the shading. We found that mirror arrangements in the scene improved the estimation of the tilt direction, and tilt angles were consistently estimated with a smaller spread than slant angles. These two phenomena can be explained using the illuminance flow theory. The illuminance flow is used to describe the 3D texture variation due to illuminated surface meso relief and can also be estimated from arbitrary natural images (Pont & Koenderink, 2004). Xia et al. (2014b) proved that the illuminance flow over a rough sphere was helpful in estimating the light direction in real scenes. Figure 13 shows photographs of the optical mixtures of Scene A with the probe under the nine light directions, P1 to P9. These photographs were converted to grayscale and posterized from 255 to 6 gray levels to more clearly show the orientation of the spatial pattern in brightness gradient due to the “illuminance flow.” We can see that it is difficult to estimate the depth of the light source (i.e., the slant angle) due to the lack of depth information, whereas the shadow patterns (e.g., the pattern of shadow edge

orientations) give salient information about the tilt angle.

To summarize, a human being’s light direction perception can be influenced by the scene content and layout in a space. The interplay between the lighting and the furnishing of a room (i.e., its materials, geometries, and the arrangement of content inside) shapes the architectural space and the light field in it (Hunter, Biver, & Fuqua, 2007; Michel, 1995; Van Doorn, Koenderink, & Wagemans, 2011). Human beings see the resulting scene in this space as a whole. Humans are able to distinguish the basic properties of lighting, shapes, and materials through millions of years of evolution. But image ambiguities cause perceptual interactions because light, material, shape, and space perceptions are truly confounded (Belhumeur et al., 1999; Dror et al., 2004; Inanoglu, 1973; Ramachandran, 1988; von Castell, Oberfeld, & Hecht, 2014). Thus, studying what human observers are capable of in extracting the basic properties of light, material, shape, and space should be done in an integrated manner.

Keywords: visual light field, light direction, real scenes, shapes, materials, scene content and layout

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