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Facilitatory mechanisms of specular highlights in the perception of depth

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A B S T R A C T

We investigated whether specular highlights facilitate the perception of shape from shading in a search paradigm and how highlights interact with shading to facilitate this perception. Our results indicated that stimuli containing highlights led to shorter searching time with the dependence on the light source direction (top lights make searching faster), suggesting that highlights indeed facilitate shape-from-shading processing. To examine how highlight processing interacts with shading processing, we tested unnatural stimuli for which the lighting directions for shading and highlights were inconsistent. The results indicated that unnatural highlights (bright spots) placed in a direction inconsistent with the shading either decrease or do not alter searching time. This suggests that highlights may facilitate, and not suppress, shading processing. With more physically plausible highlights generated from image-based lighting, we also observed facilitation with consistent highlights, but no change with inconsistent highlights. Finally, we examined whether highlights indeed work to facilitate depth perception in a discrimination task. The results showed that correct discrimination of depth increases when highlights are added to shading even when their lighting directions are inconsistent. These results indicate that specular highlights facilitate shading processing, and do not suppress it even when the highlights are placed in a direction inconsistent with shading. The results also elucidate the lighting constraints of the visual system.

1. Introduction

Specular highlights have substantial effects on the perception of shape, depth, and surface appearance. For example, a smear of white on a shaded image, called "pointillé" in oil painting, greatly enhances the perceived reality of a shape in addition to improving its surface appearance. Psychophysical studies have reported that simple specular highlights facilitate the perception of curvature and shape (Norman, Todd, & Orban, 2004; Nefs, 2008). Recently, Wijntjes et al. (2012) showed that the elimination of specular highlights from shading (matte and velvet surfaces) degrades the perception of shape. Controversially, other studies have reported that specular highlights do not facilitate the perception of the detailed structure of a three-dimensional (3D) shape. Instead, they claim that the perception of a detailed shape (surface normals) as measured by a "needle probe" depends on a bidirectional reflectance distribution function (BRDF) and lighting, but not on specular highlights and surface glossiness (Nefs, Koenderink, & Kappers, 2006; Khang, Koenderink, & Kappers, 2007). However, these experiments used stimuli that included other cues, such as complex contours and textures, which may complicate cue integration and veil the interaction between highlights and shading. The present study focused on whether specular highlights facilitate shading processing, and if so, how highlights interact with shading to facilitate perception.

An image projected onto the retina is determined by lighting, surface reflectance, and object shape. Although the appearance of shading and highlights significantly differ, shading and highlights, the diffuse and specular components of a reflection, simultaneously exist in nature except for the extreme cases of matte and mirror. They share the same constraints of lighting and shape. Understanding how the visual system processes shading and highlights in shape perception and how it utilizes their coexistence under the same constraint would shed light on the mechanisms of integration, and further on the neural mechanisms that solve the ill-posed problem of the simultaneous estimation of lighting, reflectance, and shape.

Psychophysical studies using a search paradigm have shown a crucial constraint of lighting in shape from shading (e.g., Ramachandran, 1988; Aks & Enns, 1992; Kleffner & Ramachandran, 1992). It was observed that targets pop out from distractors with a light-source direction that is the opposite of

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the target's. The time used for searching for targets is a function of light-source direction; that is, detection is fast with top-left lighting and slow with lateral lighting (Sun & Perona, 1998). This dependence is considered evidence for the light-from-above constraint in shape from shading. Champion and Adams (2007) reported that the preference for overhead lighting was not modifiable by training, which is consistent with the involvement of the constraint in pre-attentive processing.

We investigated whether specular highlights facilitate shading processing in searching time, and if so, how highlights interact with shading to do so. We utilized the light-direction dependence of searching time as an indication of shading processing. The changes in searching time and light-direction dependence, for a combination of shading and highlights, would provide evidence for the integration process of the two cues. If we observe light-direction dependence when highlights are added to shading, this suggests that highlights work, as they facilitate shading processing. Alternatively, if the dependence disappears or weakens when highlights are added, this suggests that highlights are processed independently from shading. Our results showed light-direction dependence and less searching time, suggesting that highlights work, as they facilitate shading processing (Experiment 1).

To examine further how highlight processing works with shading processing, we tested unnatural stimuli for which lighting directions for shading and highlights were inconsistent (Experiment 2). With inconsistent lighting, the perceptual degree of glossiness appeared to decrease, and the highlights could appear as bright spots (a change in albedo). The results showed light-direction dependence without an increase in searching time, suggesting that inconsistent highlights do not suppress shading processing. The results further indicated that low-level differences in the stimuli, such as the location and contrast of bright spots, do not account for searching time. Additional experiments (Experiment 3) showed the same results for image-based highlights in which the shape of the light source is visible on an object. Finally, to ascertain whether the highlight has a facilitative function in the perception of depth, we conducted experiments with a depth-discrimination task using random surfaces (Experiment 4). The results showed that the correct response rate increases when highlights are added to shading, even if their lighting directions are inconsistent so that they do not fully contribute to the perception of glossiness. These results indicate that specular highlights have a facilitative function in the perception of depth, not a suppressive function, even when the light sources are inconsistent between highlights and shading.

2. Experiment 1

To examine whether specular highlights facilitate shading processing, we utilized a search paradigm (e.g., Ramachandran, 1988; Aks & Enns, 1992; Kleffner & Ramachandran, 1992). The searching time and its light-direction dependence are expected to illustrate the characteristics of highlights. If we observe the light-direction dependence with less searching time when highlights are added to shading, it suggests that highlights work, as they facilitate shading processing.

2.1. Method

2.1.1. Stimuli

The stimuli were an array of 25 spheres generated by computer graphics (Open GL 2.1), as shown in Fig. 1(A). The visual angle of each sphere was 1.0°. The spheres were placed on a 5 × 5 grid with or without small random displacements of up to 0.37° in visual angle. Shading of spheres was rendered with a Phong model as they were illuminated by a single light source and ambient light. The strength of diffuse and ambient reflectance was set constant

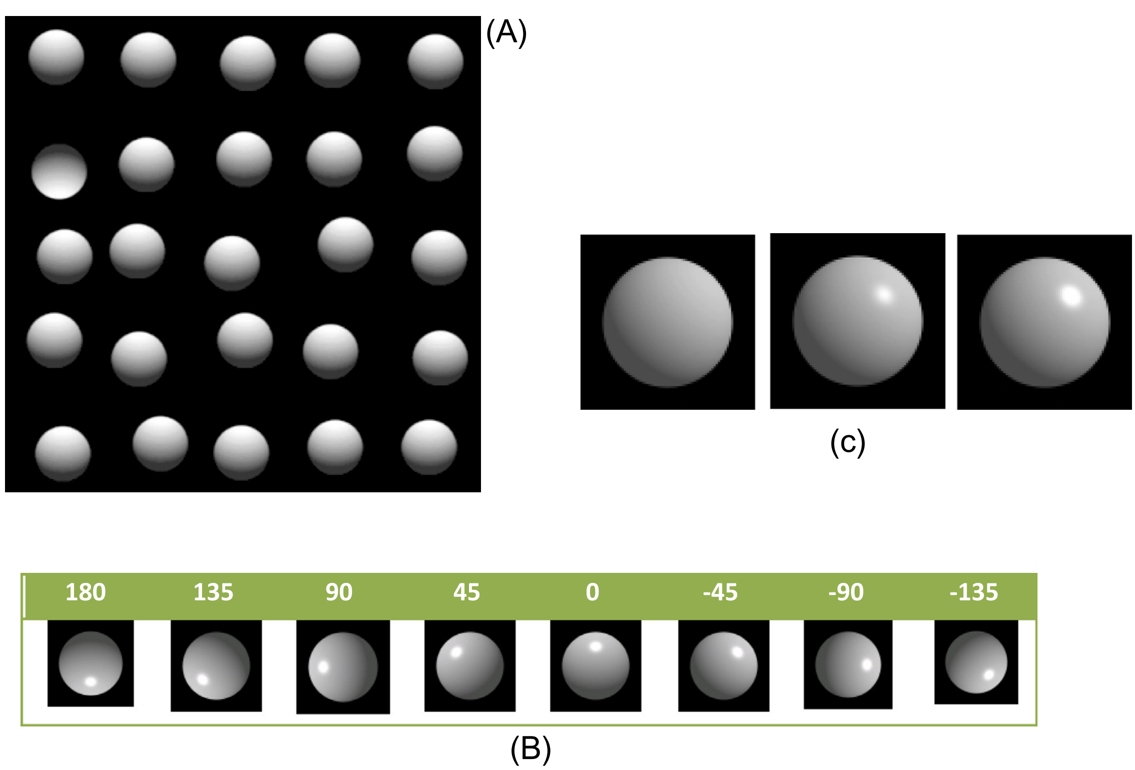

Fig. 1. (A) An example stimulus with 25 spheres. Participants were asked to judge as soon as possible whether a target existed in the stimulus. (B) The direction (tilt) of the light source varied between −135 and +180°. (C) Examples of stimuli with no highlight (left), weak highlight (middle), and strong highlight (right).