Solid Perception Effected by Spatial Frequency Components in a Shaded Pattern: Spatial Frequency Component in a Corrugated Wave Pattern

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The purpose of illumination is to allow solid perception to be obtained and depicted by a shaded pattern produced by lighting. The shading cue, as one of solid perception cues, was investigated, using a computer graphic device: Tospix-2. The corrugated wave was chosen for a test pattern, because an alternately bright and dark pattern, produced by shading, could be conveniently analyzed into contained spatial frequencies. This paper reports spatial frequency properties contained in the shading pattern. The shading patterns, which were actually shaded or were produced by computer simulation, were analyzed by Fourier Transformation by the same device. The result of the analysis indicates that the third through higher harmonics components are important. For observation of a solid shape, flat planes are assumed to be on the bottom of the completely curved solid perception. As apparent evidence for this assumption, under difficult visual conditions, a flat paneled figure was seen, in spite of the curved solid.

1. Introduction

One purpose of lighting is obtaining solid perception by shading. This paper reports the results of investigation about solid perception caused by shading, analyzing spatial frequencies contained in a shaded pattern, using a corrugated wave shape. A corrugated wave shape was used, because it was easy to investigate the spatial frequencies contained in a shading pattern.

A shading pattern was input into a computer graphic device: TOSPIX-2. The computer was used for Fourier Transformation, Filtering, Inverse Fourier Transformation and other purposes. Spatial frequencies effecting on solid perception were investigated. In this paper, a main frequency is defined as a spatial frequency originated from the object's frequency. The frequency analysis result indicated that the third through higher harmonics components were important for getting a solid perception. Sakata¹⁾ reported that a sinusoidal pattern, on which nothing was superimposed, was seen as

only a stripe and was not seen as a solid object. A sinusoidal pattern, superimposed by a low-contrast edged pattern was seen as a solid object. However a sinusoidal pattern, superimposed by a high-contrast edged pattern was seen as a flat plane. The third through higher harmonics components, indicate the position where the luminance changed largely. The space between the two edges, derived from the higher harmonics, indicates the plane having the same side facing the light direction, when the light direction is previously known.

Mingola²⁾ reported that a curved surface was seen as a flat panel, when visual conditions were insufficient. When the pattern is shrunk in the device, or when deep shadow is incurred, a slight illuminance difference is difficult to detect. Under these conditions, the pattern is not perceived as a perfect solid object, but as a object constructed from flat panels or a stripe. From these results, the following assumption is proposed, wherein solid perception by shading is derived from two procedures. One procedure is where a solid object, constructed from flat panels, is imagined by the higher harmonics components. Another procedure is for the curved surface to be imagined by the lower harmonics components. The complete solid perception is obtained by a

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combination of these two results.

2. Method

The illumination system used for the experiment is illustrated in Fig. 1. The test object is shown in Fig. 2.

A shading pattern is produced by the 20 degree or 45 degree incidence angles illumination, subtended to the normal direction of the object. The distance between an object and the light shedding lamp was 300mm. The pattern was input into the computer by a TV camera, located 400mm from the object. The main spatial frequency of the input pattern was 0.2cpd (cycle per degree).

When a seeing experiment is carried out, the pattern is exhibited again on TOSPIX-2 display as a test pattern. A function for correcting the linearity between the actual object luminance and the displayed luminance, is programed in the computer. The displayed pattern is pre-

Fig. 1 Illumination system; test object, bulb, and TV camera

Fig. 2 Corrugated wave used for test object

sented as a 165mm square shape, with 512 dots on length and breadth parameters, and with about 60 candles per square meter monochrome average luminance. Luminance was changed in 256 levels. The seeing experiment was carried out with a subject whose head was fixed on a chin rest, 400mm from the display. All the system was placed in a dark room.

Fourier Transformation and Inverse Fourier Transformation were carried out for input patterns by FFT program sampling at 256 points. The minimum spatial frequency, analyzed by the FFT procedure³, is about 0.1cpd. The maximum spatial frequency is about 10cpd.

The thickness of imagined solid object was measured by a device whose 8mm diameter white bar extruded from a plane. This device is able to be adjusted to the same apparent thickness as the pattern. Fig. 3 shows the device whose bar tip is reflected on a round mirror. The pattern and the bar were observed with two eyes.

Fig. 3 Extruded bar device used for solid perception scale; Tip of the extruded bar is reflected by a round mirror

Two subjects, N.N. and K.K., participated in the experiment. One is a 50 year old man, N.N.. His 5 meter visual acuity is 1 for his left eye and 0.5 for his right eye. However, his solid perception was normal during the experiment, in spite of his visual irregularity. The other was a 24 year old man, K.K.. His 5 meter visual acuity is 1.5 for both eyes. His visual properties were normal.

3. Results

3.1 Solid shape measurement

The imagined shape of the pattern displayed on TOSPIX-2 was measured, using the following procedure. At the beginning, tangential directions were measured at sampled measurement points. Then, an imaged curve was obtained by following the tangential directions at the points, as shown in Fig. 4. The shading pattern at a 45 degree incidence angle was imaged as a

Fig. 4 Estimated shapes from shading patterns Top picture illustrates estimating procedure

deformed shape, because of the dark shadow. However, the curved part in the object was rather easily perceived, when a slight luminance difference was detected.

3.2 Spatial frequency components

3.2.1 Spatial frequency analysis for a pattern

Therefore, spatial frequency components were analyzed by the computer. The pattern was divided into frequency components by Fourier Transformation.

The deformed imaged shape was caused by the luminance distribution. Therefore, the origin of the deformed shape imagination was considered to be in the pattern itself.

Then, the higher or lower components were filtered at the spatial frequency varied with 0.1cpd steps. At last, a new pattern was obtained by Inverse Fourier Transformation from the residual components. The regenerated patterns, aligned along the horizontal axis of spatial frequencies, are shown in Figs. 5 and 6. The third harmonic component for the main frequency seems to be the most important for the shape visualization as the key spatial frequency component.

Fig. 5 Regenerated patterns from low and high harmonics components and their luminance distribution (incidence angle: 20 degrees)

Fig. 6 Regenerated patterns from low and high harmonics components and their luminance distributions (incidence angle: 45 degrees)

3.2.2 Shrinking patterns

The imaged pattern was investigated in regard to a shrunk pattern, in which spatial frequencies became higher. The used pattern was obtained from the 45 degree incidence angles illumination. From 1cpd to 2cpd, the imaged shape began to be seen as shallower than the lower frequency pattern. Around 3cpd, a plane figure

Fig. 7 Surface inclination angles on imaged objects whose patterns are shrunk. Symbol size is about 1SD.

was imaged. At over 4cpd, the imaged shape was only a stripe and had no solid visual representation. Surface inclination angles on the imaged objects decreased owing to the main frequencies, as shown in Fig. 7.

3.3 Solid perception by generated patterns

The third through higher harmonics components are important for shape perception and also solid perception. Two kinds of patterns, generated by the computer, were investigated. One was a sinusoidal pattern with an edged pattern superimposed. Another was the simulation pattern calculated for the assumed corrugated wave by Ray Tracing method⁵.

Figure 8 shows the sinusoidal patterns with various amounts of higher harmonics components superimposed thereon.

Another experimental patterns were designed to emphasize the luminance change. The waves were constructed with two radii: 10mm and 20mm and pitch: 32mm, changing amplitudes of the waves: 3, 6, 10, and 20mm. The lighting simulation was implemented by the incidence angles: 10 degrees. Figure 9 shows the simulated patterns.

Fig. 8 Sinusoidal patterns with higher harmonics components superimposed
Upper: Most superimposition
Middle: Appropriate superimposition
Lower: No superimposition

4. Discussion

Nagata⁶⁾ reported that solid perception by shading was weak or disappeared, when the pattern was symmetrical. The reason for the weak solid perception, partially depends on symmetry of the pattern. However, another reason seemed to exist.

Based on this background, a more fundamental reason will be discussed. Higher har-

Fig. 9 Simulated patterns: Up to down, calculation amplitudes are 3, 6, 10 and 20 mm

monics components come from the large luminance difference in the actual shading pattern. The dark image is emphasized by incident angle increase or original wave amplitude increase (Fig. 10). Further, the luminance distribution causes deformation, which was imaged like the thickness variation in Fig. 11. Thicknesses at every measurement points, are converted into the thicknesses at the original object's frequencies. The luminance distribution deformation causes higher harmonics components increase. Therefore, these luminance distribution deformations, are proof of the shading pattern produced by actual illumination. In nature, a truly sinusoidal pattern, due to shading, does not seem to exist for an actual corrugated wave. In general, a pattern, regenerated from higher harmonics components, is like an edged pattern. The space between the edges indicates the side, either lighted or shaded, but there is no information about the curved surface. In words, edged patterns seem to indicate the slant of the flat panels, if the light illumination direction is previously known.

On the other hand, the curved plane information is assumed to be obtained from the lower harmonics components.

In this discussion, the 1st and the 3rd harmonic components are used, since the 1st and the 3rd harmonic components can be detached from the noise components, assuredly but with difficulty. The most curved surface is imagined between 10 and 20 percent content rate of the 3rd harmonic component, in regard to the 1st harmonic component (the main frequency

Fig. 10 Luminance change increase: pattern and luminance distribution;
 Upper: Original pattern; amplitude: 6mm
 incidence angle: 10 degrees
 Lower Left: incidence angle increase to 20 degrees but shape is
 same as original
 Lower Right: Amplitude increase to 10mm but incidence angle is
 same as original

Fig. 11 Imaged thickness in regards to assumed wave amplitude.

component), as shown in Fig. 12. The reciprocal value of the most desirable content rate becomes a rather high value. This indicates that the 1st harmonic component (the main frequency component) is important for the curved plane imaging. Then, the following assumption is proposed for solid perception. One procedure is to determine a solid object, constructed from flat panels, derived from the 3rd through higher harmonics components above 1-2cpd spatial frequency. Another procedure is to determine the curved surface, derived from the lower harmonics components under about 1cpd spatial frequency⁷⁾ (Fig. 13).

Evidence for this assumption is following. A solid object, constructed from flat panels or only a stripe is seen, when the shading pattern is observed under insufficient visual conditions

Fig. 12 (3rd harmonic component/1st harmonic component) vs Imagined amplitude measured by extruded bar scale
In the figure, "D" expresses a simulation pattern and its attached numbers indicate the wave amplitude. "Sin" expresses a sinusoidal pattern and its attached figure indicates amounts of edged pattern and its attached

or when a pattern is shrunk, resulting in a spatial frequency shift to a higher value.

5. Conclusion

Computer graphic device: TOSPIX-2 was used for the investigation in regard to solid perception about the corrugated wave shapes. Experimental results indicate that the 3rd through higher harmonics components, above about 1-2cpd spatial frequencies in the pattern, are important for shape and solid perception.

Solid perception by shading is assumed, following the visual mechanism.

- (1) The higher harmonics components indicate the aspects of the assumed planes, relating to the light direction, and present a plane figure as in architecture.
- (2) The curved surface perception is added on the plane, from the information on lower harmonics components under the 2nd harmonic component.
- (3) The complete solid perception is induced, when these two spatial frequency components exist.

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Fig. 13 Human visual neural system.
Human being perceives a solid shape by two independent neural path ways, which are consisted of Parvo-interblob and Magno

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