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A CRAIK–O'BRIEN–CORNSWEET ILLUSION FOR VISUAL DEPTH

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Abstract—A stereo analogue of the Cornsweet luminance illusion was discovered, and measured by a null method. Two flat vertical textured surfaces in the frontoparallel plane met at a vertical boundary, at which the left-hand surface curved slightly forward and the right-hand surface curved back by an equal amount. The protruding left edge was jointed to the receding right edge by a step. Result: although the two flat surfaces were equidistant, the left surface appeared to be about half a centimetre nearer to the observer than the right surface.

In the Craik–O'Brien–Cornsweet illusion, two fields of equal luminance meet at a border whose luminance profile is shaped like a double spur (Fig. 1a). As a result, the whole of the right field appears brighter than the whole of the left field (Craik, 1966; O'Brien, 1958; Cornsweet, 1970). This illusion is probably caused by lateral inhibition between visual channels sensitive to retinal luminance. The spur-shaped profile can be thought of as a luminance ramp downwards (light to dark), superimposed on a spatial luminance step upwards (dark to light)(Fig. 2). The illusion can be produced by projecting the spur-shaped pattern shown in Fig. 3(a), with the projection lens covered by a strong cylindrical lens which astigmatizes or smears the picture vertically. The astigmatizing lens converts the vertical height of any aperture in the slide into a long vertical zone of appropriate luminance, because the wider the slit in a vertical direction, the greater the luminous flux. Thus, the geometrical pattern of the white bar in Fig. 3(a) is converted into a pattern of light density: a contour profile is converted into a luminance profile. In practice, it is convenient to use a sheet of horizontally ribbed or beaded Plexiglas (lenticular screen from Lamac International, 12 West 18th St, New York, NY 10011, price about £3). This material is a Fresnel cylindrical lens, like an optician's "Maddox rod". The technique is further described by Anstis and Comerford (1975) and Anstis (1976). Figure 3(b) is identical to 3(a), except that the right-hand half of the bar has been

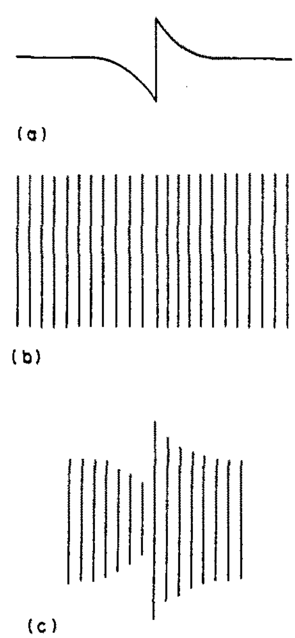

Fig. 1(a). The distribution of luminance that gives the Craik-O'Brien–Cornsweet illusion. (b) (After Mackay, 1973) Illusory distribution of line spacings. Lines on the right look more closely spaced than lines on the left. (c) (After Crovitz, 1976) Illusory distribution of line lengths. Lines on the right look longer than lines on the left.

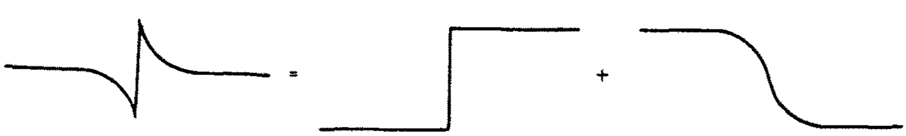

Fig. 2. Showing how a spur-shaped luminance profile can be thought of as a downwards ramp superimposed on an upwards step.

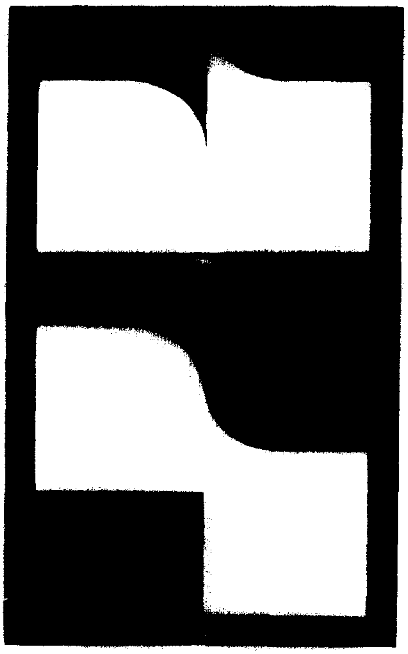

Fig. 3. A spur-shaped luminance display may be produced by projecting a slide of (a) through a graticule of cylindrical lenses. (b) produces the same luminance profile as that produced by (a) when projected in the same way.

slid downwards to give a smooth curve along the top. This gives exactly the same luminance profile when astigmatized as Fig. 3(a), but shows more clearly how the downward luminance ramp is superimposed on the upward luminance step. Inhibitory interactions would lead to a disproportionate weight being given to the sharp step discontinuity of luminance and to less weight being given to the gradual spatial luminance ramp. Overall, the spur-shaped boundary gives the subjective impression of a net shift upwards in luminance (dark to light), making the right field appear brighter than the left field.

A second component in the illusion may be that the brightness information at the contour region is extrapolated by the visual system across fairly large areas bounded by the contours (Ratliff, 1965). The processes acting at the contours of bounded surfaces produce long-distance modulation of brightness some distance from contours (Crovitz, 1976).

An analogous illusion has recently been reported for spatial frequencies (Mackay, 1973) and for length of lines (Crovitz, 1976). Mackay (1973) found an illusory spatial frequency shift in a frequency modulated grating of vertical bars presented on a CRO screen. The spatial frequency of the grating was electronically modulated by a spur-shaped form (Fig. 1b). This produced border contrast effects in the spatial-frequency domain, giving rise to illusory spatial-frequency shifts near discontinuities of texture density. This phenomenon may indicate a gradient-enhancing process acting by means of lateral inhibition between channels sensitive to texture density or spatial frequency.

Crovitz (1976) presented an array of vertical lines whose lengths corresponded to the spur-shaped luminance distribution of the Craik–O'Brien–Cornsweet illusion (Fig. 1c). This produced illusory modulation of apparent lengths distant from the modulation points.

We now report an analogous illusion for stereoscopic depth. Two flat textured vertical surfaces lying in the frontoparallel plane were presented side by side. The two surfaces met at a vertical boundary which was in the subject's median plane. At this vertical boundary, the left-hand surface curved slightly forwards and the right-hand surface curved backwards by an equal amount. The protruding left edge was jointed to the receding right edge by a step lying in the median plane (see Fig. 4). The result was that subjects reported that the flat part of the left surface (remote from the boundary) looked nearer in depth than the corresponding part of the right surface. This is an exact stereo analogue of the Cornsweet luminance illusion. The reader may experience this effect by binocularly fusing the random-dot stereogram of Fig. 5. For technical reasons this was produced with an upper and lower field joined by a horizontal boundary, instead of a left and right field joined by a vertical boundary. The principle is, of course, unaffected. The left and right margins have been left visible as an aid to binocular fusion: these could be masked off if it is considered desirable to remove monocular cues.

Qualitative data were obtained by stopping 50 students at random in the university cafeteria and showing them at about arm's length a wooden block with a curved surface made into a spur-shaped profile, and asking them whether the left or right half looked nearer to them in depth. Two judgements were collected from each subject, with the forward-curving surface on the left on one trial and on the right on the other, in random order. If there were no systematic effect and students responded at chance level, one would expect the forward-curving surface to be judged nearer on 50% of the trials and further away on 50%. In fact, it was judged nearer on 76% of trials ($P < 0.001$). Thus the effect was robust enough to be seen consistently in fairly uncontrolled conditions.

The illusion was measured quantitatively using a null method of adjustment. The curved surfaces of the left and right halves of the display were made by bending pieces of card over suitable formers mounted on two wooden blocks, and covering the card with random-dot texture (Letratone LT99). Each block was mounted on a rod attached to a reversible

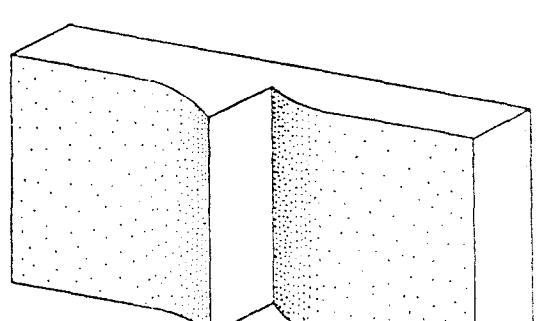

Fig. 4. Perspective sketch of the illusory depth surface. Left part looks apparently nearer than the right part.

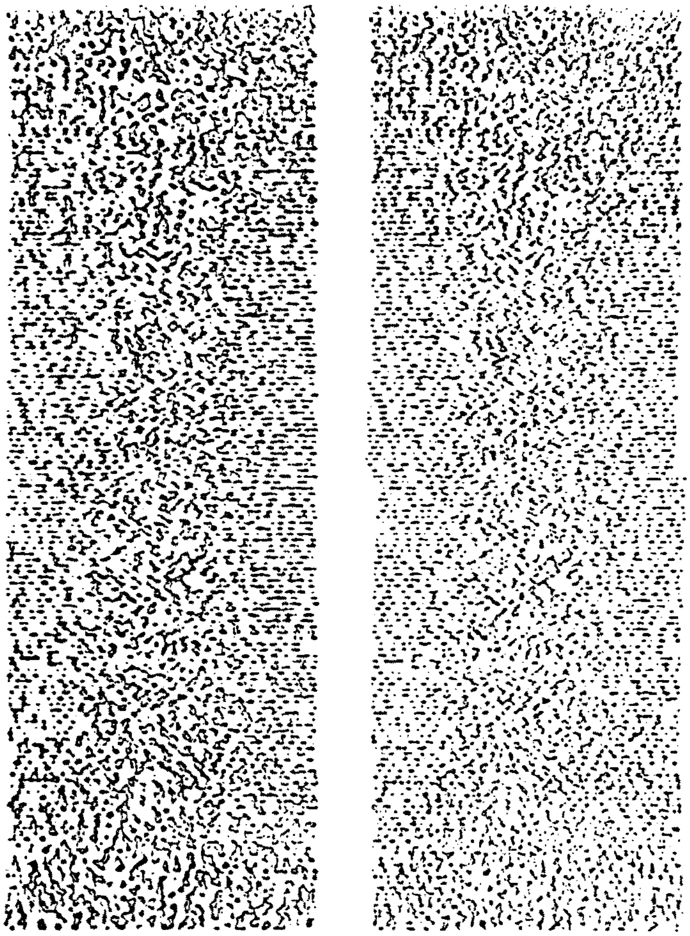

Fig. 5. Random-dot stereogram, photographed from an oscilloscope screen. When fused binocularly in a stereoscope, it gives a depth surface like Fig. 6, but with upper and lower halves divided by a horizontal boundary. There is a strong depth illusion, with the upper part looking apparently nearer than the lower part.

motorized lead screw under the subject's control in such a way that the left block advanced towards the subject as the right block receded, or vice versa. His task was to adjust the position of the two blocks in depth until they appeared to be equidistant from him. If the illusion caused the left block to appear nearer when the two blocks are actually equidistant, the subject would set the left block physically farther away than the right block, when asked to set them to the same apparent distance. The amount of this error, as shown on an accurate dial gauge, indicated the strength of the illusion.

Each block was 10 cm high and 30 cm wide. The depth of the step from undershoot to overshoot (when the flat part of the surfaces were aligned) was 2.5 cm, and the width of the curved transition surfaces on each block was 5 cm (10 cm on both blocks together). Thirteen subjects made a group of six settings at each of three viewing distances: 72, 145 and 290 cm. The order of viewing distances was randomized over subjects. In each group of six trials, the forward-curving block was placed on the left for three trials and on the right for the other three trials. Before and after each group of six trials, the subject made a control setting in which a 10 cm square of black card occluded the curved portions of the two blocks. The experimenter randomly offset the blocks in depth before each trial.

RESULTS

A systematic depth illusion was found in the expected direction at each viewing distance. At the judged null point, the forward-curving surface was set further away (to offset its apparent nearness), compared with the backward-curving surface, by about half a centimetre at all three viewing distances (see Table 1).

Table 1. Distance in cm by which forward-curving surface was set further (to null out its apparent nearness) compared with backward-curving surface. Mean of 13 Ss

Viewing distance (cm)	Mean setting (cm)	s.d.	P
72	0.41	0.42	<0.01
145	0.49	0.44	<0.01
290	0.50	0.56	<0.01

We noticed informally a cross-modal effect of visual capture. If the two flat portions of the wooden block sketched in Fig. 4 were held between the thumb and index finger of each hand, with the eyes open, the part that looked apparently nearer to the eyes also felt thicker to the hands. This tactual illusion disappeared if the eyes were closed. We thank Drs. Arien Mack and Bruce Bridgemen for calling our attention to this phenomenon.

DISCUSSION

The spur-shaped depth profile we used can be thought of as a step or discontinuity in depth, say from near left to far right, superimposed on a gradual ramp or S-shaped curve in depth of opposite sign (far left to near right). The depth is changing with predominantly high spatial frequencies near the step and with low spatial frequencies along the ramp. The fact that the visual system emphasises the discontinuity at the expense of the depth ramp suggests that it has a stronger response to high spatial frequency components of depth change, than to low frequency components. It would be interesting to measure directly the spatial frequency characteristics of visual sensitivity to depth change, using disparity gratings made to look like sheets of corrugated iron, lying in the frontoparallel plane. The number of furrows per degree of visual angle determines the spatial frequency whilst the depth of the furrows determines the amount of disparity. Tyler (1974) has published a swept-frequency, swept-amplitude disparity grating in the form of a random-dot stereogram, which might be used for this purpose.

In the case of luminance gratings, the poor sensitivity to low spatial frequencies is usually attributed to lateral inhibition between luminance detectors (see review by Anstis, 1975). We speculate that the poor sensitivity to gradual (low-frequency) changes in depth may also be caused by lateral inhibition; in this case between visual channels which are selective for binocular disparity. Such inhibition would be between disparity-selective units which lie adjacent in the frontoparallel plane, i.e. in slightly different visual directions. This should be distinguished from the lateral inhibition, suggested by Richards (1972), which would occur between units lying along the same mean visual direction but sensitive to different amounts of disparity.

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APPENDIX: A CHEAP WAY TO MAKE RANDOM DOT STEREOGRAMS

Julesz (1971) has devised computer-generated random-dot stereograms which contain no monocular cues to depth, and which have greatly enhanced our understanding of binocular depth perception. This Appendix describes a method of making such patterns very cheaply and quickly without computers, cameras or oscilloscopes. A universal template or contour former was purchased for $1.99 from a hardware store. This device consists of about 150 thin steel rods or wires, 1 mm diameter and 8 cm long, which are clamped together to form a plane of parallel rods somewhat like the teeth of a comb. Each rod is free to slide independently in the clamp along its own length, but in no other direction. If a carpenter wishes to copy a profile, such as a chess piece or a turned candlestick, he presses the tips of the rods firmly against the desired profile, producing a template which can be used, say, when turning up a copy on a lathe. The rods were painted matt white with typist's correction fluid and then carefully dotted all over with a fine-tipped black felt pen to give a quasi-random dot texture.

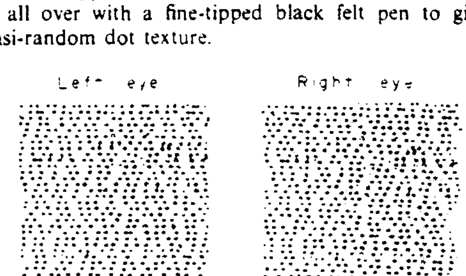

Fig. 6. Random-dot stereogram using template former, showing disparity grating of horizontal bars.

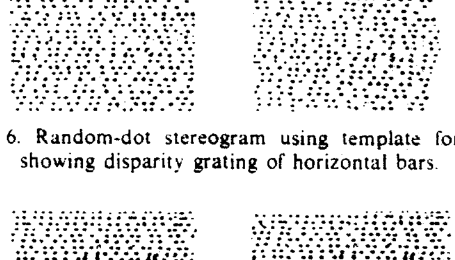

Fig. 7. Random-dot stereogram using template former, showing Cornsweet depth illusion.

To make a stereogram, the tips of rods are lined up into a straight edge by firmly pressing them against a flat surface. The template is then copied on an IBM Copier II ($0.07 per copy). To ensure a sharply focused image the template should be placed flat on the glass, and the tips of the rods tilted down until they touch the glass plate of the copier. After this, the rod tips are adjusted by hand to give any desired disparity profile, and the template again photocopied. Generally, only 1–2 mm of disparity is necessary. If the two photocopies are viewed one with each eye in a stereoscope, the disparity profile is seen as a 3-D surface, consisting of horizontal ridges and furrows lying in depth.

Figure 6 shows a stereograting, produced by adjusting the rod tips by hand to match a sine wave drawn on graph paper. Figure 7 shows the Craik–O'Brien–Cornsweet illusion for visual depth. These figures were cut out from the photocopies. The right-hand margins of the stereograms reveal the disparity profiles, and have been left visible to aid binocular fusion. They could be cropped off in cases where monocular cues are considered undesirable.

This technique will never replace the computer. It can produce only depth zones which run across the full horizontal width of the stereogram, and it can never produce the isolated squares, truncated hyperbolic paraboloids in depth, and ambiguous depth with which Julesz (1971) has regaled us. However, its speed and cheapness make it useful for student projects, or for trying out ideas rapidly when a computer is not available.

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