
Line at shape-from-shadow border tested with stereo

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Abstract. Kennedy and Bai (2000 *Perception* **29** 399–408) argued incorrect border polarity blocked perception of faces in shape-from-shadow ‘Mooney faces’ with dark lines at the contour, a display inspired by Hering. Their hypothesis was tested with several displays, notably binocular gratings made of lines of dots. The stereo-induced depth involved a shadow falling on two surface planes. Most of a dark-dotted (shadow) region appeared to be on one surface, but a strip of dark dots at the shadow’s border appeared to be on another—to the fore or rear. Control conditions involved ‘negative’ images (white dots). Subjects saw the shadowed object as easily in dark-dotted images with stereo depth as in an image with uniform depth for all the dots, and more readily than in the negatives. Our results favour the border-polarity hypothesis.

1 Introduction

Shadows convey information about spatial layout (Yonas 1979; Gilchrist et al 1983; Cavanagh and Leclerc 1989; Kersten et al 1996; Cavanagh and Kennedy 2000). Here, we test a border-polarity hypothesis about shape-from-shadow perception, offering demonstrations and a stereo-depth experiment.

Figure 1a (from Mooney 1957) shows an elderly person in strongly directional illumination, a fragmented ‘puzzle picture’ or ‘Mooney face’ (Ramachandran et al 1998). Dark parts depict shadow, and bright parts illuminated regions. The luminance contour is a shadow’s border on the continuous surface of the face. Figure 1b, a line drawing, suggests parts of the face, and figure 1c adds dashed lines for the shadow borders.

Figure 1a is a ‘positive’. The polarity—the direction of change of luminance—of the large regions fits a photographic positive. The contour is also polarised, correctly, dark to bright from shadowed to illuminated. In a negative such as figure 1d, the shadowed region is white, the illuminated region black. The polarity of the large regions is incorrect, and so too is the contour’s. In the negative the face is hard to discern.

Kennedy and Bai (2000) noted that a figure with the shadow in gray worked well in showing the face (see ‘pure gray’ figure 2a), but when a black line is added at the gray-shadow border, the face is hard to recover, as in ‘black line at border’ figure 2b (Hering 1874/1964; Howard and Rogers 2002; Mausfeld 2003). It looks flat like a map, much as does the negative.

A line is a thin strip with two contours. The line’s contour alongside the shadowed region is polarised from gray to the black line itself, as in a negative. The line along the illuminated region is from the black line itself to white, ie positive. Kennedy and Bai (2000) argued that, despite the presence of the positive contour, the incorrectly polarised contour diminished shape-from-shadow perception. They found that adding a gray line (of the same thickness as the black line), which has positive polarity at both contours, allowed the face to appear. Figure 2c adds a red line with positive polarity. It is more distinctive than a gray line, but the face is still apparent. (The reader is viewing a print with its own characteristics, but it may be helpful to know it was designed with Microsoft® Paint luminance 0 for black, 160 for red, and 240 for white.) Other positive lines with varied hues also leave the face visible. Figure 2d puts the red

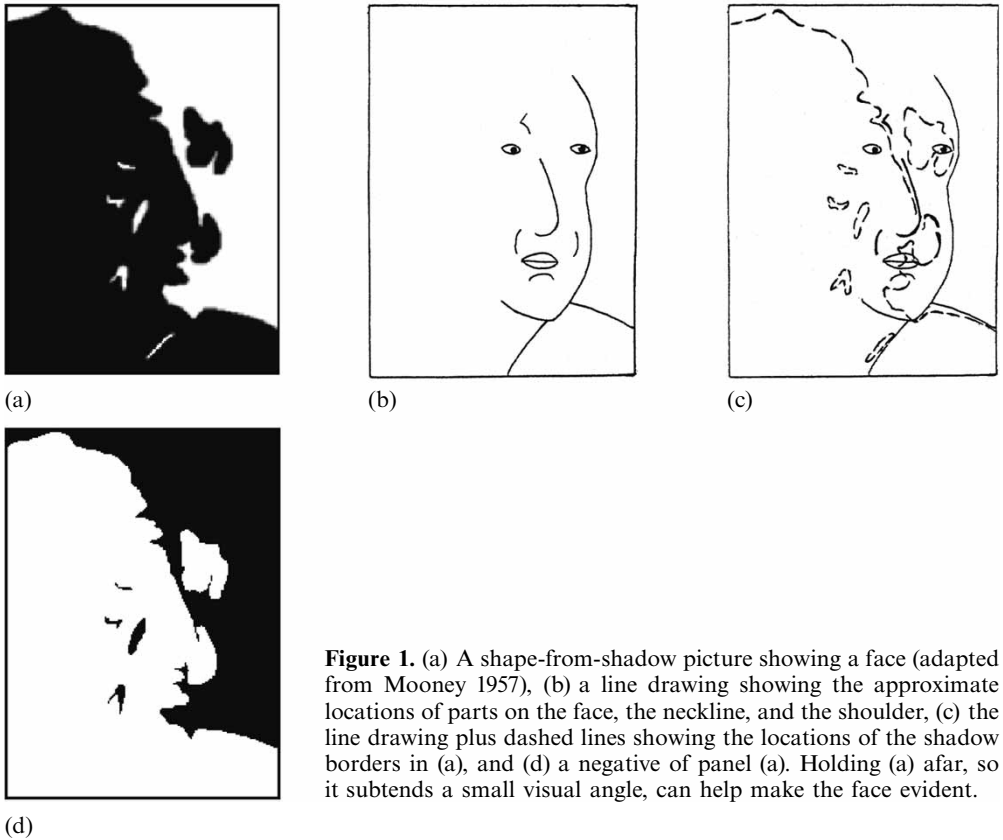


Figure 1. (a) A shape-from-shadow picture showing a face (adapted from Mooney 1957), (b) a line drawing showing the approximate locations of parts on the face, the neckline, and the shoulder, (c) the line drawing plus dashed lines showing the locations of the shadow borders in (a), and (d) a negative of panel (a). Holding (a) afar, so it subtends a small visual angle, can help make the face evident.

line as a negative alongside a light-gray area (Microsoft[®] Paint luminance 184), and the face is not obvious.

An alternative account is an ‘apparent belongingness’ hypothesis derivable from figure–ground theory (Rubin 1915/1958; Kennedy 1974; Peterson 2001). “When two fields have a common border, and one is seen as figure and the other as ground, the immediate perceptual experience is characterized by a shaping effect which emerges from the common border of the fields and which operates only on one field or operates more strongly on one than on the other” (Rubin 1958, page 194). In a standard figure–ground display, eg a dark patch surrounded by white, the luminance border segregates two perceptual entities: the figure on one side of the border to which the border belongs and which is shaped by the border, and the ground on the other side, to which the border does not belong and which it does not shape. However, in Mooney faces the situation is quite different, since the shadow border curls along a continuous surface. Thus it does not necessarily belong to the shaded region only. If perception took it as belonging to one side only, that could impede shape-from-shadow processing.

Border elements trigger apparent belongingness to neighbouring regions in several ways. In Nakayama et al’s (1989) terms, a contour of the black line may appear to be an ‘intrinsic’ border (ie the boundary of a foreground surface, which could be, say, a left gray region or a right white region). “Intrinsic borders aid in segmentation of image regions and thus prevent grouping” (Nakayama et al 1989, page 55). If so, the continuous surface of a face bearing a luminance border and stretching into the white region, towards the face’s profile, might be unavailable to perception.

By way of illustration, consider a possible implication of the belongingness account. Extending the black line to outside the rectangular picture frame (as shown in figure 2e)

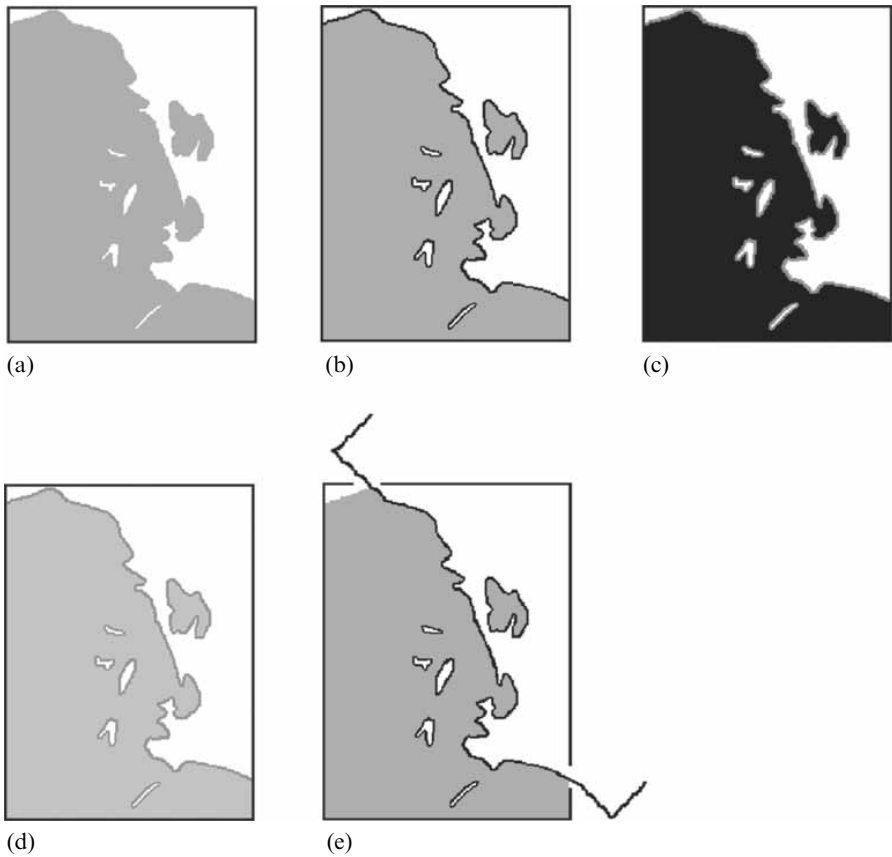


Figure 2. The elderly face is evident in (a) the ‘pure gray’ version, but not in (b) the ‘black-line-at-border’ version. It is evident in (c) the ‘light-red-line-at-dark-shadow-border’ version (see colour version at <http://www.perceptionweb.com/misc/p5235>), but not in (d) the version with an especially light-gray shadow. It is not visible in (e) the ‘extended line’ version.

might ‘disconnect’ the line and the gray shadowed region, and allow shape-from-shadow perception to use the gray shadow region’s contour to see the face. Inspection reveals, however, that this is not the case. (Also, in an experiment using twelve naïve undergraduate students, the subjects’ ratings for the ease with which the elderly person could be seen in figures 2b and 2e were the same, and both were significantly lower than their ratings for figure 2a.) So the belongingness hypothesis is not supported.

Lines distinct in luminance, colour, and extension do not block perception of the face. But it could be argued that these manipulations were not strong enough to disrupt belongingness. Would depth?

Perhaps perception treats the black line as belonging to an entirely independent foreground figure—like a wire—and the gray region and the white region are independent of it and each other. Gillam et al’s (1999) experiments, on stereo produced by two displays differing by only a single vertical line, found the line appeared as an opening dividing two independent surfaces. Further, lines readily appear as convex and concave corners between two distinct surfaces at different slants. Evidently, there are several perceptual options for lines.

Note that if the line is taken as bounding a foreground white region, the black region may have no contour available to trigger shape-from-shadow perception. Also, both the gray shadowed region and the white non-shadowed region may appear to continue

behind a black line as wire. In either case, perception may find no contour appears to belong to the shadowed region to trigger shape-from-shadow processing.

Stereo can be used to affect the belongingness of each border element of a shadowed region. As Nakayama et al (1989) noted, when a surface is partially occluded by another surface the “common border is attached to and regarded as intrinsic to the closer region, and detached from and regarded as extrinsic to the farther region” (page 55). Extrinsic edges of a region “can and should be shielded from the process of pattern recognition” (page 64) of that region, they concluded. In addition, they proposed that the classification of the intrinsic versus the extrinsic “could be made on the basis of depth alone” (page 58) and the perceived belongingness of a contour between two regions in an image can be manipulated by stereoscopic depth information, with the advantage that “relative depth can be easily manipulated without varying other aspects of the image” (page 58).

Stereoscopic depth information can influence dots at shadow borders so they belong to a front surface or a back surface, and so we devised stereo stimuli made of dots, in the form of dotted-line gratings.

Figure 3a demonstrates that a line grating can also show the elderly face. In figure 3b, black dots approximately four times thicker than the lines are added at the line termini at the shadow border. In this ‘line-plus-dot’ figure, mean luminance decreases at the border from light gray to dark gray. As the border-polarity hypothesis would have it, inspection reveals that shape-from-shadow perception is diminished compared with figure 3a.



Figure 3. The elderly face is evident in (a) the ‘line-grating’ version, but not in (b) the ‘line-plus-dot’ version, though it is in (c) the ‘all-dot’ version.

A figure might fail simply because it contains dots. However, figure 3c is an ‘all-dot’ figure that succeeds in showing the face. (An experiment with twelve naïve subjects found the ease of shape-from-shadow-perception rating for figure 3c was not significantly different from the rating for figure 3a, and both were significantly higher than the rating for figure 3b.)

On average the dotted region is dark gray. Interestingly, on average the rows of dots at the border and in the interior have a negative’s incorrect polarity on one side, since there is white space alongside. If shape-from-shadow vision relies solely on the border dots, the negative border could interrupt perception of the face. But, if the negative border of the final row of dots is not significant when the region alongside it is equally dotted (with many pairs of positive and negative borders), the face should be seen: the border-polarity hypothesis could predict that the all-dot figure would succeed in showing the shape-from-shadow face, and indeed it does.

The success of a dotted figure is helpful. Consider some binocular possibilities (figure 4). The face is evident in the pure gray version in figure 4a (left), but when reduced to a black line it is not. Interestingly, when the gray and line displays are free-fused (or combined by using a stereoscope), the face simply disappears. Fused, with little or no binocular rivalry, the shadow region would have an effective luminance of light gray (combining medium gray with white in the line display). Similarly, the shadow border would be dark gray (combining medium gray and the black line). The border polarity would be incorrect from the shadow to the black line, which could explain the failure to see the face.

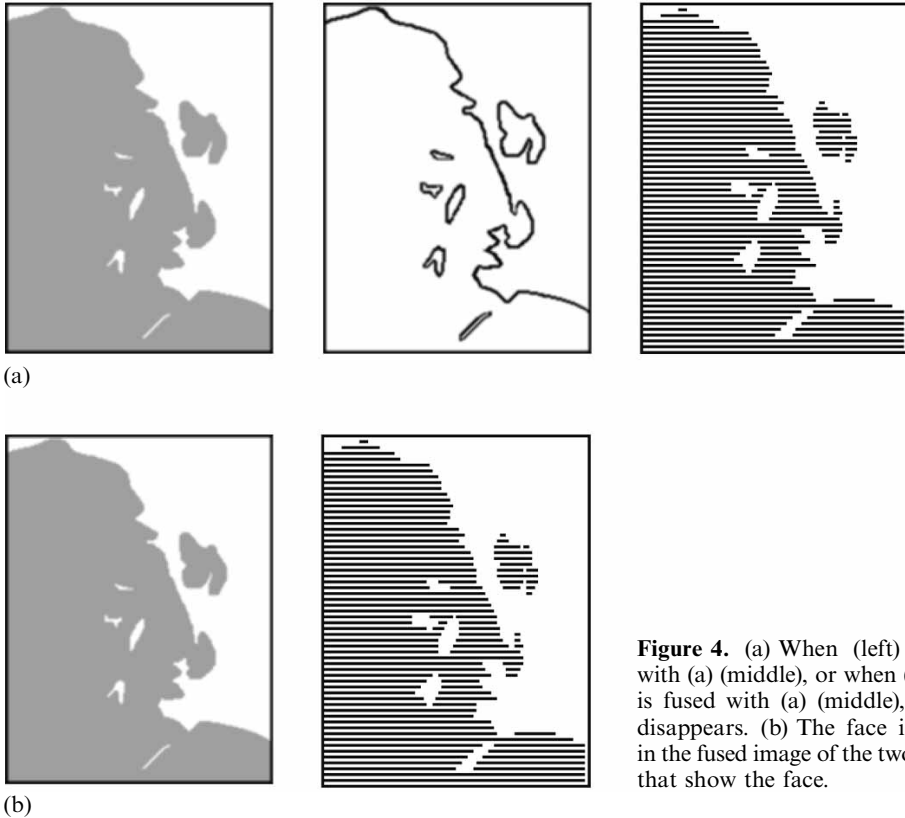


Figure 4. (a) When (left) is fused with (a) (middle), or when (a) (right) is fused with (a) (middle), the face disappears. (b) The face is evident in the fused image of the two versions that show the face.

Similarly, when the line and line-grating [figure 4a (right)] displays are fused, the face once again disappears, though it is evident in the line grating alone. Fusing the gray and grating figures (by using figure 4b) allows the face to persist (despite some rivalry) which could be because the combination has correct polarity at the border if fused.

That an all-dot display shows the face allows us to test belongingness and the border-polarity hypothesis using a stereo-depth edge cutting through the dark region. Most of a dark-dotted (shadow) region can appear to be on one surface, but a strip of dark dots at the shadow border on another (foreground or background). In Nakayama et al's (1989) account, the strip of dots at the shadow border would not belong to the shadow region formed by the majority of dots, and in our experiment we check if the result is that the face fails to appear.

2 Experiment

Figures made of dots served as half images. Figure 5a (left) was made of large dots. Another (middle) duplicates it and adds an extra line of distinctive (smaller) dots at the shadow border (as in figure 5b). The observer was presented with the pair, one eye seeing one more row of dots than the other. The binocular disparity provides stereo depth information. Also, each half image and the binocular combinations should allow shape-from-shadow perception, since the border polarity in each is positive.

Negatives with white dots (figures 5c and 5d) provided baselines where shape-from-shadow perception should fail but stereo should succeed.

Consider first the case where the right eye sees all the dots presented to the left eye, plus an extra set. It is seeing behind a frontal surface that bears the dots both eyes see—ie the majority of dots (figure 6a). The large white illuminated region bears the extra dots, so it also appears to be farther away than the majority of dots.

This outcome can be called a ‘most-shadow-in-front’ percept. (In the corresponding negative-binocular percept, most of the original shadowed region formed by the majority of white dots should appear to be in front.)

Consider now the case where a line of dots at the shadow border can be seen by the left eye but not by the right eye. A line of foreground dots may occlude another, background line of dots (figure 6b), ie two lines of dots in the left eye correspond to one in the right, as in “Panum’s limiting case” (Nakayama and Shimojo 1990). The occluding dots are close. The majority of dots (together with the occluded dots) appear to be to the rear. The white non-shadow region bears the occluding dots, so it can appear to be the front surface, a ‘most-shadow-at-back’ percept. (Again, in the corresponding negative, most of the original shadowed region formed by the majority of white dots appears to be at the back.)

In Panum’s limiting case, the occlusion interpretation is not always adopted (Howard and Ohmi 1992; Howard and Rogers 1995; Shimono et al 1999). In our experiment, a few subjects reported the opposite depth percept for the stimulus layout, mostly for the negative-binocular percepts.

According to the border-polarity hypothesis, all images with correct border polarity should succeed in shape-from-shadow perception, while stereo depth varies. The belongingness hypothesis, on the other hand, contends that an occluding edge close to the border and splitting the shadow region onto two surfaces would interfere.

3 Method

3.1 Design

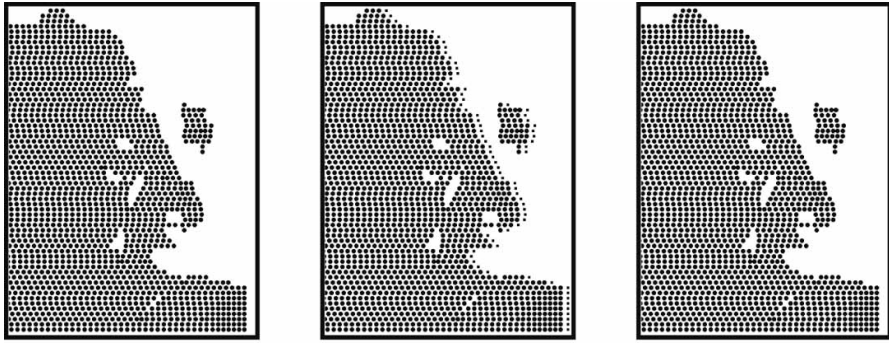
The experiment was a within-subjects design with repeated measures for two independent variables: stereo depth and positive–negative. The dependent variable was the ease with which the elderly person could be seen in the binocular images, on a 10-point scale (1 very difficult, 10 very easy).

3.2 Subjects

Twenty-two undergraduates (fourteen women and eight men, mean age 21.1 years, SE = 0.5 years) participated, sixteen for payment, others as a class project. All reported normal or adjusted-to-normal vision, and were tested individually. One additional subject did not complete the study because of problems with stereopsis on a criterion task.

3.3 Apparatus and materials

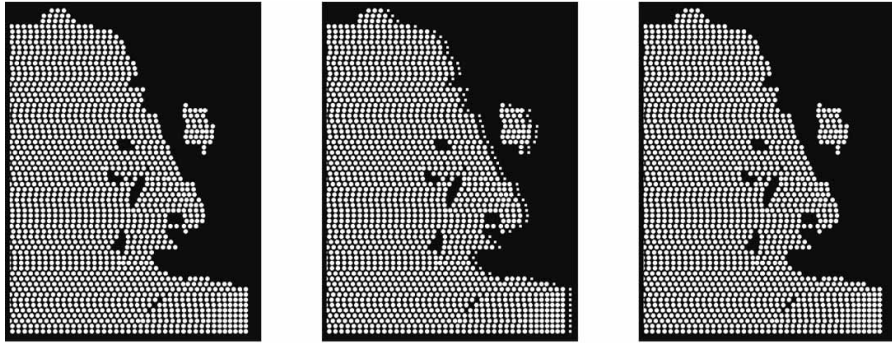
The equipment was a stereoscope about 12 cm high. The distance between the two glasses was adjustable for each subject.



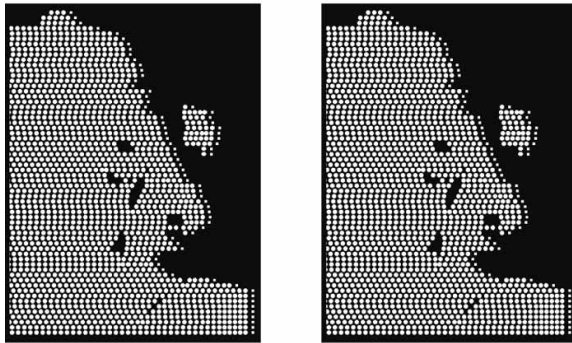
(a)



(b)



(c)



(d)

Figure 5. Test images used in the binocular experiment. Positive versions include half images where the right eye sees an extra line of distinctive border dots (a) (left and middle by uncrossed fusion), where the left eye sees an extra line of distinctive border dots (a) (middle and right by uncrossed fusion), and where both eyes see identical images with distinctive border dots (b) (left and right). Panels (c) and (d) are negative versions.

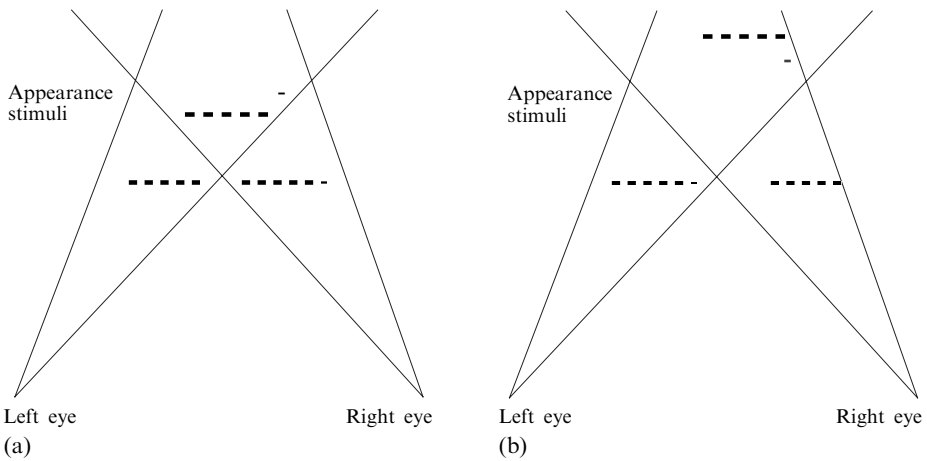


Figure 6. Top view of the arrangement (a) with the right eye seeing one more set of border dots and the outcome is ‘most shadow in front’; (b) with the left eye seeing one more set of dots and the outcome is ‘most shadow at back’—ie Panum’s solution.

The materials included the following:

- (i) Two demonstration pictures were adapted from Kennedy (1997), an easily deciphered shape-from-shadow picture of a man’s face (with uniform-black and uniform-white regions), and its line counterpart (a black line copying the contour).
- (ii) A random-dot stereogram from Rock (1975) tested each subject’s stereopsis. (The one not asked to complete the study failed to see stereo depth in this test.) It provides a ‘T’ closer to the viewer than the other random dots. The ‘T’, not evident in either half image alone, can be called a ‘cut-out T’. The left-eye/right-eye reversal of the stereogram provides a ‘T’-shaped window onto more-distant dots.
- (iii) Six pairs of test stimuli were presented one pair at a time in random order, with a different order for each subject. The left-eye/right-eye spatial layout of each pair was figures 5a(left)/5a(middle), figures 5a(middle)/5a(right), figures 5b(left)/5b(right), figures 5c(left)/5c(middle), figures 5c(middle)/5c(right), and figures 5d(left)/5d(right).

All of the materials were printed onto A4-sized paper with an HP LaserJet printer. The demonstration pictures were printed side by side on one page. Shape-from-shadow, figure 1a, and its line version, figures 1b and 1c, were each printed onto one page. Each pair of the ‘T’-figures was printed onto one page. Each pair of the half images in the test stimuli was also printed on one page. Each half image measured 4.7 cm × 3.6 cm. The distance between the two half images was about 0.5 cm

The subjects achieved binocular vision using a stereoscope, so fusion was uncrossed.

3.4 Procedure

First, the shape-from-shadow demonstration picture was shown to the subjects. The subjects were told that the picture showed a man’s face partly in deep shadow. They were told that people might rate this picture as 9 on a 10-point scale (10 being very easy) in terms of how easy it was to see the person in the picture. They were then told the line version might be rated as 2 on the same scale. Numbers less extreme than 1 and 10 were chosen to have room on either side of the example numbers.

Then the subjects saw the two versions of the stereo ‘T’, one pair at a time, alternating orders between subjects. They were instructed to use a stereoscope to see the binocular figure, and to adjust the stereoscope until a clear central image was formed by binocular fusion. (They were told that seeing the half images on the sides of the central image was a normal part of successful fusion.) For each pair, they were asked whether they could see anything new in the binocular version that they could

not see in the two single images. All but one subject reported seeing the cut-out ‘T’ and the window ‘T’, either by themselves or with a hint from the experimenter.

Those who saw the ‘T’s were told that in the next binocular images, they were to find the apparent relative depth, if any, of a set of border dots compared with a dotted region and to report how easy it was to see a person’s face in shadow in each binocular image. They were shown figure 1a so that they knew the face to look for. If they could not see the face, they were shown figures 1b and 1c, and then figure 1a again. This time, the eyes, nose, mouth, chin, and shoulder of the person in figure 1a were pointed out. All subjects reported being able to see the face.

Next, the subjects were shown the test images, one pair at a time. For each pair, the subjects were asked to adjust the stereoscope and fuse the two half images. They were asked whether the dots at the shadow border in the fused percept seemed raised above the dotted region containing the majority of dots, below the dotted region, or at the same depth as the dotted region, and how easy it was to see the elderly face in the fused image. They were allowed to look back at the elderly face in figure 1a if necessary.

4 Results

Of the twenty-two subjects, fourteen (nine women and five men, mean age 20.7 years, SE = 0.4 years) reported uniformly the following depth percepts. They used the ‘right-eye-sees-around-the-edge’ solution for figures 5a(left) and 5a(middle) (positive) and for figures 5c(left) and 5c(middle) (negative), and saw ‘most shadow in front’. Their vision adopted Panum’s solution for figures 5a(middle) and 5a(right) (positive) and for figures 5c(middle) and 5c(right) (negative), and saw ‘most shadow at back’. They reported not seeing any apparent stereo depth when no stereo depth was predicted, ie for figures 5b(left) and 5b(right) (positive), and figures 5d(left) and 5d(right) (negative). The mean ratings are plotted in figure 7.

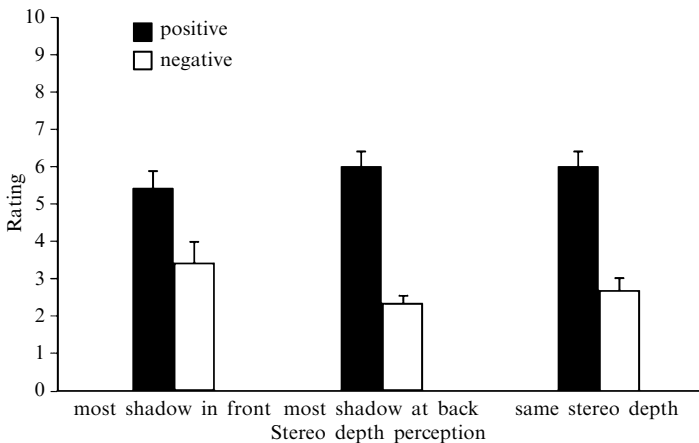


Figure 7. Mean ratings of the ease with which the subjects perceived the shape-from-shadow face on a 10-point scale as a function of positive–negative and stereo depth. Error bars indicate standard errors.

The mean rating from these fourteen subjects for the ‘most-shadow-in-front’ positive percept was 5.4 (SE = 0.5), for the ‘most-shadow-at-back’ positive percept was 6.0 (SE = 0.4), and for the ‘same-depth’ positive percept was 6.0 (SE = 0.4). For the ‘most-shadow-in-front’ negative percept the rating was 3.4 (SE = 0.6), for the ‘most-shadow-at-back’ negative percept 2.3 (SE = 0.3), and for the ‘same-depth’ negative percept 2.7 (SE = 0.4). The ratings were not at the extremes of the scale, so there was no floor or ceiling effect. The ratings of the dotted figures were not as high as those

given to the uniform-black and uniform-white figures, which can be explained by the loss of detail of the contour.

For an ANOVA, when the average of the Greenhouse–Geisser and Huynh–Feldt epsilon estimates of deviation from sphericity was greater than 0.70, Tukey a posteriori tests with specific mean-squared error terms were used (following Stevens 1992, pages 448–454; Rahman and Muter 1999). When the average epsilon estimate was less than 0.70, Bonferroni tests were used. In both cases, the alpha for a posteriori tests was 0.05 overall; the alpha for each individual a posteriori test was therefore much less than 0.05 (Rahman and Muter 1999).

ANOVA for repeated measures on two independent variables was performed on the positive–negative and stereo-depth factors, and the positives were rated higher than the negatives ($F_{1,13} = 51.48, p < 0.001$). There was no significant main effect of stereo depth ($F_{2,26} = 0.29, p < 0.8$). However, the positive–negative and stereo-depth factors interacted ($F_{2,26} = 8.35, p < 0.002$). The Greenhouse–Geisser epsilon correction for deviation from sphericity (Stevens 1992) resulted in $p < 0.004$, and the Huynh–Feldt correction resulted in $p < 0.002$.

The Tukey tests on the positive figures showed no significant difference among them. The Tukey tests on the negative figures yielded a significant difference between the rating for the ‘most-shadow-at-back’ binocular figure ($M = 2.3$) and that for the ‘most-shadow-in-front’ binocular figure ($M = 3.4$) ($t_{26} > 3.51, p < 0.05$). This significance was largely due to an outlier who rated the negative ‘most-shadow-in-front’ percept to be much higher (8 on the 10-point scale) than the negative ‘most-shadow-at-back’ percept (3 on the scale). After dropping data from the outlier, there was still a significant main effect from the positive–negative factor, and not from stereo depth. The interaction was still significant ($F_{2,24} = 7.63, p < 0.003$). The Greenhouse–Geisser epsilon correction for deviation from sphericity (Stevens 1992) resulted in $p < 0.006$, and the Huynh–Feldt correction resulted in $p < 0.004$. This interaction was due to ‘most shadow at back’ being rated slightly higher ($M = 6.1, SE = 0.4$) than ‘most shadow in front’ ($M = 5.2, SE = 0.5$) for the positives, but slightly lower ($M = 2.2, SE = 0.3$) than ‘most shadow in front’ ($M = 3.0, SE = 0.5$) for the negatives. However, none of the differences among the positives or negatives was significant.

Of the remaining eight subjects, five had uniform responses for stereo depth. Although they used Panum’s solution for the positives when the left eye saw more dots, they did not use Panum’s solution for the negatives. Two of the remaining three did not use Panum’s solution for either the positive or the negative, and one did not use this solution for a negative. This is in accord with previous findings that for Panum’s limiting case, when the elements seen by the left eye only are on the nasal side, many subjects see the extra elements farther than the elements seen by both eyes (Nakayama and Shimojo 1990; Howard and Rogers 1995).

When the subjects did not use Panum’s solution, instead of seeing the extra dots as closer than the majority of dots, they saw them as farther (six trials) or at the same depth as the majority of dots (four trials). When the subjects could not see the depth, it is possible that they could not pick up enough stereo depth information from the test stimuli, even though they could easily obtain and use the abundant stereo depth information in the random-dot stereograms and pass the screening test. This could be due to the test stimuli relying on relatively few elements (one line of dots) to create stereo depth.

For these eight subjects who did not have uniform responses, in fourteen of eighteen pairs they gave higher shape-from-shadow ratings for the positive binocular percepts than the negatives ($M = 4.8$ for positives and $M = 3.5$ for negatives). The mean ratings were 4.9, 4.5, and 4.6 for positive ‘most shadow in front’, positive ‘most shadow at back’, and positive ‘same stereo depth’, respectively; 3.1 and 3.8 for negative ‘most shadow in

front' and negative 'same stereo depth', respectively. None of the eight subjects reported a 'most shadow at back' as negative. The belongingness hypothesis is about what would follow from certain depth percepts, and the inconsistent depth percepts of these eight indicates they should be treated separately, but their ratings fit with the overall conclusion that positives are rated higher than negatives and depth of border elements is not significant.

5 Discussion

In stereo, the positive images showed the face in shadow, and the negatives did not. Changing depth did not alter shape-from-shadow perception. This result accords with Cavanagh and Leclerc's (1989) finding: "It appears that the interpretation of the shadows ignored binocular disparity and relied solely on luminance information" (experiment 3, page 12). Indeed, their result could be used to reject one version of the belongingness hypothesis. They used stereoscopic random texture to display the shadow and non-shadow areas at different depth planes. In their binocular images, all elements in the dark region fell on one surface plane (eg a foreground surface), and all elements in the bright region fell on another surface plane (eg a background surface). In Nakayama et al's (1989) account, when the shadow region is on the back surface, the shadow border would not belong to the shadow region.

However, in Cavanagh and Leclerc's (1989) stimuli, where there was a change of luminance, there was also a change of depth—a point of difference. In our experiment, luminance defined border polarity, stereo provided information about belongingness of elements at the shadow border, and the shadow border defined by luminance was not the same as the surface border defined by stereo depth.

One condition that was especially important in our experiment was Panum's limiting case. In this case, depth conditions suggest no visible dark–light border belongs to the dotted shadow region, predicting failure to see the face. However, it appeared.

Since the structure of the elderly face has its own apparent depth (eg the convexity of the nose, the concavity of the eye, etc), stereo depth is independent of shape-from-shadow depth to a considerable degree. When a shadow lies on a continuous surface, both sides of the luminance border are parts of a single foreground figure: the face. Since the stereoscopic border cut across the continuous surface, vision supported two surface arrangements simultaneously—one the continuous face, the other a foreground with an occluding boundary and a background. Seeing two surface arrangements here is analogous to monocular picture perception, for the flat surface of a picture is perceived at the same time as the pictured scene's depth.

There are many ways to produce borders besides stereo—luminance, hue, and motion, each of which may be varied in lots of ways. Our manipulations simply sample the set and deserve to be extended.

The present method involves ratings, after establishing subjects can see the relevant face. Though a stereo manipulation allied with a more indirect tactic would be helpful, one advantage is that the typical reader (and experimenter) can check the manipulations directly from prints in this paper (and we do concur with our subjects).

One of the telling demonstrations we offer here is the binocular combination of a dark line (white on both sides) with its positive Mooney counterpart. It is striking that the black line wipes out perception of the face in the binocular percept, though the black shadow makes itself evident as a gray tone on the shadow side of the black line. The observer is not simply alternating between two rivalrous images with no fusion. Rather, in the fused image the face vanishes, favouring our interpretation of our results as following from the fusion requested rather than monocular or rivalrous images. Likewise, we find half-image all-dot figures, one with extra-large dots at the border and no face visible, and one with no extra border dots so the face is visible,

combine so the face is not apparent. But further tests are possible of course and a direct measure of fusion and rivalry would be useful.

The width of the black line deserves exploration, since a very wide line would surely cover the shadow areas so much the positive contour would be left unaffected by a distant negative. Moving textured patches that come together momentarily to offer the Mooney-face-plus-line for a brief interval would allow useful tests of the luminance hypothesis monocularly and binocularly. The shapes and sizes of the block elements we added at grating termini could be varied to examine many variables (rate of luminance change, across various widths of the Hering line, in motion and stereo etc). These manipulations will support the border-polarity hypothesis we suggest.

The line-grating, figure 3a, and the all-dot, figure 3c (as well as the positive-binocular percepts), have lots of white in the shadowed region. However, the average luminance is positive, and all of these figures showed the shape-from-shadow face. In normal ecological circumstances, shadows often fall on speckled surfaces, and the average large region and border polarities will be positive. But if some spots are very light, then at some parts of the large regions and border there will be incorrect polarity. Hence shape-from-shadow vision should accept luminance variation, and use average luminance. This would help explain the success of grating figures in showing the shape-from-shadow face, and the ability of the all-dot figure to show the face despite the presence of incorrectly polarised contours of border dots and large-region dots. Blurred vision can facilitate averaging the luminance over a region, and lessening effects from the high spatial frequencies given by contours. However, since blurring is not needed to see the face in dotted figures, shape-from-shadow perception is able to select suitable spatial frequencies. In this connection, it is striking that the negative contour could indeed have an effect, since at very low spatial frequencies its contribution is limited. However, it must be noted that at these low-frequencies contributions from details of contour shape, which are the information for the face shape, are minimal. There must be a correspondence between the spatial frequencies at which the negative contour is present and those at which the depicted-object and shadow-contour information are present.

Photographic negatives disrupt shape-from-shadow more when they are two-valued than when they are standard multilevel gray scale. The latter allow faces to be seen as faces, though detection of age and expression, and recognition of the person are lessened. In dichotomised (black–white) negatives the object is unrecognisable as a face. Thus, wrong luminance polarity may have different degrees of severity, depending on the number of gray values. The information retained in the gray-scale negatives deserves exploration.

In sum, demonstrations and a binocular experiment support a border-polarity hypothesis about a black line at a shadow's border.

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References

- Cavanagh P, Kennedy J M, 2000 "Close encounters: Details veto depth from shadows" *Science* **287** 2421
- Cavanagh P, Leclerc Y G, 1989 "Shape from shadows" *Journal of Experimental Psychology: Human Perception and Performance* **15** 3–27
- Gilchrist A, Delman S, Jacobsen A, 1983 "The classification and integration of edges as critical to the perception of reflectance and illumination" *Perception & Psychophysics* **33** 425–436
- Gillam B, Blackburn S, Nakayama K, 1999 "Stereopsis based on monocular gaps: Metrical encoding of depth and slant without matching contours" *Vision Research* **39** 493–502
- Hering E, 1874/1964 *Outlines of a Theory of the Light Sense* translated into English by L M Hurvich, D Jamieson (Cambridge, MA: Harvard University Press) page 8 [originally published in 1874]

-
- Howard I P, Ohmi M, 1992 "A new interpretation of the role of dichoptic occlusion in stereopsis" *Investigative Ophthalmology & Visual Science* **33**(4) 1370
- Howard I P, Rogers B J, 1995 *Binocular Vision and Stereopsis* (New York: Oxford University Press)
- Kennedy J M, 1974 *A Psychology of Picture Perception* (San Francisco, CA: Jossey-Bass)
- Kennedy J M, 1997 "How the blind draw" *Scientific American* **276**(1) 60-65
- Kennedy J M, Bai J, 2000 "Cavanagh and Leclerc shape-from-shadow pictures: Do line versions fail because of the polarity of the regions or the contour?" *Perception* **29** 399-408
- Kersten D, Knill D C, Mamassian P, Bülthoff I, 1996 "Illusory motion from shadows" *Nature* **379** 31
- Mausfeld R, 2003 "Conjoint representations", in *Looking into Pictures. An Interdisciplinary Approach to Pictorial Space* Eds H Hecht, R Schwartz, M Atherton (Cambridge, MA: MIT Press) pp 17-60
- Mooney C M, 1957 "Age in the development of closure ability in children" *Canadian Journal of Psychology* **11** 219-226
- Nakayama K, Shimojo S, 1990 "Da Vinci stereopsis: Depth and subjective occluding contours from unpaired image points" *Vision Research* **30** 1811-1825
- Nakayama K, Shimojo S, Silverman G H, 1989 "Stereoscopic depth: its relation to image segmentation, grouping, and the recognition of occluded objects" *Perception* **18** 55-68
- Peterson M A, 2001 "Object perception", in *Blackwell Handbook of Perception* Ed. E B Goldstein (Oxford: Blackwell Publishers) pp 168-203
- Rahman T, Muter P, 1999 "Designing an interface to optimize reading with small display windows" *Human Factors* **41** 106-117
- Ramachandran V S, Armel C, Foster C, Stoddard R, 1998 "Object recognition can drive motion perception" *Nature* **395** 852-853
- Rock I, 1975 *An Introduction to Perception* (New York: Macmillan)
- Rubin E, 1915/1958 *Synsoplevede Figurer* (Copenhagen: Gyldendalske Boghandel) [translated into English as "Figure and ground", in *Readings in Perception* Eds D C Beardslee, M Wertheimer (1958, Princeton, NJ: Van Nostrand) pp 194-203]
- Shimono K, Tam W J, Nakamizo S, 1999 "Wheatstone-Panum limiting case: Occlusion, camouflage, and vergence-induced disparity cues" *Perception & Psychophysics* **61** 445-455
- Stevens J, 1992 *Applied Multivariate Statistics for the Social Sciences* 2nd edition (Hillsdale, NJ: Lawrence Erlbaum Associates) pp 448-454
- Yonas A, 1979 "Attached and cast shadows", in *Perception and Pictorial Representation* Eds C F Nodine, D F Fisher (New York: Praeger) pp 100-109

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Line at shape-from-shadow border tested with stereo

John M Kennedy, Juan Bai

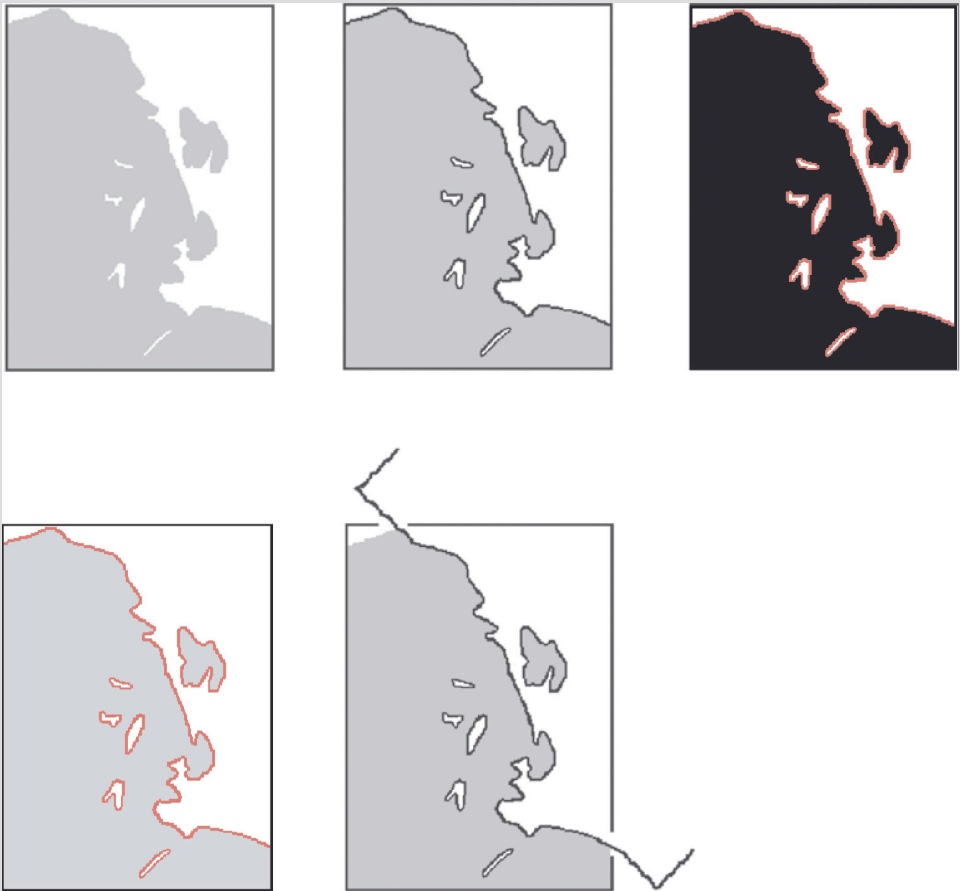


Figure 2.