Apparent surface curvature affects lightness perception

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THE human visual system has the remarkable capacity to perceive accurately the lightness, or relative reflectance, of surfaces, even though much of the variation in image luminance may be caused by other scene attributes, such as shape and illumination. Most physiological[1,2], and computational models[3–6] of lightness perception invoke early sensory mechanisms that act independently of, or before, the estimation of other scene attributes. In contrast to the modularity of lightness perception assumed in these models are experiments that show that supposedly 'higher-order' percepts of planar surface attributes, such as orientation, depth and transparency[7–10], can influence perceived lightness. Here we show that perceived surface curvature can also affect perceived lightness. The results of the earlier experiments indicate that perceiving luminance edges as changes in surface attributes other than reflectance can influence lightness. These results suggest that the interpretation of smooth variations in luminance can also affect lightness percepts.

Figure 1*b* shows a version of the type of illusion used to motivate many models of lightness perception[3,11,12]. Computational models explain the phenomenal appearance of the front face of the polyhedron using a two-stage mechanism, which we will refer to as edge-integration. A lateral inhibitory process acts on the image to filter out the gradual changes in luminance on the front face, leaving only the step change in the middle. An integration process then fills in constant values of lightness in the two halves, based on the luminance difference across the step change. For more general scenes, the filtering stage factors out those changes in image luminance caused by smooth variations in incident illumination, leaving the sharp changes due to changes in surface reflectance. What would be seen, however, if the smooth luminance gradients were due not to the illumination of the surface, but to the shape of a smoothly curved surface? Figure 1*a* shows a modified version of the illusory stimulus in which the bounding contours have been changed from straight to curved. The modified bounding contours, well known cues for surface shape[7,13,14], evoke a percept of two abutting cylinders. The effect of such a change in perceived shape on perceived lightness is clear; the difference in perceived lightness of the two halves of the surface disappears when the surface appears curved. The visual system seems to take into account the cause of the smooth luminance gradient before determining surface lightness.

We did a simple experiment to obtain quantitative support for the effect of perceived surface shape on perceived lightness. The experiment made use of a lightness effect first presented by Arend *et al.*[15]. They showed that the perceived lightness difference between the two halves of a stimulus like that in Fig. 1*b* 'propagates' to darkened patches placed in the middle of each half of the stimulus. Thus, a patch placed in the phenomenally darker half of the stimulus appears darker than an equally luminous patch placed in the phenomenally lighter half. The difference in perceived lightness of the two patches is consistent with what would be predicted by edge-integration lightness models. If, however, perceived surface shape modulates perceived lightness in the way phenomenally demonstrated in Fig. 1, we would predict the disappearance of the effect for surfaces that appear curved. We tested this prediction by measuring the difference in Arend's lightness effect for images similar to that of the cylinders in Fig. 1*a* and images similar to that of the polyhedron in Fig. 1*b*.

Schematic diagrams of the stimuli used for the experiment are shown in Fig. 2. The strength of Arend's lightness effect was measured by presenting a darkened patch in one half of a stimulus image and having subjects adjust the luminance of an equivalent patch in the other half of the image so that its apparent surface colour appeared to be the same shade of grey as the test patch (the equal-lightness point). Half of the group of 24 subjects were presented with images of the curved surfaces as stimuli, and the other half were presented with images of the flat surfaces. Because the vertical luminance profiles for the two sets of images were equivalent, the only stimulus variable that differed for the two groups was the form of the bounding contours of the projected surfaces and the target patches. We will refer to the images of the quarter-cylinders as having 'curved' boundary contours, and the images of the flat surfaces as having 'jagged' contours.

Figure 3 shows the results from the experiment. The 5.8% average increase in luminance needed to make the target patch

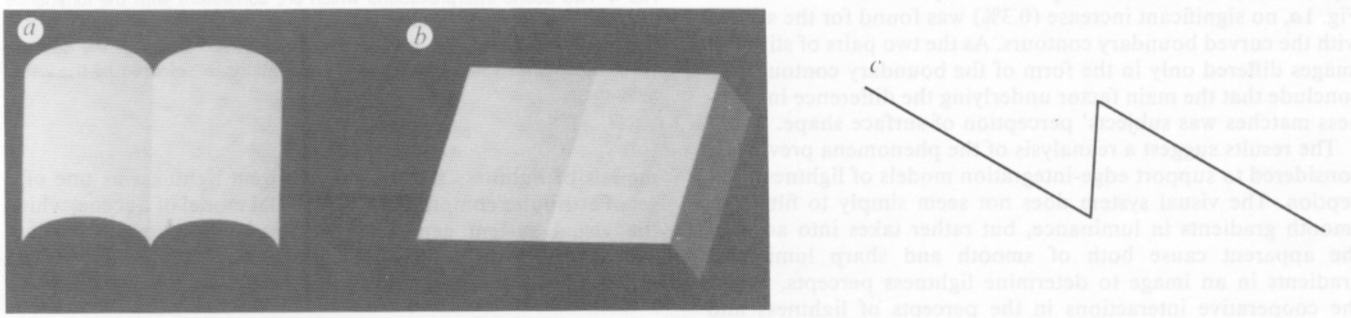

FIG. 1 *a*, Two abutting cylinders rendered to have a horizontal luminance profile consisting of two linear luminance ramps, shown in *c*. *b*, A rectangular polyhedron, the top face of which also has the horizontal luminance profile shown in *c*. The only difference between the two images is in the shape of the bounding contours of the surfaces, leading to the different shape percepts, which in turn determine one's percept of the reflectance patterns on the front faces of the two surfaces.

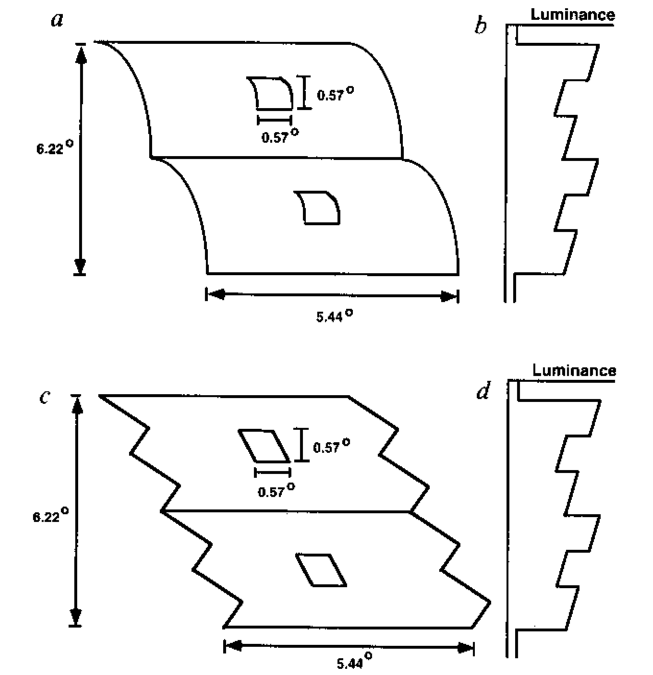

FIG. 2 *a* and *c*, Three-dimensional plot of the surfaces rendered to create the stimulus images. Dimensions are given in visual angle. *b* and *d*, Luminance profile along a vertical cross-section of each stimulus. The parameters defining the shape of the jagged edge boundary were selected to equate its length to the length of the curved edge boundary and to equate the angle made by the boundary at the corner formed in the middle of the stimulus to the angle made by the same corner for the curved edge boundary. Stimulus images were generated on a Stellar GS1000 computer using a three-dimensional rendering program developed by the author. Stimuli were displayed on a Macintosh IIx work-station with an 8-bit colour display monitor. The experiment consisted of a lightness matching task in which subjects were asked to adjust the brightness of a patch in one half of a stimulus image so that its apparent surface colour was the same shade of grey as an equivalent patch in the other half of the image. The half of the stimulus image in which the test patch was placed was varied randomly between trials. In each trial, the luminance of the test patch was scaled by one of three values: 0.7, 0.8 or 0.9. Subjects adjusted the luminance of the matching patch by moving the mouse up or down on a table to vary a factor by which the luminance of the patch was scaled. Subjects indicated a lightness match by pressing the mouse button. A total of 216 trials per subject were used. At the beginning of each trial, the luminance of the matching patch was randomly scaled by a value in the range 0.2–1.8.

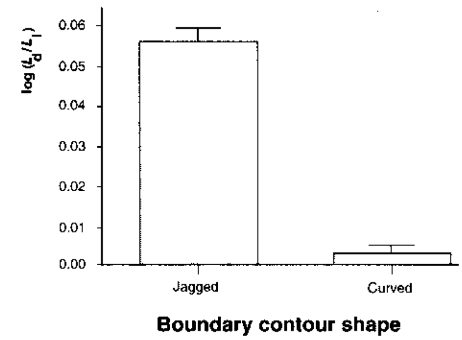

FIG. 3 Results of the matching experiment. In describing the results, we refer to the half of a stimulus image that would appear darker under the illusory lightness effect as the 'dark' half, and the half that would appear phenomenally lighter as the 'light' half. A subject's score on each trial was computed as the log ratio between the luminance of the patch in the 'dark' half of the stimulus image (L_d) and the luminance of the patch in the 'light' half (L_l) at the reported equal-lightness point (regardless of which patch served as the test patch). A score greater than zero indicates that when the patches appeared equally light, the patch in the 'light' half of the stimulus was actually less luminous than the one in the 'dark' half (conversely, such a score suggests that when the patches were equi-luminant, the patch in the light half appeared lighter than the patch in the dark half; Arend's result). The graph shows the average log ratio scores for the two main conditions of the experiment. The average score for the group which viewed stimulus images with jagged surface boundary contours was 0.056, which corresponds to a 5.8% difference in patch luminance at equal apparent lightness. The average log ratio score for the group which viewed stimulus images with curved surface boundary contours was 0.003%, corresponding to a difference of 0.3%. The difference in average scores between the two groups was highly significant ($T(22)=16.8$, $p<0.0001$).

in the phenomenally dark half of the images of the flat surface equal in lightness to the patch in the phenomenally light half replicates Arend's result. As predicted by the demonstration in Fig. 1*a*, no significant increase (0.3%) was found for the stimuli with the curved boundary contours. As the two pairs of stimulus images differed only in the form of the boundary contours, we conclude that the main factor underlying the difference in lightness matches was subjects' perception of surface shape.

The results suggest a reanalysis of the phenomena previously considered to support edge-integration models of lightness perception. The visual system does not seem simply to filter out smooth gradients in luminance, but rather takes into account the apparent cause both of smooth and sharp luminance gradients in an image to determine lightness percepts. Either the cooperative interactions in the percepts of lightness and surface shape occur quite early in visual processing, or illusory lightness effects once thought to reflect properties of low-level image proccessing mechanisms are actually the result of higher-level processes designed to extract information about multiple surface attributes from images. The results support functional models of lightness perception that treat lightness as one of a set of attributes comprising a perceptual model of a scene, which the visual system generates cooperatively to maintain consistency between its perceptual model and the luminance data provided in an image[16], as illustrated in Fig. 4. □

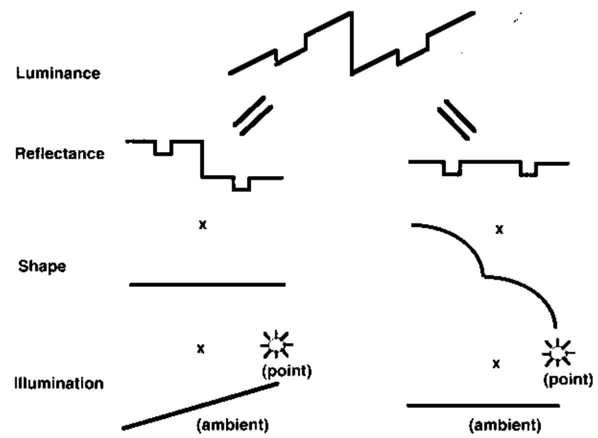

FIG. 4 Two scene interpretations which are consistent with the luminance pattern in the stimulus images used for the experiment. The shape of the surface boundary contour determines the perceived shape of the surface, which determines which of the two interpretations is 'selected' by the visual system.

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