On the nature of inducing forms generating perceptions of illusory contours

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Illusory contours of the Schumman/Kanisza type cannot be induced using forms defined solely by stereopsis, motion, or flicker. Two experiments using computer-generated random-dot stereo cinematograms support the notion that the inducing elements must be defined in the brightness domain for the illusion to occur.

Contours are usually defined as "that which is perceived at locations of sharp changes in stimulus." An edge is an indicator of such sharp change in some variable detectable by the visual system (e.g., brightness, hue, texture, relative motion, depth). Certain stimulus configurations, however, elicit the perception of a contour in the absence of corresponding physical (and therefore measurable) stimulation. This phenomenon is usually called illusory or anomalous contour.

Schumman (1904) was probably the first to notice this effect in the brightness domain, although it became widely known only through the work of Kanisza (1955, 1976, 1979). Anomalous contours have also been observed in the disparity domain, where clear-cut edges bounding a disparate form can be seen in stereograms with densities as low as 3% (Gullick & Lawson, 1976; Julesz, 1971). Such "depth edges," while certainly illusory, may not be the same phenomenon as that reported by Schumman and Kanisza, where it is the presence of a certain configuration of *inducing forms* (and not only the absence of a measurement) that leads to the perception of a superimposed, illusory object bounded, in part, by the illusory contour. In this communication, we investigate the nature of inducing forms only in the Schumman/Kanisza type of illusory contours.

Viewing such illusions,¹ one can usually discern three distinguishable components: A surface bounded by an edge in regions of homogeneous stimulation (illusory edge) is seen superimposed in front of inducing figures (illusory stratification) while there is a phenomenal brightness difference between such outlined form and its immediate background (illusory brightness difference). The (illusory) brightness enhancement as well as the illusory stratification may sometimes be absent (e.g., Kanisza, 1979). The illusory contours show, in some nontrivial sense, our fundamental lack of understanding of problems and processes of visual perception. Despite their physical simplicity (some displays consist of only three inducing

elements), there is no generally agreed upon explanation: the literature is full of competing proposals. The phenomenon epitomizes the ancient problem of stimulus equivalence—giving a physical characterization of a psychologically defined equivalence relation.

Theoretical accounts of the effect are either physiologically (e.g., Brigner & Callagher, 1974; Frisby & Clatworthy, 1975; Ginsburg, 1975; Jory & Day, 1979) or cognitively (Coren, 1972; Gregory, 1972; Kanisza, 1955, 1979; Rock, 1983) oriented. Without going into too much detail (see, e.g., Halpern, 1981, or Parks, 1984, for recent reviews), we note that there is evidence against some physiologically based theories. For example, it has been shown (Prazdny, 1983) that illusory contours and stratification can be perceived in displays constructed from inducing elements with opposite contrast (Figure 1a). Theories that postulate that anomalous contours derive from various forms of local contrast effects which somehow spread across regions that are marked by real edge fragments, line ends, and other features may encounter difficulties in these situations because contrast enhancements of opposite sign, on the one hand, must somehow interact to produce the illusion but, on the other hand, must not simply average out. The opposite-contrast displays also argue against a form of a physiologically based theory (Becker & Knopp, 1978; Ginsburg, 1975), which suggests that anomalous contours are not completely illusory in the sense that they are physically present in the low spatial frequency components of a Fourier transform of the inducing stimuli. Figure 1b illustrates why such an explanation is bound to fail in the displays containing inducing forms of opposite contrast: any (brightness domain) filtering of such stimuli will necessarily produce edges lying perpendicular to the perceived illusory contours. These conclusions are supported by recent neurophysiological observations by Heydt, Peterhans, and Baumgartner (1984), who reported that signals related to illusory contours were found in prestriate, but not in striate, cortex. They interpreted these findings as ruling out retinostriate mechanisms such as lateral inhibition, spatial-frequency filtering, or interpolation by elongated receptive fields, as explanations of illusory contours.

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a

b

Figure 1. (a) A display in which the inducing elements have opposite contrast generates the subjective contour effect. (b) A sign representation of the bandpass filtered image in Figure 2a. Positive filter values are displayed as white, negative values are displayed as black. Any spatial frequency filtering of "opposite-contrast displays" will produce edges perpendicular to the perceived illusory contour.

A figure can, in principle, be defined by any variable detectable by the visual system (e.g., brightness, hue, texture, relative motion, depth). Is it the particular configuration of inducers that is the important determiner of subjective contours? Can illusory contours be perceived independently of how the inducing elements were generated? There is some evidence that illusory contours of the Schumann/Kanizsa type are associated with the brightness-domain processing. For example, inducing forms defined solely by hue (i.e., the forms and the surrounding areas are isoluminant) seem to produce, at most, only weak subjective contours (Frisby & Clatworthy,

1975; Gregory, 1977). In the first experiment, we investigated whether illusory contours could be brought about by inducers defined in other domains (spatial and temporal correlation, and flicker) in the absence of monocular luminance-domain cues.

EXPERIMENT 1

A random-dot field is, by itself, void of any information (for our purpose, at least). Using random-dot stimuli, forms can be defined by relative motion, relative disparity, or flicker. Motion and stereopsis are (physically) defined as temporal (across the time) or binocular (between the two eyes) correlation. Flicker is the time change in the absence of motion. Random-dot images containing such correlations do not contain any information when viewed monocularly as static pictures. It is only when presented binocularly and/or in a rapid succession that one perceives the inducing forms. In our first experiment, we used random-dot stereo cinematograms (stereoscopically viewed computer-generated movies). Both the forms and the surround with respect to which they are defined can be varied along two independent dimensions: binocular (the forms and the background can be correlated, or uncorrelated, resulting in rivalry) and spatial (the forms and the background can be correlated, resulting in coherent motion, or uncorrelated, resulting in the perception of random dynamic noise similar to "falling snow") correlation.

Let c denote correlation and u its absence (or "uncorrelation"). Let subscripts s and t denote space and time, respectively. Then c_t denotes correlation across time, or coherent motion, and u_t denotes the lack of correlation across time (such stimulation results in the impression of dynamic or "snow" noise, like in detuned television). The doublet $[c_t, u_s]$ denotes the situation in which a region moves coherently but is binocularly uncorrelated (i.e., the first element denotes the state of the time correlation, and the second, the state of the binocular correlation). In our stimuli, we have basically only two regions: the inducing forms and the background. Thus, there are 16 possible combinations of couples of such doublets. For example, $[[c_t, u_s], [u_t, c_s]]$ denotes a condition in which the surround (first doublet) moves coherently and is binocularly uncorrelated, and the forms (second doublet) while binocularly correlated, are uncorrelated across time and thus appear as dynamic noise ("falling snow"). Only 15 of the 16 possible combinations are meaningful for our purpose. $[[u_t, u_s], [u_t, u_s]]$ is a situation in which there is no relative motion or disparity, that is, the forms cannot be visible. Such displays can also be viewed monocularly by inspecting only one half-image of the stereo cinematogram.

Method

The displays corresponding to the above described conditions were produced on a Symbolics 3600 LISP machine and displayed on a high-resolution noninterlaced CRT (refresh rate 60 Hz) with fast

Figure 2. Stereogram of four inducing elements in the field of (binocularly) uncorrelated random dots, when fused illusory contours are perceived independently of the depth position of the inducers with respect to the enclosing frame.

(P4) phosphor. The random-dot fields were constructed so that the black and white picture elements (pixels) occurred with equal probability. The stimulus duration of 100 msec and no interstimulus interval (ISI) were used in displaying the movie sequences. The displays had the form shown (as a static luminance-domain picture) in Figure 1. Each half-image of the stereogram was 200×200 pixels and subtended about 4° of arc from the viewing distance of 150 cm. One pixel was thus about $13'$ arc. The radius of the inducing elements was $27'$ arc. For flicker displays, the flicker frequency was 12 Hz, that is, each pixel (either within the inducing figures or in the background) changed its contrast polarity 12 times a second. Stereo cinematograms were viewed using free fusion by crossing the eyes in front of the stereogram. The lack of this skill in the (untrained) general population limited the number of observers used in our experiments to nine psychophysically experienced subjects who were all (by virtue of their profession) well acquainted with the concept of an illusory contour. The observers were instructed to report the illusory contours as occurrences of subjective boundaries enclosing a stratified figure. The order of presentation was completely randomized.

Results and Discussion

The obtained reports were unequivocal. None of the

observers reported seeing the illusory contours or stratification in any condition. In the monocular, uncorrelated inducers/correlated surround condition, the observers reported that the surround was seen as one plane with "holes" through which one could see the "falling snow" noise. In the correlated inducers/uncorrelated surround condition, the correlated forms were perceived in front of the dynamic noise background. Thus, the uncorrelated portion of the display is always seen as a "background," positioned at an "indeterminate" distance behind the correlated (coherently moving or stationary) regions. In both flicker conditions, the observers reported that the flickering regions were seen as being behind the nonflickering regions. The manipulation of depth position of the inducers (using stereopsis) did not have any effect on the absence of perception of illusory contours. In short, inducing elements defined solely by stereopsis, motion, or flicker do not lead to the perception of illusory contours.

It is possible that the failure to observe the illusory con-

Figure 3. Stereogram of four inducing elements in the field of (binocularly) correlated random dots. Illusory contours may be observed when the inducing elements are perceived behind the surrounding random-dot field (bottom stereogram when fusion is obtained by crossing the eyes in front of the display, and top stereogram otherwise). No illusory contours are seen when the inducing elements are positioned in front of the surrounding field (top stereogram when fusion is obtained by crossing the eyes in front of the display and bottom stereogram otherwise).

tours in these situations is caused by an implicit depth ordering imposed by the visual system on inputs of time-varying nature. The nonflickering regions in our flicker displays were always seen in front of the flickering regions. Such a phenomenal stratification effect has apparently been noticed before (Wong & Weisstein, 1984). Similarly, the uncorrelated portion of the display is always seen as a background to the correlated (moving or stationary) regions.² Thus, our methods to generate the inducing elements make them stand out as distinct entities segregated from the background in depth. It is known that depth information incompatible with the stratification produced by illusory contours reduces the strength of the illusory contours (Gregory & Harris, 1974).

Another possible factor causing the absence of illusory contours in our motion situations may be the similarity of motion within the region that is normally perceived as

the subjective contour object (a square in our situation) to the motion in the remaining parts of the display corresponding to the background. The organizational principles of "common fate" based on such similarity could tend to produce a signal associated with a single uniform surface, which contradicts any possible depth stratification tendencies. We have observed, however, that such organizational tendencies do not inhibit the occurrence of illusory contours and stratification when the inducing forms are defined in the brightness domain. Thus, even when the background random-dot field in Figure 2 moves in an arbitrary fashion (either coherently or as dynamic noise), one can clearly perceive the subjective contours (and particularly clearly when the inducing forms also move). This compelling percept suggests again that illusory contours of the Schumman/Kanizsa type may be somehow associated with the brightness-domain process-

ing. To investigate this issue, Experiment 2 was performed in which the inducing elements were defined in the brightness domain.

EXPERIMENT 2

The displays in Experiment 2 were equivalent to those in Experiment 1 with the difference that the individual inducers were monocularly visible as solid pie-shaped figures (see Figures 2 and 3). The relevant dimensions of the independent variable were the spatial (monocular, binocularly correlated, or uncorrelated) and temporal (static, correlated, or uncorrelated) viewing parameters. The subjects were the same nine observers used in Experiment 1. The order of presentation was chosen at random by the computer.

Results and Discussion.

The results are summarized in Table 1, which shows the number of observers reporting the occurrence of an illusory contour under various stimulus conditions.³ Monocularly viewed displays produced illusory contours both on coherently and randomly moving surround and both when the inducing elements were stationary or (rigidly) moved across the background.

Stereo cinematograms portraying inducers on the binocularly uncorrelated surround produced clear subjective contours independently of the perceived depth position (with respect to the enclosing frame) of the inducers (Figure 2). When the inducers as well as the surround were moving, however, the resultant percept was bistable: periods of clear subjective contour alternated with the perception of inducers lying in front of the randomly moving surround without any impression of stratification or illusory contours.

When the surrounding random-dot field was binocularly correlated, the percept was a function of the inducer's depth position with respect to the surround (Figure 3). When the inducers were positioned (by stereopsis) behind the surround, the observer clearly perceived the effect. It was weakly present when a static stereogram was viewed, but was quite pronounced when the inducers moved. In both cases, the surrounding random-dot field was perceived as a transparent plane through which one could see the moving inducers with a superimposed sub-

jective square. Interestingly, the illusory contours and stratification were also observed when the inducing elements were lying in the plane of the surround. All nine observers reported a clear and convincing perception of the illusory contour resembling a square of a clear glass with well-defined edges (this result is not entered in Table 1). None of the subjects reported the perception of an illusory contour when the inducers were positioned in front of the surrounding random-dot field.

CONCLUSIONS

Our first experiment suggested that inducing elements created by flicker and spatial and/or temporal correlations were ineffective in bringing about the illusion. Our second experiment showed that the absence of subjective contours in the displays was not caused simply by similarity of motion of the surround and the area associated with the subjective figure: when the inducers were defined in the brightness domain, subjective figures occurred despite such common motions. Illusory contours occurred even despite the depth organization that placed the inducers in front of the (temporally uncorrelated) background in Experiment 2.⁴ Here, the stratification effects due to the subjective contour phenomenon are apparently able to dominate the inducers' tendencies to appear in front of the surround. This suggests that the inability to evoke an illusory contour in Experiment 1 may not be caused solely by the unfavorable depth ordering produced by stimuli of time-varying nature.

The second experiment showed several other interesting phenomena. In both monocular and the binocular viewing conditions, the subjects reported that the effect was much more compelling with moving inducers: the illusory edges could clearly be localized and seen as moving rigidly together with the inducers. Such increase in salience may possibly be related to the kinetic subjective contour effect recently reported, for example, by Kellman and Cohen (1984). This impression was particularly strong when the display was slightly defocused.

The percept of subjective edges occurred in the absence of accretion/deletion along the illusory edges, thus suggesting that accretion/deletion is not a necessary ingredient of the perception of occlusion in the displays of time-varying nature. The accretion/deletion that occurred along the edges of the moving inducing elements did not preempt the perception of illusory contours. Preliminary observations suggest that the occlusion relation specified by the accretion/deletion of texture along the occluding edge (as suggested by, e.g., Gibson et al., 1969) may be a local, attentional effect.

Monocularly visible, brightness-domain inducing elements appearing in front of the surround in displays with binocularly correlated surround do not lead to the perception of subjective contours despite the fact that such contours are clearly present monocularly in each half-image of the stereogram. This shows the dominance of cyclopean organization (which places the regions of "sub-

Table 1
Number of Subjects Reporting Perception of Illusory Contour
in Experiment 2

Time Parameters	Binocular Parameters			
	Monocular	Correlated		Uncorrelated
		Front	Back	Front Back
Correlated	9	0	9	9 9
Uncorrelated	9	0	9	9 9
Stationary	9	0	5	9 9

Note—"Front" and "back" denote the depth position (manipulated by stereopsis) of the inducers with respect to the surrounding random-dot field.

jective figure" at the same relative depth as the surround) over the monocularly perceived organization (in which the subjective figure is seen superimposed on top of the inducers, and therefore the surround). It is an example of inverse cyclopean stimulation (Julesz, 1971), which shows that whenever binocular fusion occurs, this process dominates a monocularly perceivable organization.

In summary, our experiments support the notion that the illusory contour effects of the Schumman/Kanisza type are tied to the brightness-domain processing in the sense that the inducing elements defined in the brightness domain seem necessary to bring about the illusion.⁵

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NOTES

1. Perhaps one should not speak about illusions at all. A phenomenon can be an illusion only if one expects a rigid, one-to-one relationship between the physical and psychological variables. This, of course, does not exist! A better description of such phenomena may be "nonveridical perception." We will use the term "illusion" for historical reasons.
2. It is even possible that such perceptual stratification has a common origin: the uncorrelated portions of the display are always seen as a background to the correlated regions. Flicker is perfect temporal "uncorrelation" (in the brightness domain) because an element is replaced by another element of exactly the same shape but opposite contrast.
3. Assuming that under the null hypothesis an observer is as likely to report the perception of an illusory contour as not, the exact (binomial) probability of 9 reports out of 9 is 0.002. The probability of 5 reports out of 9 is 0.246.
4. A moving filled-in figure is perceived in front of its (randomly moving) random-dot surround. This percept may be due to the accretion/deletion along the borders of the figure.
5. There are situations in which the illusory contours are not perceived in the static mode (because the inducing forms are not present simultaneously) but are perceived when kinetic information is provided. For example, Kellman and Cohen (1984) generated subjective contours by successively exposing the inducers. This resulted in perception of apparent motion of the subjective figure. Clearly, some kind of "memory," or information integration over time, is required. Observe, however, that even here the inducers were defined by the luminance changes (so that a static subjective figure would be perceived if the inducing forms were displayed at the same time).

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