TEXTURE AND VISUAL PERCEPTION

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Random-dot patterns generated by computer show that the recognition of familiar shapes is not needed for the discrimination of textures or even, as had been thought, for the binocular perception of depth.

Because we are surrounded every waking minute by objects of different sizes, shapes, colors and textures we are scarcely surprised that we can tell them apart. There are so many visual clues to the distinctiveness of objects that we hardly ever make the mistake of believing that two different objects are one object unless we have been deliberately tricked.

Four years ago I became interested in studying the extent to which one can perceive differences in visual patterns when all familiar cues are removed. In this way I hoped to dissociate the primitive mechanisms of perception from the more complex ones that depend on lifelong learned habits of recognition. To obtain suitable patterns for this investigation a computer was used to generate displays that had only controlled statistical, topological or other properties but entirely lacked familiar features.

This method is basically different from those employed earlier by workers interested in visual perception. One method that has been widely used is to impoverish or degrade the images presented to the subject. This can be done by adding visual "noise," by presenting the stimuli for a limited time or by otherwise impairing the normal conditions of viewing. Another approach is to study human subjects whose perceptual mechanisms are known to be deficient (for example people who are color-blind) or animals whose perceptual mechanisms have been altered by surgical operations. I hoped that my approach of "familiarity deprivation" might be a useful addition to these other methods.

In a broad sense I was interested in the same kind of problem that has long concerned psychologists of the Gestalt school. One such problem has been to explain why it is that under certain conditions an outline drawing is seen as a unified whole—as a Gestalt—and under other conditions is seen as having two or more parts. I undertook to reduce this problem to one discriminated between the parts (or did not discriminate between them). In my investigations, which have been conducted at the Bell Telephone Laboratories, I have been concerned with two specific questions. First, can two unfamiliar objects connected in space be discriminated solely by differences in their surface textures? Second, can two unfamiliar objects with identical surface textures be discriminated solely on the basis of their organization in space?

To make these questions less abstract let me give examples that could arise in real life. The first question would be involved if you wanted to replace a section of wallpaper and discovered that the original pattern was no longer available. If the pattern happened to be nonrepresentational and irregular, you might be able to find a new pattern that could not easily be discriminated from the old one when the two were placed side by side. Yet if you studied the two patterns closely, you might find that they differed substantially in detail. You would conclude that the matching must be attributable to the similarity of certain critical features in the two patterns.

The second question has its counterpart in aerial reconnaissance to detect objects that have been camouflaged. Flying at a height of several thousand feet, an observer can easily be deceived by the camouflage because normal binocular depth perception is inoperative beyond 100 feet or so. But if he photographs the ground from two points several hundred feet apart and views the resulting pictures stereoscopically, he will usually discover that even a camouflaged object will stand out vividly in three dimensions.

Of course neither of these examples provides an adequate test of the discrimination problems I hoped to examine with artificial displays. The weakness in the wallpaper analogy is that most wallpaper patterns, including irregular ones, have repetitive features and even forms that suggest familiar objects. The aerial reconnaissance example has the important defect that most camouflaged objects have contours that can be recognized monocularly as TEXTURE DIGNICATION in random fields of colored dots is highly dependent on the way the component colors are paired. The two patterns at the top of the opposite page are basically the same as those shown one above the other on the cover of this issue. Neither version adequately reproduces the author's laboratory demonstration, in which the patterns are created by colored lights of equal subjective brightness. To simulate this condition the yellow picture elements on the cover have been reduced in brightness by a linear-scale overlay of black dots. They have the drawbacks, however, of making the yellow areas look greenish. In the version on the opposite page the black-dot overlay has been omitted, with the result that the yellow elements are much too bright. On the whole the cover comes closer to achieving the desired effect, which is to show that a texture composed chiefly of red and yellow dots is readily discriminated from a texture composed chiefly of blue and green dots (top half of cover), whereas a texture composed chiefly of red and green dots is not so readily discriminated from one composed chiefly of blue and yellow dots (bottom half of cover). These paired textures—one easily discriminable, the other less so—are respectively repeated at top left and right on the opposite page. The makeup of each top panel is shown in the four panels below it. The only difference is in the transposition of yellow and green.
The importance of proximity and similarity was emphasized early in the work of the Gestalt psychologists, par-

Some other difficulties are quite easily circumvented by using a computer to generate random-dot patterns in which all familiar cues and other unwanted factors are eliminated. For the purpose of studying the first problem—the role of texture in discrimination—random-dot patterns with different properties were generated side by side. The objective was to determine those pattern properties that make it possible to discriminate between the adjacent visual displays. I was concerned primarily with the discrimination that can be achieved immediately. Such discrimination can be regarded as a spontaneous process and thus can be ascribed to a primitive perceptual mechanism.

An example of spontaneous discrimination is given by the illustration at bottom left on the opposite page. Both fields of the pattern contain black, gray, and white dots with equal first-order, or overall, probability, therefore if the pattern is viewed from a distance, both fields appear uniformly gray. When the two fields are viewed at close range, however, they exhibit a different second-order, or detailed, probability. This shows up immediately as a difference in granularity.

The illustration at bottom right on the opposite page represents a case in which there can be no spontaneous discrimination between two fields. In this case discrimination can be achieved only by someone who knows the difference between English words and random sequences of letters. Here discrimination requires a sophisticated kind of pattern recognition. This article is concerned only with discrimination of the spontaneous type.

In the case of random-dot patterns one might think that discrimination of visual texture is fundamentally governed by variations in the statistical properties of the patterns, i.e., in the general sense, because any two different patterns must differ in some such property. However, that simple statistical measurements of brightness distribution are not adequate to describe perceptual performance.

This is demonstrated in the illustration at upper left on this page, which consists of two patterns made up of black, gray, and white dots. In one quadrant the dots are distributed with equal probability; in the other, they are randomly placed. The surrounding area matches the quadrant in overall brightness, but it also contains small triangular units composed of black, white, and gray dots in various arrangements. Although these triangular units occur with equal probability, the only ones observed are those made up entirely of black dots; the others pass unnoticed.

This indicates that discrimination of visual texture is not based on complex statistical analysis of brightness distribution but involves a kind of preprocessing. Evidently the preprocessing extracts neighboring points that have similar brightness values, which are perceived as forming clusters or lines. This process, which should not be confused with the actual spatial connection of objects, might be called connectivity detection. It is on the relatively simple statistics of these clusters and some simple description of them, such as spatial extent, that texture discrimination is really based.

The lower pair of illustrations above shows this connectivity detection even more clearly. In the left member of the pair two textures are easily discriminated; in the right member discrimination is difficult, if not impossible. In the pattern at the left every fifth horizontal and vertical row is gray, in the pattern at the right, which is otherwise identical, every fifth row is randomly peppered black and white. The "noise," added to the pattern at the right has only a minor effect on the statistics of the two subpatterns to be discriminated, yet it breaks up the connectivity of the subpatterns enough for them to merge into one field. The black and white "S" shapes that appear so clearly in the pattern at the left are completely destroyed in the pattern at the right. If the disrupted pattern is viewed at a sharp angle, however, the line clusters reappear and discrimination is facilitated.
STEREOSCOPIC PRINCIPLE is simply that identical areas that appear in both fields must be shifted horizontally with respect to each other. Because these areas are themselves random-dot patterns they cannot be seen monocularly against a random-dot surround. In these diagrams A identifies the area common to both fields. In the upper pair of fields, A is shifted inward, leaving two areas, X and Y, that are filled in with different random-dot patterns. When viewed stereoscopically, A seems to float above the surround. When A is shifted outward as shown in the two lower fields, A seems to lie behind the surround.

Evidently this clustering, whether it is of adjacent brightness levels or of adjacent hues, represents a pre-processing mechanism of great importance in the visual system. Instead of performing complex statistical analyses when presented with complex patterns, the visual system wherever possible detects clusters and evaluates only a few of their relatively simple properties. One now

TO USE PRISM hold it about six inches in front of the right eye, thin edge toward the nose. Adjust the prism so that both stereoscopic images can be seen through it. Each image should then be visible to the left eye, as shown in the upper two diagrams. With a little difficulty the images should rearrange themselves so that there appear to be only three images, of which the center one is the fused stereoscopic image. These binaural cues that has occurred the image can be made sharper by moving the prism closer to the right eye.

STEREOSCOPIC IMAGES investigated by the author consist of random-dot patterns generated by a computer. When these two images are viewed with a stereoscope or with a prism held in front of one eye, a center panel should be seen floating above the background, as illustrated at the far right. The principle employed in making such stereoscopic images is explained below.

GELATIN PRISM provides a simple stereoscopic viewer. A clear plastic box for holding the gelatin can be obtained at a five-and-ten-cent store. Use four parts of very hot water to one part of household gelatin and mix thoroughly. Tilt the box about 15 degrees and pour in the gelatin solution. In about 30 minutes, when the solution has gelled, dampen the surface and press a rectangular sheet of clear plastic (or glass) against it. The prism will ordinarily work without this top sheet, but images may appear fuzzy.

GELATIN PRISM

PLASTIC SHEET

LEFT EYE RIGHT EYE

LEFT PATTERN

FUSED PATTERN

RIGHT PATTERN

LEFT EYE RIGHT EYE

TO USE PRISM hold it about six inches in front of the right eye, thin edge toward the nose. Adjust the prism so that both stereoscopic images can be seen through it. Each image should then be visible to the left eye, as shown in the upper two diagrams. With a little difficulty the images should rearrange themselves so that there appear to be only three images, of which the center one is the fused stereoscopic image. These binaural cues that has occurred the image can be made sharper by moving the prism closer to the right eye.
has a formula for matching wallpaper patterns. As long as the brightness value, the spatial extent, the orientation, and the density of clusters are kept similar in two patterns, they will be perceived as one. Even for familiar patterns with recognizable and different forms discrimination can be made very difficult or impossible if the simple rules that govern clustering are observed. Thus a wallpaper pattern made up of seven-letter nonsense would form clusters that could not be discriminated spontaneously from English words. These findings answer the affirmative the first question raised at the beginning. Objects can indeed be discriminated by differences in their surface texture alone even if they are spatially connected and cannot be recognized. The basis of this texture discrimination depends on simple properties of clusters, which are detected according to simple rules. Cluster detection seems to be a quite primitive and general process. Recent neurophysiological studies of frogs and cats have disclosed that their visual systems extract certain basic features of a scene prior to more complex processing (see "Vision in Frogs," by W. R. A. Muntz, SCIENTIFIC AMERICAN, March, 1984, and "The Visual Cortex of the Brain," by David H. Hubel, SCIENTIFIC AMERICAN, November, 1965). The "bug" detector in the frog's visual system and the tilt detector in the cat's visual system are special cases of connectivity detection. It will be interesting to neurophysiologists can find evidence for cluster detectors of the type suggested by these experiments.

We are now ready to consider the second question: Can two unfamiliar objects of identical texture be discriminated solely on the basis of their spatial separation? To study this question it was necessary to create patterns that were unfamiliar, that had the same surface texture and that could be perceived in depth. Again the problem was solved with the help of random-dot patterns generated by a computer. This time the computer was used to generate pairs of patterns that were identical except for a central area that was displaced in various ways. I had hoped that one would obtain a sensation of depth when the two patterns were viewed stereoscopically, and I was delighted when that turned out to be the case. This proved that one can perceive a camouflaged object in depth even when the camouflaged object is perfect and the hidden object cannot be discerned monocularly. In short, the answer to the second question is also yes. A pair of these random-dot stereoscopic patterns is shown in the upper illustration on page 8. The two patterns are identical except for a central square that is shifted horizontally to the left by six dots. This pattern at the right. By virtue of this shift the square seems to float above the background when it is viewed stereoscopically. If the reader does not have an old-fashioned stereoscopic viewer at hand, by following the instructions on page 6 he can easily make a prism of gelatin that will serve the same purpose. The phenomenon demonstrated by the binocular fusion of such random-dot patterns has a number of surprising implications. First of all, as the original statement of the problem requires, the stereoscopic picture is completely devoid of all familiarity and depth cues. Although the area selected for stereoscopic displacement in the first example is a simple square, it could be of any shape and it could also give the illusion of having more than one level [see illustration above]. The fact that the center square and its surround are horizontally shifted by different amounts in the fields at left and right corresponds to the different depth levels that are perceived. Thus spatial dis-
The German physiologist Ewald Hering believed that this processing involves the crossing or uncrossing of images that are initially perceived as double because they lie either in front of or behind the eyes' point of convergence. The extent to which this cue is utilized could not previously be determined because double images were inherent in stereoscopic presentation. The random-dot stereoscopic images, on the other hand, do not contain recognizable images prior to their actual perception in depth; thus it is impossible to perceive double images either before or after fusion.

It could still be argued that although random-dot stereoscopic pairs do not contain recognizable shapes, some similar patterns can be perceived in the two fields and these might serve as the basis for fusion. This possibility can be tested in several ways. In the top stereoscopic pair on page 8 the field at the left has been blurred by being printed out of focus. Even when the patterns are almost obliterated in this way, stereopsis is easily obtained. What is more surprising is that the perceived image resembles the sharp one. The blurred image serves only to convey the required disparity information and is then suppressed.

The bottom stereoscopic pair on page 8 carries the disruption of patterns still further. This is achieved by breaking the diagonal connectivity in the field at the left. Along one diagonal whenever three adjacent dots were black, the middle dot was changed to white, and along the other diagonal whenever three adjacent dots were white, the middle one was changed to black. In the field at the right diagonally adjacent groups of three black or white dots were left unchanged. This procedure changes 20 percent of the picture elements in the field at the left and so removes them from the fusion process. The fact that the two fields look so different when viewed monocularly and yet can be perceived in depth when viewed stereoscopically provides additional evidence that no monocular pattern recognition is necessary and that the ultimate three-dimensional pattern emerges only after fusion has taken place.

Although the random-dot stereoscopic images lack monocularity cues, which normally govern stereoscopic perception, they are actually easier to perceive in depth than stereoscopic images of real objects. The explanation is that each black or white dot in a random pattern contributes depth information, whereas in actual objects there are large homogenous areas that carry no depth information. Thus random-dot stereoscopic fields that differ by 10 percent or more can easily be perceived in depth [see middle illustration on page 8].

It is probably obvious that these findings have important implications for Gestalt psychology. According to this school stereoscopic perception is not a result of the complex of stimuli projected on the retina; rather each eye works up its complex of stimuli into a Gestalt and it is the difference between the two Gestalts that gives rise to the impression of depth. The fact that stereopsis can be obtained in random-dot images without any monocular cues decisively settles this question, since no Gestalt can be worked up. It might still be argued that Gestalt factors operate after the binocular fusion of the two fields. In this connection it is interesting to look closely at the vertical boundaries of the raised panel formed by the top stereoscopic pair on page 7. The boundaries are fuzzy. The reason is that the black-and-white picture elements along the boundary have an equal probability of being perceived as belonging either to the raised panel or to the surround. Because a square has a "good Gestalt" one might expect to perceive these points as forming a straight line. That they do not suggests that perception is governed by simple considerations of probability.

In presenting random-dot stereoscopic pairs for the first time, one might expect to perceive these points as forming a straight line. That they do not suggests that perception is governed by simple considerations of probability. The finding was made while I was trying to measure the minimum time needed to present random-dot images. The time cannot be measured simply by presenting the images for periods of time. For the reason that afterimage remains on the retina for an indeterminate time, I found that it was possible to "erase" these afterimages by a new technique. If the first pair is seen, then the afterimage remains on the retina for an indeterminate time. If a second pair is then seen, the first afterimage is erased. When the presentation time of the first pair was long enough, the ambiguous panel in the second pair consistently remained at the same location as the panel in the first pair. A presentation time adequate to produce this result was about 40 milliseconds; it can be regarded as the "minimum perception time" for stereopsis. When the first pair is presented for a shorter time, or when the second pair is delayed by more than a certain interval, which I have called the "attention time," the second pair is removed from the subliminal influence of the first and is perceived ambiguously. These experiments suggest that the first pair serves as a "depth marker" and determines which of the two possible depth organizations in the second pair should be favored. All this processing must take place in the central nervous system because the times are too short for any eye motion to be initiated.

The various studies described in this article indicate that visual texture discrimination and binocular depth perception operate under simpler conditions than has been thought, since they do not require the recognition of form. This finding makes it attractive to try to design a machine that will automatically produce contour maps according to information contained in aerial stereoscopic photographs. As long as it seemed that such a task could only be done by a machine that could recognize complex and virtually unpredictable shapes, the job seemed all but hopeless. On the basis of the new findings I have helped to devise a computer program (called Automap-1) that can be used to produce contour maps from high-resolution stereoscopic images [see illustration on page 12]. This computer program not only should be useful for reducing the tediousness of pro-
AUTOMAP-1 is a computer program that compiles a three-dimensional contour map from two-dimensional stereoscopic images. The program compares left and right fields point by point and subtracts the brightness of each point from its counterpart. Where the two fields match, the difference is zero, shown above as a white area. Thus the surround \( D_0 \) is white except where there is a shifted center panel. The program repeats the point-by-point comparison after shifting one field horizontally (both left and right) by one unit, two units and so on. This provides an ordered set of depth planes \( D_1, D_2, \ldots \). When a shift such as \( D_2 \) or \( D_{-2} \) brings a shifted panel into alignment, the points in the panel cancel and show up as zero (white). Form recognition is not needed.

Producing such maps but since it is based on psychologically observed phenomena it is also a crude model of part of the visual system.

This article has described methods for studying visual texture discrimination and depth perception in their purest form. The methods have shown that connectivity detection is basic to both visual tasks and that it is a more primitive process than form recognition. It remains to be seen if on the psychological level a simpler "explanation" can be given. I hope that the next findings in this area will come from neurophysiologists.

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**Bibliography**


