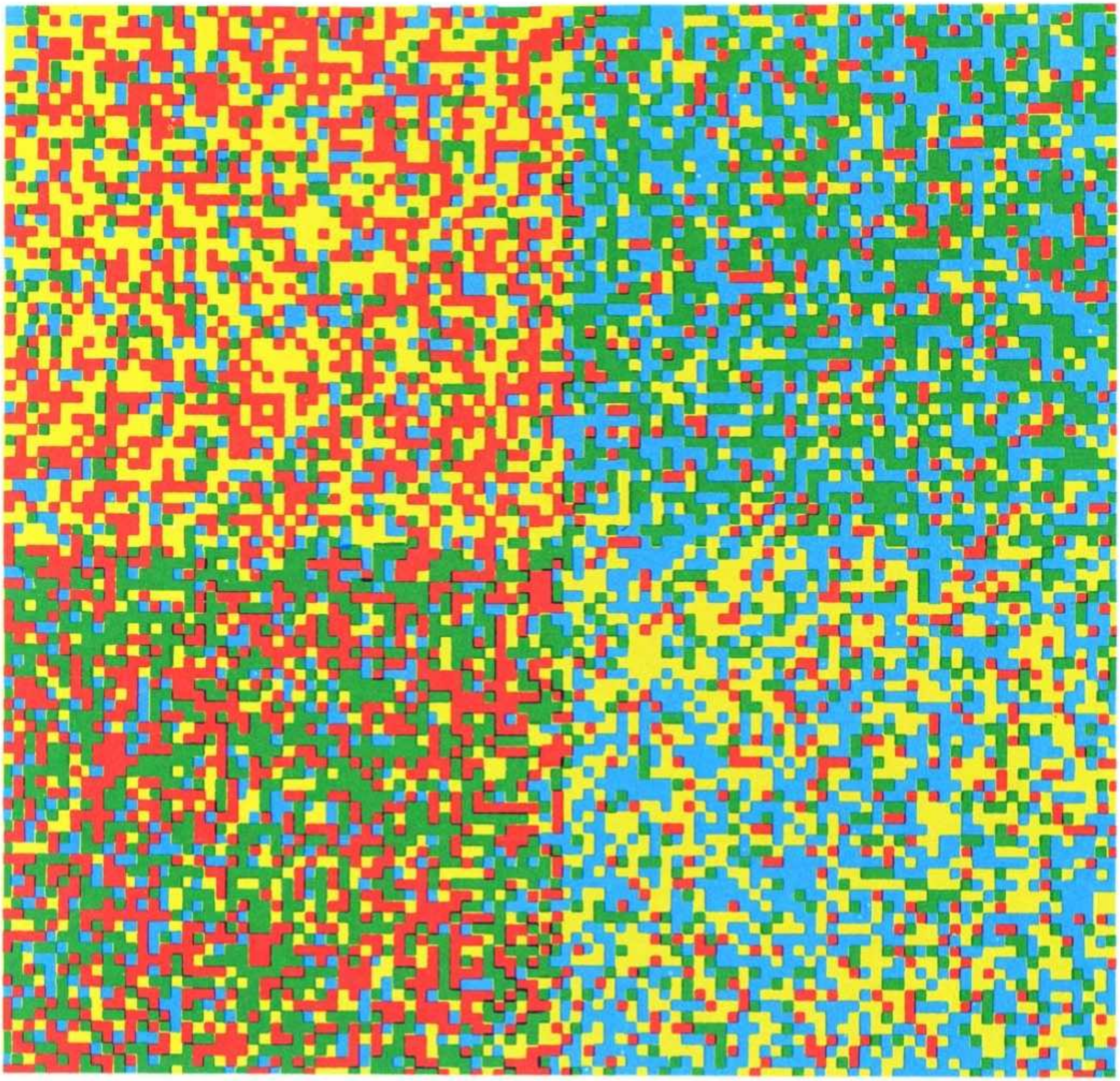


# TEXTURE AND VISUAL PERCEPTION

by BELA JULESZ

REPRINTED FROM
SCIENTIFIC AMERICAN
FEBRUARY 1965
VOL. 212, NO. 2 PP. 38-48

PUBLISHED BY W. H. FREEMAN AND COMPANY 660 MARKET STREET, SAN FRANCISCO, CALIFORNIA 94104

# Texture and Visual Perception

*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*

by Bela Julesz

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 subtly 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 how 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 texture? Second, can two unfamiliar objects with identical surface texture be discriminated solely on the basis of their separation in space?

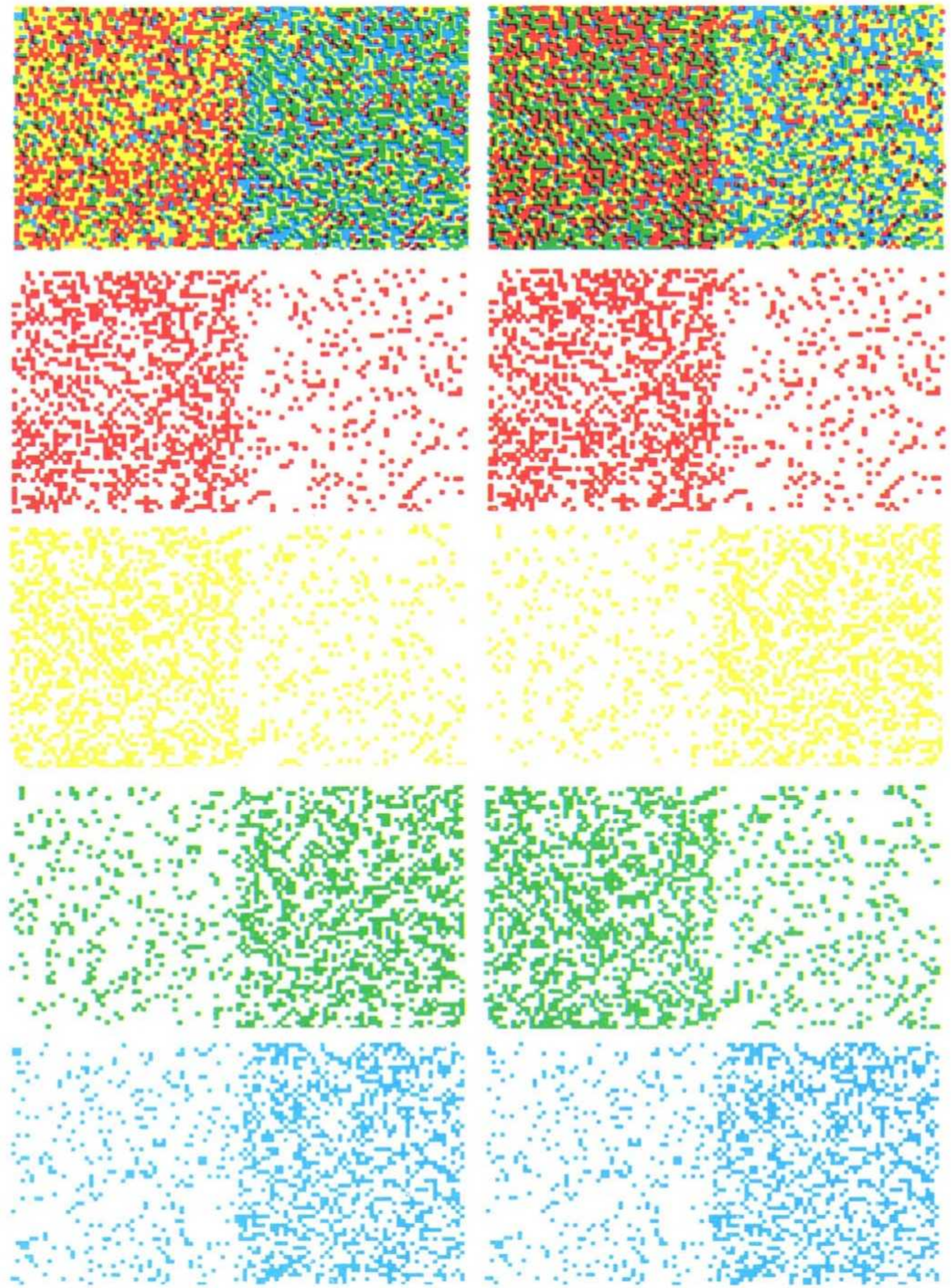
To make these questions less abstract let me give examples that could arise in real life. The first question would be involved if you wanted to replace a section of wallpaper and discovered that the original pattern was no longer available. If the pattern happened to be nonrepresentational and irregular, 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.

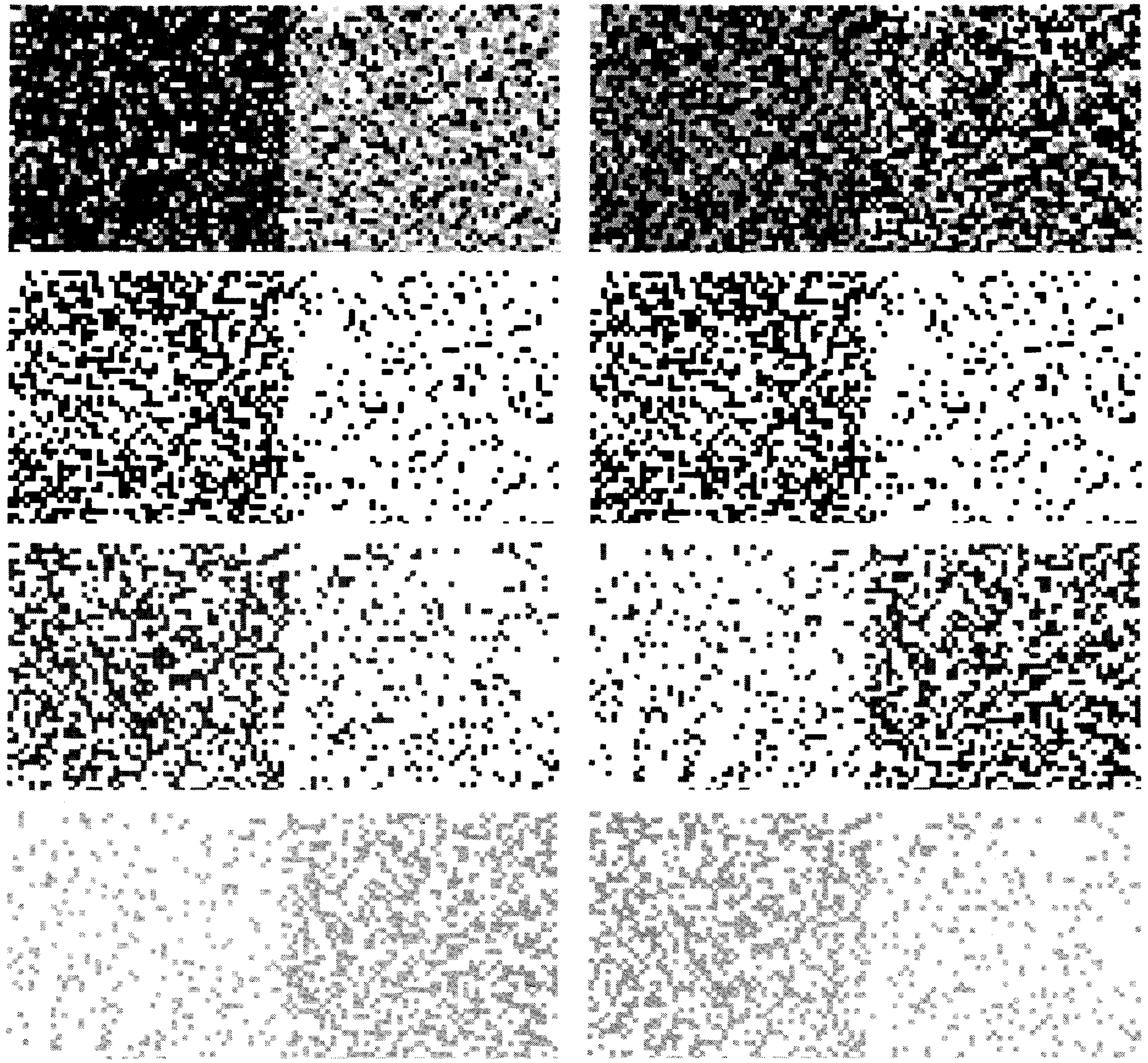
The second question has its counterpart in aerial reconnaissance to detect objects that have been camouflaged. Flying at a height of several thousand feet, an observer can easily be deceived by the camouflage because normal binocular depth perception is inoperative beyond 100 feet or so. But if he photographs 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

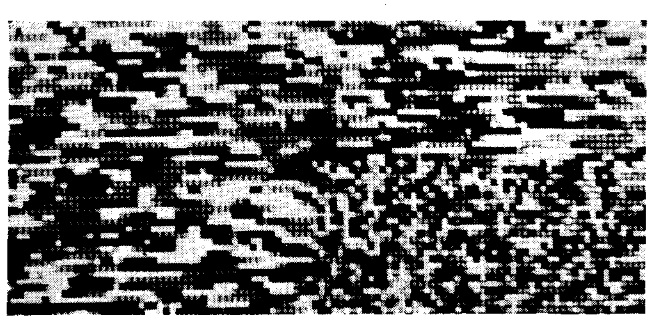
**TEXTURE DISCRIMINATION in random fields of colored dots is highly dependent on the way the component colors are paired. The two patterns at the top of the opposite page are basically the same as those shown one above the other on the cover of this issue. Neither version adequately reproduces the author's 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 fine-mesh overlay of black dots. They have the drawback, 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.**



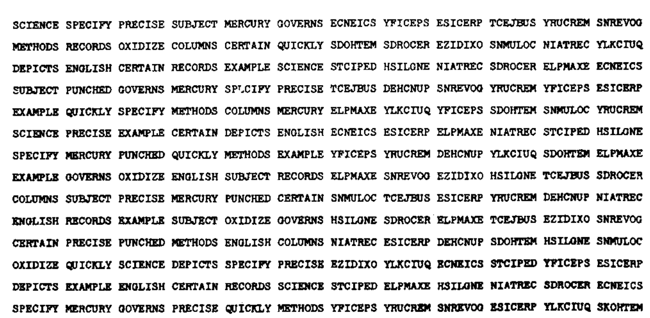




**EASE OF DISCRIMINATION** in random patterns of various brightness levels seems to depend on whether or not adjacent dots of different values form clusters. The pattern at top left forms two easily discriminated areas because the half field on the left contains mostly black and dark gray dots, which form dark clusters, whereas the half field on the right contains mostly light gray and white dots, which form light clusters. When the dark gray and light gray components are reversed (*top right*), the clustering does not take place and the half fields are not so readily discriminated. The composition of each top pattern is shown in the three panels below it.



**SPONTANEOUS DISCRIMINATION** occurs even though the smaller field has the same average tonal quality as the larger field because the granularity of the two fields is different. At a distance the granularity is less noticeable and discrimination more difficult.




**NONSPONTANEOUS DISCRIMINATION** is represented by two half fields that have the same apparent texture and granularity. The left half field, however, contains familiar English words, whereas the right half field contains only random sequences of seven letters.



shapes of some sort; they are not, in other words, random patterns.

These and 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.

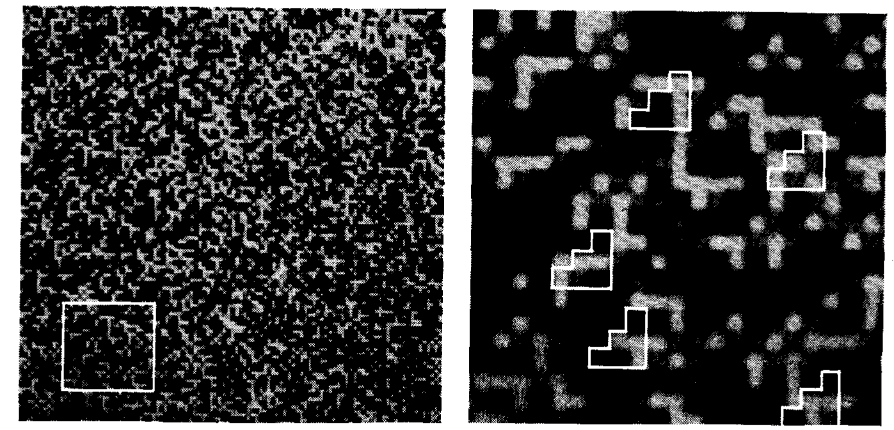
In the case of random-dot patterns one might expect that discrimination of visual texture is fundamentally governed by variations in the statistical properties of the patterns. That is true in the most general sense, because any two different patterns must differ in some such property. It turns out, 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 and completely at random. 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.

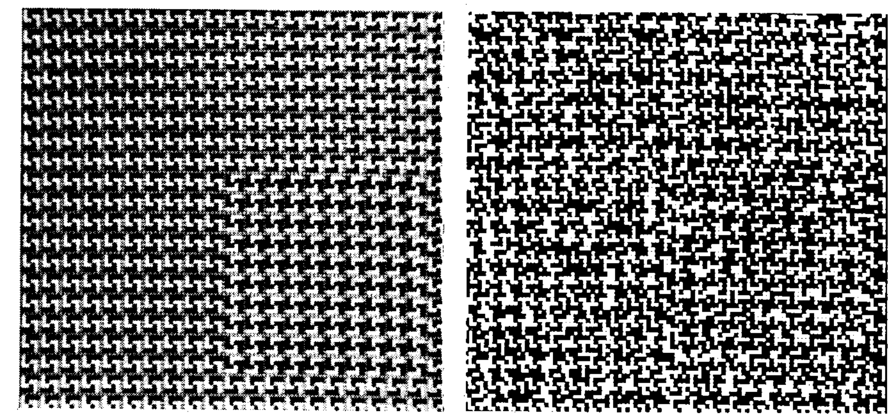
This indicates that discrimination of visual texture is not based on complex statistical analysis of brightness distribution but involves a kind of preprocessing. Evidently the preprocessing extracts neighboring points that have similar brightness values, which are perceived as forming clusters or lines. 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.

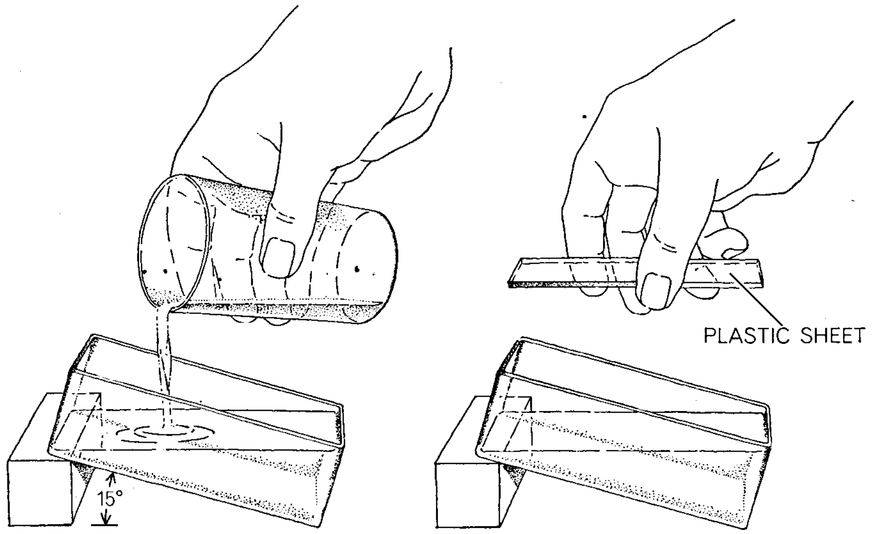
The importance of proximity and similarity was emphasized early in the work of the *Gestalt* psychologists, par-



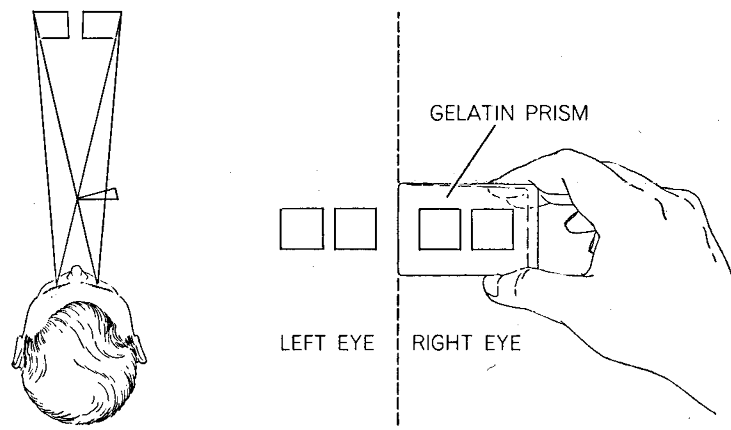
**CLUSTER IDENTIFICATION** in the pattern at left extends only to triangular shapes made up entirely of black dots. Other equally probable triangles containing dots of mixed brightness do not form clusters. These are marked in the enlargement at right.

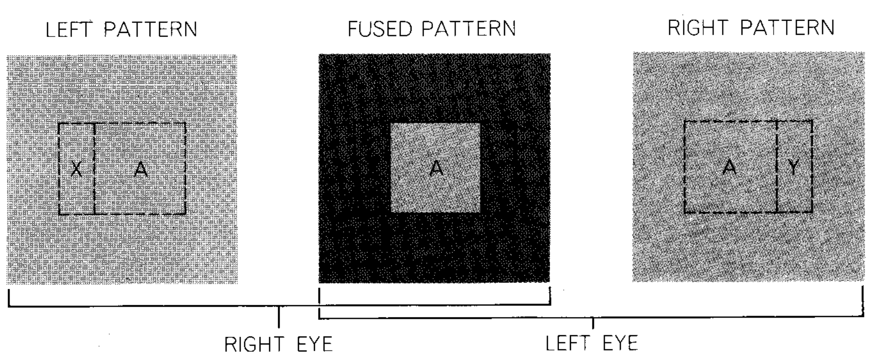


**EFFECT OF "NOISE"** is demonstrated in these two patterns. In the pattern at left the two subpatterns containing either black or white "S" shapes are easily discriminated. Moreover, every fifth horizontal and vertical row is gray. The pattern at right is identical except that the dots in the gray rows have been made black or white at random. By breaking up the connectivity of the pattern in this way the subpatterns are almost obliterated.




**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 five 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.**



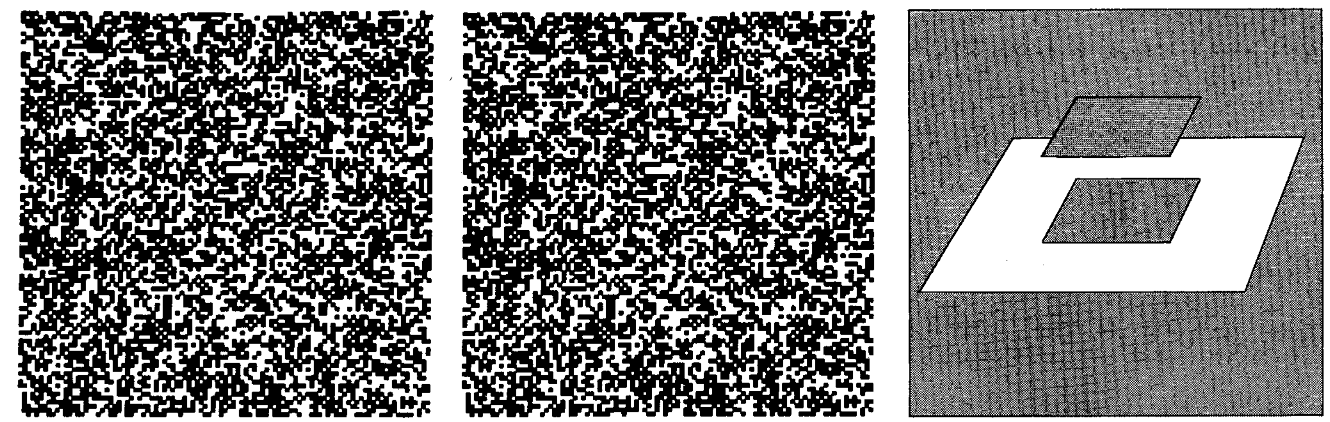

**TO USE PRISM hold it about six inches in front of the right eye, thin edge toward the nose. Adjust the prism so that both stereoscopic images can be seen through it. Both images should also be visible to the left eye, as shown in the upper two diagrams. With little difficulty the images should rearrange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

ticularly that of Kurt Koffka and Max Wertheimer. Now, with the help of the random-dot-pattern technique one can give a more precise meaning to these notions. For example, the last experiment, in which the disrupted pattern is viewed at an angle, shows that neighboring points need not touch each other to appear connected. This notion comes as no surprise. On the other hand, when one observes that neighboring points of similar brightness are perceived as clusters, the meaning of "similar brightness" requires further clarification. How dissimilar in brightness can adjacent points be and still be perceived as clusters? In order to examine this question two computer patterns were generated.

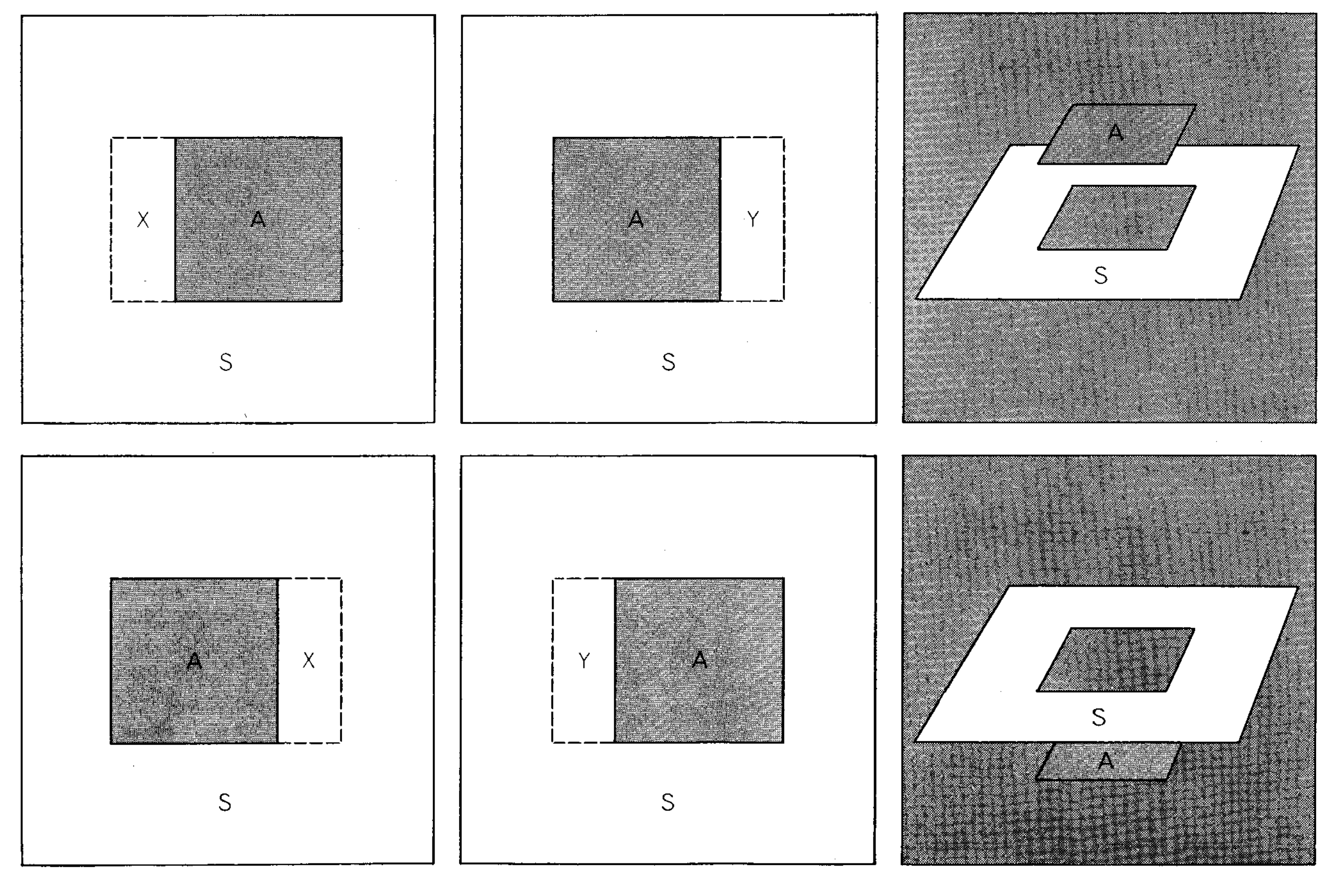
In one pattern, shown at top left on page *4*, the field at the left is composed chiefly of black and dark gray random dots; the field at the right contains mostly white and light gray dots. As a result the field at the left forms a large dark cluster and the field at the right forms a light cluster, with a fairly sharp boundary between them. In the adjacent pattern the light gray and dark gray dots are transposed so that the field at the left contains chiefly black and light gray dots and the field at the right contains chiefly white and dark gray dots. Here discrimination between the two fields is more difficult. These and similar results suggest that the visual system incorporates a slicer mechanism that separates adjacent brightness levels into two broad categories: dark and light. The level of slicing can be adjusted up and down, but it is impossible to form clusters by shifting our attention to dots that are not adjacent in brightness.

One might argue that the eye could hardly respond otherwise when brightness levels are involved. It can be shown, however, that the same connectivity rules hold for patterns composed of dots of different colors adjusted to have the same subjective brightness. This is the demonstration shown on the cover of this issue of *Scientific American* and also on page *3*. Since these patterns are made up of colored inks that do not reflect light with equal intensity, they do not fully simulate the laboratory demonstration, in which the dots are projected on a screen in such a way that their subjective brightness can be carefully balanced. Nonetheless, the printed demonstration, particularly the one on the cover, is reasonably effective. In the pattern on the cover what one observes is that the top half of the pattern is immediately discriminated into a red-yellow field on the left and a blue-green field on the right, whereas the bottom half of the pattern seems more or less uniform in texture across its entire width. This uniformity in texture is achieved simply by transposing the yellow and green random elements so that the field at the left is composed mostly of red and green dots and the field at the right is composed mostly of blue and yellow dots. The first demonstration shows that red and yellow dots form clusters that are easily discriminated from the clusters formed by blue and green dots. The second demonstration shows that dots of nonadjacent hue, such as red and green or blue and yellow, do not form clusters.

Evidently this clustering, whether it is of adjacent brightness levels or of adjacent hues, represents a preprocessing 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

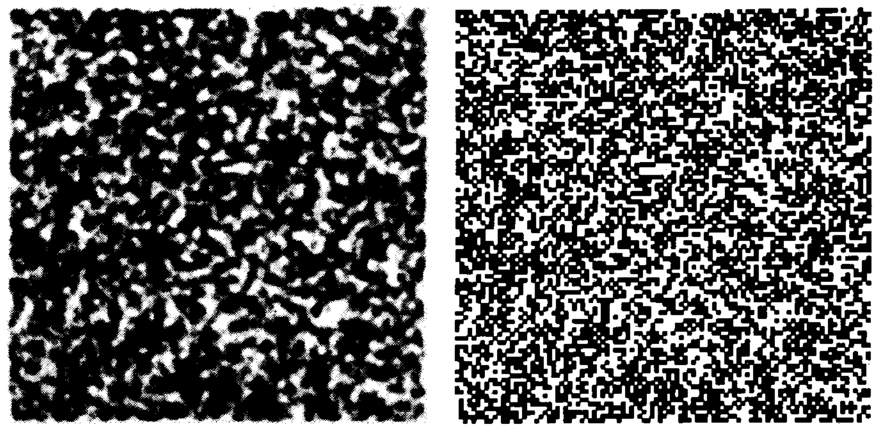


**STEREOSCOPIC IMAGES investigated by the author consist of random-dot patterns generated by a computer. When these two images are viewed with a stereoscope or with a prism held in front of one eye, a center panel should be seen floating above the background, as illustrated at the far right. The principle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



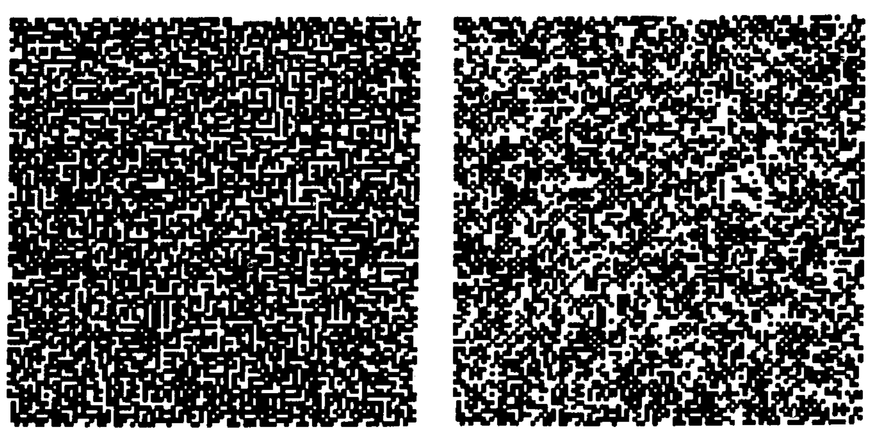

**STEREOSCOPIC PRINCIPLE is simply that identical areas that appear in both fields must be shifted horizontally with respect to each other. Because these areas are themselves random-dot patterns they cannot be seen monocularly against a random-dot surround. In these diagrams *A* identifies the area common 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.**

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 English words arranged in columns, as in the illustration at bottom right on page *4*, would



**BLURRED IMAGE was produced by defocusing the field at left in the random-dot stereoscopic patterns on the preceding page. The field at right is unchanged. In spite of the blurring the two fields will fuse into a stereoscopic image; moreover, the image looks sharp.**

**REDUCED IMAGE also does not interfere seriously with the ability to obtain a good stereoscopic image. The two random-dot patterns are again those shown on the preceding page. The stereoscopic field at left, however, has been reduced about 10 percent in size.**



**NOISY IMAGE (*left*) is produced by breaking up triplets of black dots along one diagonal and white triplets along the other diagonal wherever they occur in the left field on the preceding page. Nevertheless, the two fields will still fuse stereoscopically.**

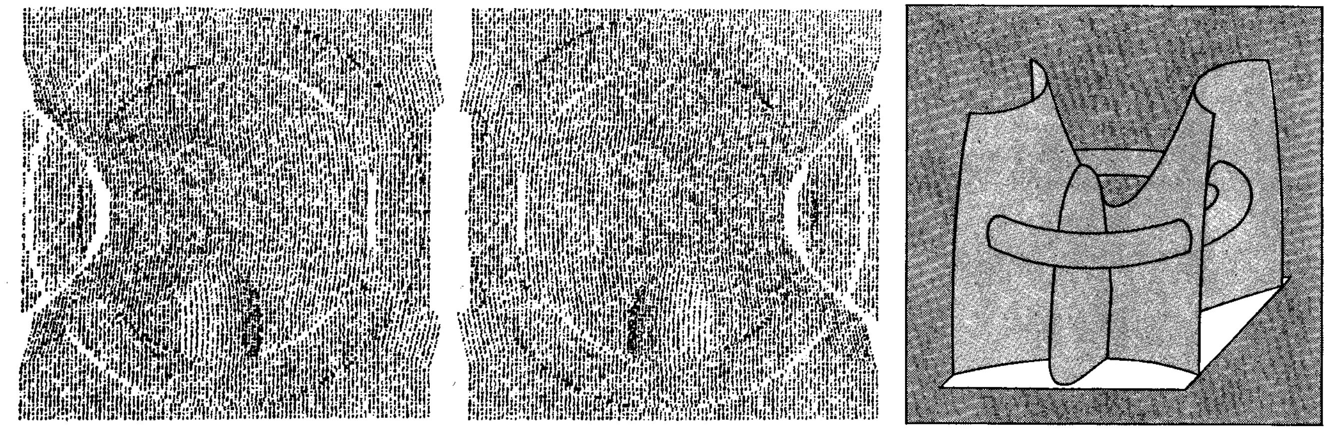
appear to be matched by a similar pattern containing nonsense sequences. The seven-letter nonwords would form clusters that could not be discriminated spontaneously from English words.

These findings answer in 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, 1964, and "The Visual Cortex of the Brain," by David H. Hubel, SCIENTIFIC AMERICAN, November, 1963]. The "bug" detector in the frog's visual system and the slit detector in the cat's visual system are special cases of connectivity detection. It will be interesting to see if neurophysiologists can find evidence for cluster detectors of the type suggested by these perception 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 camouflage 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 the preceding page. The two patterns are identical except for a center square that is shifted horizontally to the left by six dots in the pattern at the right. By virtue of this shift the





**SADDLE-SHAPED FIGURE (*far right*) was transformed into left and right stereoscopic fields by a computer program devised by the author. The picture elements consist of 64 standard characters randomly selected but paired in the left and right fields.**

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 disconnectivity alone is enough for the center square and its surround to be perceived as two distinct objects.

The demonstration also demolishes a long-standing hypothesis of stereopsis, or binocular depth perception, in which it is assumed that the slightly different images that are simultaneously projected on the retinas of the two eyes are first monocularly recognized and then matched. The process was thought to be somewhat analogous to the operation of an optical range finder, in which the corresponding separate images are first recognized and then brought into alignment. This last step corresponds to measuring the amount of displacement between patterns and determining the amount of depth by simple trigonometry (which the range finder performs automatically).

Research in stereopsis has traditionally been devoted to the problem of relating the displacement, or disparity, of images and the perception of depth. It has become increasingly apparent that depth perception involves many cues and cannot be described by trigonometry alone. Little or no attention was paid to the more fundamental problem of how the visual system is able to identify the same object in the separate two-dimensional images formed on each retina. The studies with random-dot patterns have now shown that monocular recognition of shapes is unnecessary for depth perception.

The method of producing random-dot stereoscopic images is shown in the lower illustration on page *7*. The surround (*S*) is composed of randomly selected but identical dot patterns in the fields at left and right. The center panel (*A*) is also identical in the two fields but is shifted in one field with respect to the other as if it were a solid sheet. If the shift is inward (toward the nose of the observer), the center panel seems to float in front of the surround. If the shift is in the opposite direction, the panel seems to lie behind the surround. The greater the parallax shift, the greater the perceived depth.

If one simply cut a panel out of a random-dot pattern and shifted it, say, to the left, an empty space would be exposed along the right edge of the panel. The empty region (labeled *Y* in the middle diagram on page *7*) is simply filled in with more random dots. A similar region (labeled *X*) must be filled when the panel is shifted to the right. Each region is projected onto only one retina (*X* onto the left retina and *Y* onto the right) and therefore exhibits no displacement. It is curious that these regions are always perceived as being the continuation of the adjacent area that seems to be farthest away.

By further manipulation of the random-dot patterns, it is possible to produce panels whose apparent location in space is ambiguous. If the *X* and *Y* regions described above are filled in with the same random-dot pattern, which we will label *B*, then when the two fields are viewed stereoscopically the center panel *A* may seem to be raised above the surround or area *B* may seem to lie below the surround. The diagram on page *10* illustrates the reason for this ambiguity. If the center panel is to be wider than the parallax shift (that is, wider than *B*), it must contain repeating vertical stripes of *ABAB* and so on in one field and stripes of *BABA* and so on in the other. An ambiguous panel created in this way is shown in the lower pair of stereoscopic images on page *11*.

All these depth phenomena can be perceived in a very short interval, provided that the two fields are presented to the observer in reasonable alignment. The presentation time is so short (a few milliseconds) that there is no time for the eye to move and thus no time for a range-finder mechanism to operate. One must therefore conclude that depth perception occurs at some point in the central nervous system after the images projected onto the left and right retinas have been fed into a common neural pathway. This was actually demonstrated as long ago as 1841 by Heinrich Wilhelm Dove of Germany, who used brief electric sparks to illuminate stereoscopic images only three years after Charles Wheatstone of England had first shown how the young art of photography could be used to produce them. Evidently the convergence movements of the eye serve mainly to bring the images on the left and right retinas into approximate register. This does not mean, however, that convergence motions do not influence the perception of depth when the presentation time is of long duration.

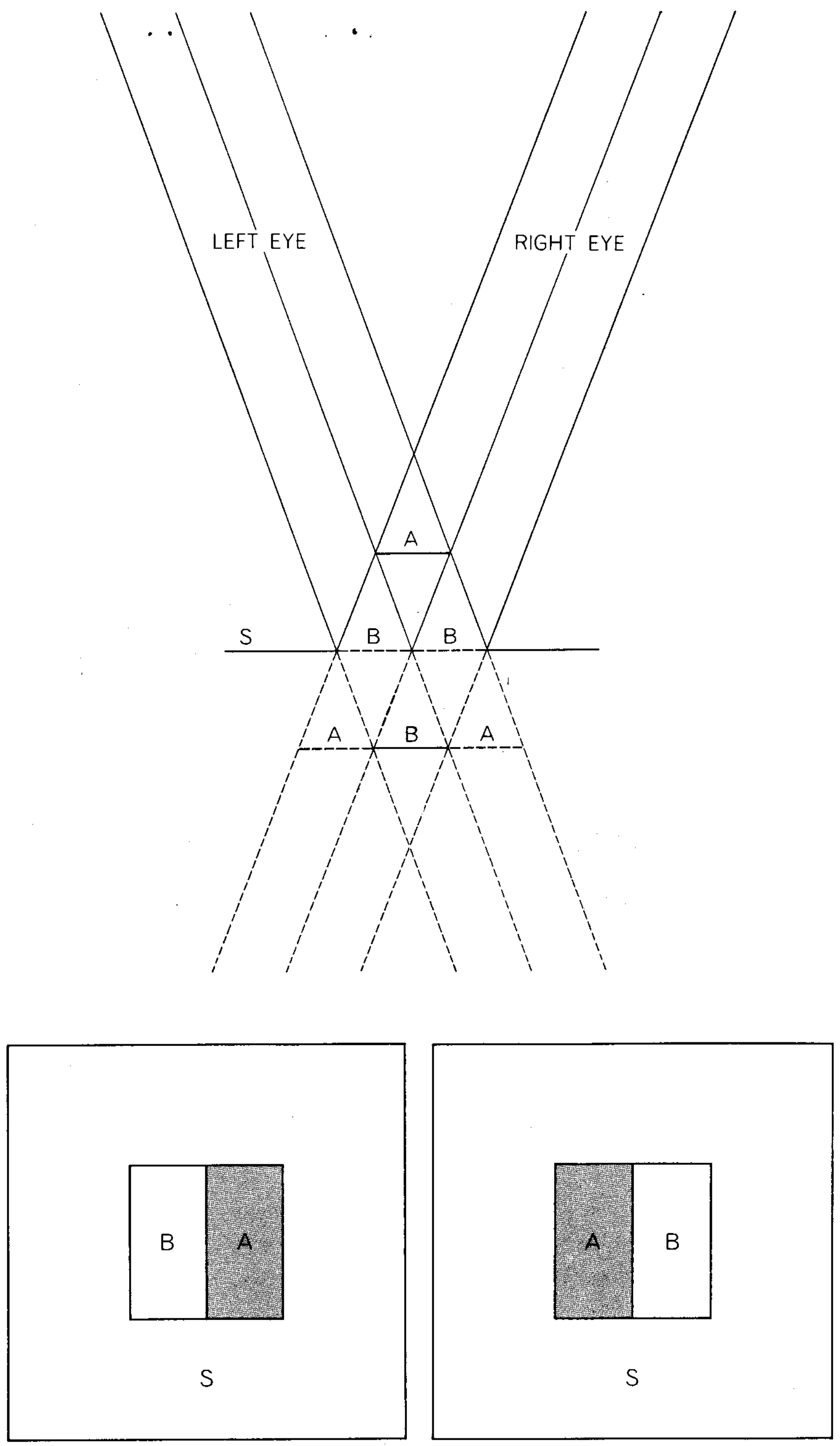
The processing in the nervous system that gives rise to depth perception is now more of a mystery than ever. The German physiologist Ewald Hering believed that this processing involves the crossing or uncrossing of images that are initially perceived as double because they lie either in front of or behind 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 monocular depth cues, which normally augment depth 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 homogeneous areas that carry no depth information. Thus random-dot stereoscope fields that differ in size 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 stereoptic perception is not a result of disparity in the images projected on the two retinas; rather each eye works up its complex of stimuli into a *Gestalt* and it is the difference between the two *Gestalten* 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 *Gestalten* can be worked up.




**AMBIGUOUS DEPTH EFFECT can be obtained by transposing the *A* and *B* fields in the random-dot patterns. When viewed stereoscopically (*top diagram*), area *A* may seem to be raised above the surround or area *B* may seem to lie below it. In either case the nonfused area seems to be a continuation of the field that looks farthest away.**

It might still be argued that *Gestalt* factors may 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.

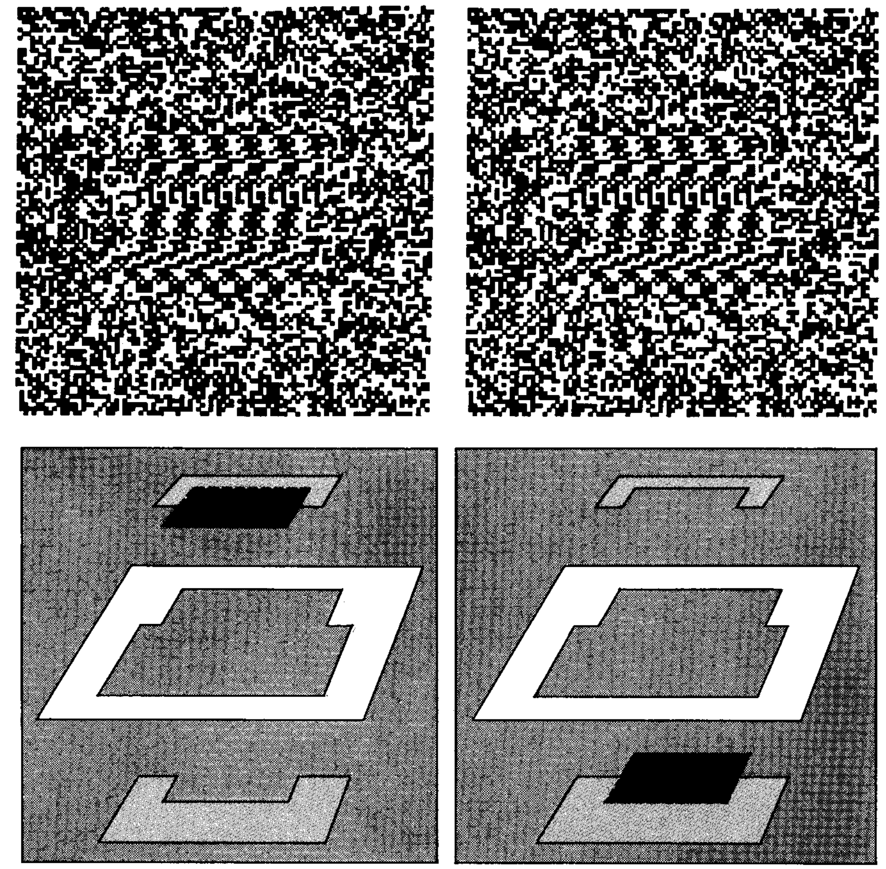
In presenting random-dot stereoscopic pairs for very brief intervals I have found evidence for a restricted but unmistakable kind of subliminal perception. This term refers, of course, to the idea that an individual can be influenced by a stimulus he does not consciously perceive. Efforts to demonstrate this phenomenon by other techniques have been inconclusive and controversial.

The finding was made while I was trying to measure the minimum time needed to perceive stereopsis in random-dot images. The time cannot be measured simply by presenting the images for briefer and briefer periods, for the reason that an afterimage remains on the retina for an indeterminate time. I found that it was possible to "erase" these afterimages by a new technique in which a second stereoscopic pair of random-dot images is flashed onto a screen almost immediately after the first pair.

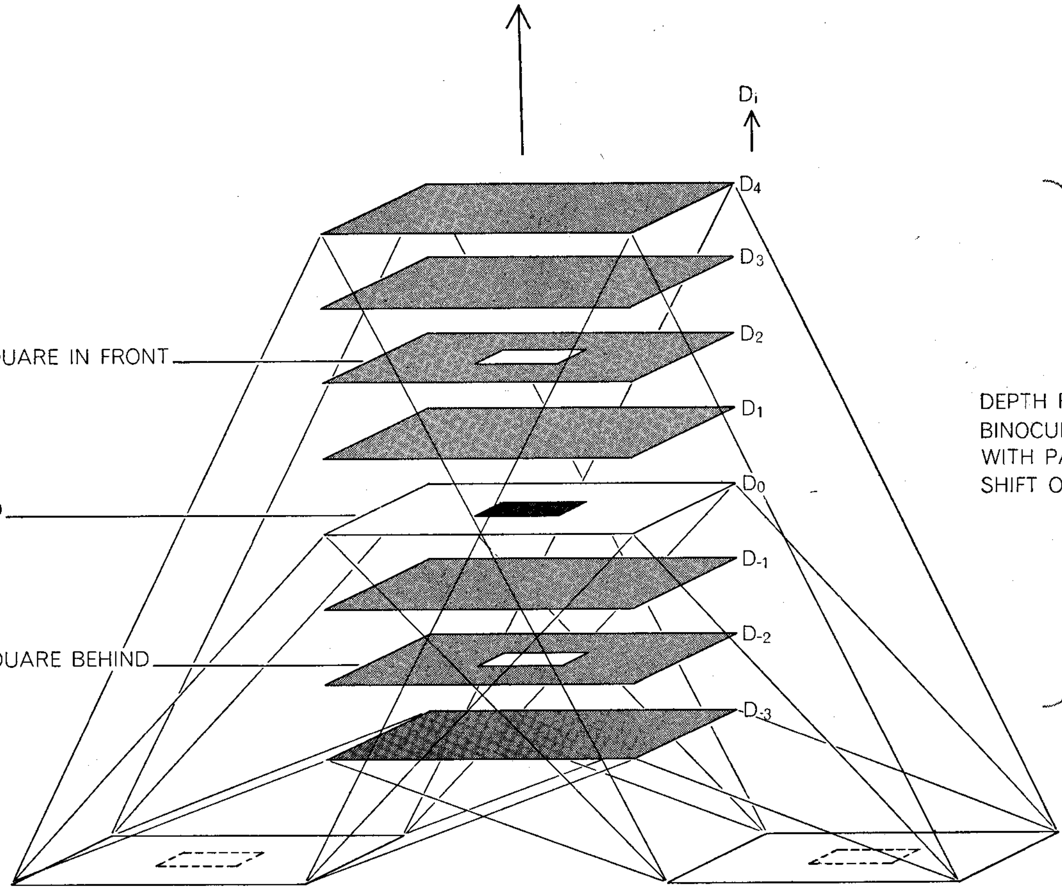
In these short-interval experiments the first stereoscopic pair flashed onto a screen has a panel that is unmistakably either in front of the surround or behind it. This pair is followed quickly by another in which the location of the panel is ambiguous; under more leisurely viewing conditions it will seem to lie either in front of or behind the surround. Not only were the subjects unaware that the second pair was ambiguous but if the interval between the two presentations was made short enough they were also unaware that they were seeing anything but the second pair. The second pair erased all conscious knowledge of the first. The real presentation time of the first pair could therefore be established because it was governed by the time allowed to elapse before presentation of the second pair.

The main result was that the first stereoscopic pair, although not consciously perceived, can influence the way in which the second pair—the ambiguous pair—is perceived. When the presentation time of the first pair was long enough, the ambiguous panel in the second pair consistently seemed to be at the same depth 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 compile a three-dimensional contour map from high-resolution stereoscopic images [*see illustration on page 12*]. This computer program not only should be useful for reducing the tedium of pro-



**AREA OF AMBIGUOUS DEPTH appears in the middle of this periodically striped stereoscopic pattern. Sometimes it will seem to be a continuation of an elevated panel (*lower left*); at other times it will seem to be part of a depressed panel (*lower right*).**




**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 ($D_i$). 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.**

ducing 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.

## The Author

BELA JULESZ is head of the Sensory and Perceptual Processes Department at the Bell Telephone Laboratories. A native of Hungary, he was graduated from the Technical University of Budapest and the Hungarian Academy of Sciences. He taught and did research in communications systems in Budapest until 1956, when he joined Bell Laboratories. At Bell he was first engaged in studies of systems for reducing television bandwidth and of digital methods for processing pictorial information. Since 1959 he has devoted full time to visual research, particularly in depth perception and pattern recognition.

## Bibliography


BINOCULAR DEPTH PERCEPTION WITHOUT FAMILIARITY CUES. Bela Julesz in *Science*, Vol. 145, No. 3630, pages 356–362; July, 1964.

THE OPTICAL SPACE SENSE. Kenneth N. Ogle in *The Eye, Vol. IV: Visual Optics and the Optical Space Sense,* edited by Hugh Davson. Academic Press, 1962.

STEREOPSIS AND BINOCULAR RIVALRY OF CONTOURS. B. Julesz in *Bell Telephone System Technical Publications Monograph 4609,* 1963.

TOWARDS THE AUTOMATION OF BINOCULAR DEPTH PERCEPTION. B. Julesz in *Information Processing 1962: Proceedings of IFIP Congress 62.* North-Holland Publishing Company, 1962.


912