Binocular Depth Perception without Familiarity Cues

Bela Julesz

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Random-dot stereo images with controlled spatial and temporal properties clarify problems in stereopsis.

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Research in stereopsis (*1*) is traditionally devoted to quantifying the relationship between disparity (*2*) and perceived depth. Problems of the horopter, perceptual limits of disparity, the metric of the perceived space, and so on, are all examples of this classical problem-posing and have been thoroughly investigated (*3*). Strangely enough, the related problem of how disparity is derived—that is, how the corresponding left and right retinal projections of an object are found—has been ignored. This lack of interest is the more remarkable since the matching of the horizontally shifted corresponding point domains in the left and right fields is accomplished almost without deliberation, although these point domains generally differ in brightness and shape (owing to reflections and perspective). Perhaps the inherent limitations of the stimuli used may have caused researchers to shy away from studying binocular depth perception as a pattern-matching process. Indeed, simple line drawings were too limited for the exploration of pattern matching, while real-life pictures were unsatisfactory because of the many complex familiarity cues which interacted in uncontrollable ways.

Four years ago I posed two intimately related questions along these lines, which constituted a new paradigm. They were: (i) Would it be possible to create an artificial sensory environment devoid of all depth and familiarity cues except disparity? (ii) Could depth still be perceived under these conditions of "familiarity deprivation" (*4, 5*)? This paradigm was never systematically raised before, and yet it is so familiar. It is a long-known fact, exploited in aerial reconnaissance, that objects camouflaged by a complex background are very difficult to detect monocularly but jump out if viewed stereoscopically. Nevertheless, despite the difficulty, the hidden objects can be monocularly detected. Even if every surface of the three-dimensional environment were covered with a homogeneous random texture, the closer surfaces would seem to have coarser granularity than the ones farther away. [This retinal gradient of textures which is attributable to perspective yields a strong monocular depth cue (*6*).] Therefore the questions of whether an environment can be *ideally* camouflaged and of whether objects that are hidden when viewed monocularly can be perceived in depth still remained to be answered.

In order to obtain such an answer a novel technique of random-dot stereo images was devised. Such a stereo pair is shown in Fig. 1. When viewed monocularly, both fields of Fig. 1 give a homogeneous random impression without any recognizable features. But when viewed stereoscopically, this image pair is vividly perceived in depth, with a center square in front of its surround. [A prism in front of one eye greatly facilitates fusion of the stereo pairs. A satisfactory prism can be made of gelatin, as described in (*7*).]

The emphasis, in this brief article, is on demonstrating this and similar recently observed perceptual phenomena, with comments on certain implications of these findings for stereopsis.

Stereopsis without Familiarity Cues

Figure 2 illustrates how Fig. 1 and similar random-dot stereo images (particularly Fig. 3) are generated. It represents a small stereo pair composed of a matrix of 9 × 10 picture elements. The equally probable randomly selected black and white picture elements which are contained in corresponding areas in the left and right fields are labeled in three categories. (i) Those contained in corresponding areas with zero disparity (which when viewed stereoscopically are perceived as the surround) are labeled 0 or 1. (ii) Those contained in corresponding areas with non-zero disparity (which when viewed stereoscopically are perceived in front of or behind the surround) are labeled *A* or *B*. (iii) Those contained in areas which have no corresponding areas in the other field (that is, project on only one retina and thus have no disparity) are labeled *X* and *Y*. The 0 and 1 picture elements are identical in corresponding positions of the two fields. The positions of the *A* and *B* picture elements belonging to corresponding areas in the two fields are also identical, but are shifted horizontally as if they were a solid sheet. Because of this shift some of the picture elements of the surround are uncovered and must be assigned new brightness values (*X* and *Y*). Since these areas lack disparity, they can be regarded as undetermined in depth. Figure 2 contains three rectangles in the left and right fields, composed of *A* and *B* picture elements. Each field contains an upper, middle, and lower rectangle which can be regarded as corresponding left and right "projections" of a rectangular planar surface located in depth when viewed from different angles. The projections of the upper rectangle (that is, the corresponding upper rectangles in the left and right fields) are horizontally shifted relative to each other in the nasal direction by one picture element, the corresponding lower rectangles are shifted in the temporal direction to the same extent, while the corresponding middle rectangles have a one-picture-element periodicity and may be regarded as being shifted in either direction. The low density of picture elements and the large disparities would prevent stereopsis in a pattern corresponding to Fig. 2. In order to achieve stereopsis, the number of picture elements would have to be increased con-

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The author is a member of the technical staff in the Human Information Processing Department, Bell Telephone Laboratories, Murray Hill, N.J.

siderably. For this reason a computer is used.

It would be impractical to generate without a computer adequately complex stimuli of several thousand brightness elements and given constraints for each experiment. Figure 3 is a computer-generated version of Fig. 2; it has 100 × 100 picture elements, and for each of its three rectangles the disparity is six picture elements. The disparity is always chosen to be an integral multiple of the width of the picture element; therefore, when viewed monocularly, each of the two fields gives an impression of homogeneous randomness, without gaps or boundaries (*4, 5*). The upper rectangle, when the images are fused, is seen in front of the surround (as in Fig. 1). The lower rectangle is perceived behind the surround, while the middle rectangle can be seen in front or behind at will.

Of course, instead of two brightness levels, any number of levels can be introduced, and instead of rectangular surfaces, any complex surface can be portrayed by this technique and give rise to stereopsis (*8*). Minimum area size, dot density, disparity, perception time, number of brightness levels, and other factors show strong interdependencies, which can be explained by statistical analysis. But before considering such interdependencies, I discuss some interesting observations which can be readily made when Figs. 1 and 3 are viewed stereoscopically.

The main result of these observations is that the paradigm mentioned above is answered in the affirmative: Stereopsis can be obtained in the absence of monocularly recognizable objects or patterns. As a consequence, the many depth cues for monocular vision—cues such as the apparent size of familiar objects, interposition (the superimposing of near objects on far objects), and linear perspective—which in a familiar environment strongly influence the final percept, do not operate here. In this case the complex pattern-recognition processes (which themselves are based on involved learning and memory processes) can be overcome, and this greatly simplifies the study of binocular depth perception. The problem is reduced to that of finding how similar patterns are matched.

It is important to note that in these observations the quality of stereopsis (that is, the time required for stereopsis, the stability of the fused image, the amount of binocular rivalry, and so on) is excellent in spite of the absence of all other depth cues. As a matter of fact, since every picture element has disparity (in contrast to ordinary pictures, which contain large homogeneous areas without depth information) the random-dot stereo images are usually *easier* to perceive in depth. For these effective stimuli, several quantitative limits of various parameters which were determined as borderline values for stereopsis can be extended.

It should also be mentioned that the statistical, topological, and heuristic properties of the random-dot stereo images are controlled by the experimenter; thus the observations are more amenable to analysis.

The basis of stereopsis is disparity,

Fig. 1. Basic random stereo pair. When the two fields are viewed stereoscopically, the center square appears in front of the background. [See (*7*) for a description of an aid useful in stereoscopic viewing.]

1	0	1	0	1	0	0	1	0
1	0	X	A	A	B	B	0	0
0	0	Y	B	A	B	A	1	1
0	1	0	0	1	1	1	0	1
1	1	A	B	A	B	A	0	0
0	0	B	A	B	A	B	1	0
1	1	0	1	0	1	1	0	0
1	0	A	A	B	A	X	0	1
1	1	B	B	A	B	X	1	0
0	1	0	0	0	1	1	1	1

1	0	1	0	1	0	0	1	0
1	0	A	A	B	B	Y	0	0
0	0	B	A	B	A	X	1	1
0	1	0	0	1	1	1	0	1
1	1	B	A	B	A	B	0	0
0	0	A	B	A	B	A	1	0
1	1	0	1	0	1	1	0	0
1	0	Y	A	A	B	A	0	1
1	1	Y	B	B	A	B	1	0
0	1	0	0	0	1	1	1	1

Fig. 2. Illustration of the method by which the stereo pair of Fig. 3 was generated.

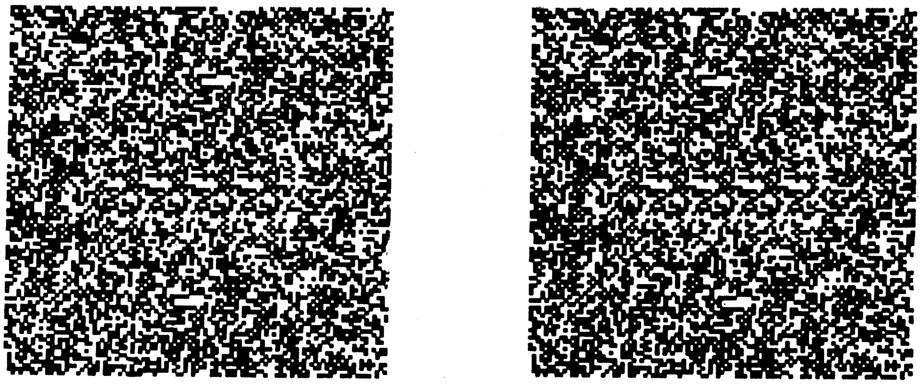

Fig. 3. Stereo pair which, when viewed stereoscopically, contains an upper rectangle perceived in front of the surround, a lower rectangle perceived behind the surround, and an ambiguous middle rectangle perceived either in front of or behind the surround.

as was demonstrated by Wheatstone with his stereoscope (*9*). Nevertheless, there are special instances when depth can be perceived in the absence of disparity. An example is the Panum phenomenon (*10*), where one image of a stereo pair consists of two parallel vertical lines in a homogeneous surround while the other image contains a single vertical line. When one of the vertical lines in the two images is fused (when the images are viewed stereoscopically), the other line, for which there is no corresponding representation in the other member of the pair, is also perceived in depth; it has a somewhat "floating" look but appears clearly behind the fused line. Such stimuli are particularly unsuitable for getting better insight into this phenomenon since they are "simple" only from a most irrelevant point of view—they are simple to draw. In fact, line drawings are *degenerate* forms of real-life images (which are composed of objects with textured surfaces) and as a result the perceptual performance to be studied becomes needlessly complicated and disguised. Indeed, the areas in Figs. 2 and 3 which are without disparity (the areas represented in Fig. 2 by X and Y and in Fig. 3 by the corresponding dots) are a generalization of Panum's unpaired line, and their perception (which is quite stable) can be simply described and explained: Undetermined areas (areas without disparity) are perceived at the depth of the most distant adjacent determined area (area with disparity) (*4, 5*). This rule is illustrated in Fig. 3, where undetermined areas at the left and right edges of the rectangle that is seen in front when the images are viewed stereoscopically are perceived as continuations of the background, while, for the rectangle seen behind the surround, the undetermined areas are perceived as belonging to the rectangle. (This is the reason why the lower rectangle looks wider than the upper one.)

This perceptual phenomenon is in agreement with the common experience that the image of each point of a closest surface is projected on both retinas, whereas a surface behind it has points which are totally or partly hidden. Thus, an area which is partly hidden and represented only on one retina is perceived as a continuation of the exposed parts of the surface behind the superimposed one. This effect is even more apparent for random-dot patterns, since the undetermined and the determined areas which are perceived as being at the same depth have identical textures.

The Panum phenomenon can be approached also in the context of binocular rivalry. In this interpretation, the determined area exerts an additional stabilizing effect, namely the prevention of binocular rivalry in the proximate undetermined areas. A remark on the implications of those findings for Gestalt psychology is given in (*11*).

Stereopsis under Brief Exposures

Besides disparity, there are two secondary depth cues for binocular vision: convergence and correlative accommodation (differential focusing). Both depend on muscle action. Since Dove in 1841 (*12*) demonstrated stereopsis under very brief exposures (much too short for any muscle activity), the importance of focusing and convergence is regarded as negligible. (In addition, the fact that, in a stereo image, areas in front and behind can be simultaneously perceived is hard to explain in terms of convergence.) Therefore, contrary to naive belief, stereopsis is the result of central nervous system processing, and the main purpose of convergence is the coarse alignment of corresponding retinal areas. This coarse alignment insures that the corresponding retinal areas are within the region of patent stereopsis. This does not mean that, for longer exposures, convergence motions and proprioceptive influences might not affect stereopsis. Dove's result, and many similar findings since (*13*), have conclusively demonstrated that stereopsis can occur as a result of central nervous system processing alone, and this view is generally accepted by workers in this field (*3*). However, von Karpinska (*14*) believed that these tachistoscopic experiments were successful only when the subject knew beforehand what he was expected to see. This and similar arguments are still voiced, and therefore the finding (*15*) that random stereo images (such as that of Fig. 1) can also be perceived in depth under conditions of tachistoscopic presentation is not without interest. Since, in such experiments, the subjects have no familiarity with the stimulus at all and nevertheless, in a 1-millisecond exposure, correctly perceive the middle square in front or behind (when the two cases are presented in a randomly mixed order), the most plausible objection to Dove's finding is removed.

Perhaps an even more important consequence of the finding that random stereo pairs are perceived in depth in brief exposures is that Hering's theory on the role of double images is disproved. According to this theory, images not fused are seen double and are crossed or uncrossed depending on whether they lie in front of or behind the point of convergence. The extent to which this cue is utilized could not be previously determined, since double images were inseparable from the applied stimuli. The forms in random stereo pairs, on the other hand, are not recognizable until the forms are perceived in depth, and thus it is impossible to perceive double images either before or after fusion (*15*).

It is surprising that, without secondary depth cues, space sense can develop so rapidly (the effective presentation time is longer than the flashes, due to the persistent afterimages, but is, nevertheless, very brief). The time required for stereopsis increases with larger parallax shifts, smaller area size, and more complex (that is, nonplanar) surfaces.

Perception and Attention Time

These tachistoscopic experiments were useful only for studying perceptual performance in the absence of eye motions. In order to get better insight into the temporal aspects of perception, particularly into the perception time required, the afterimages have to be "erased." A new "stereo erasing" technique was developed, in which the erasing stimulus is a random-dot stereo pair.

This new technique also utilizes the ambiguous depth phenomenon (random wallpaper effect) which is demonstrated in Fig. 3 (*16*). If the upper rectangle perceived in front of the surround is viewed first, then the ambiguous middle rectangle is also seen in front of the surround. On the other hand, if the lower rectangle perceived behind the surround is viewed first, then the ambiguous middle rectangle is seen behind the surround. This finding holds for tachistoscopic exposures too, and thus is not the result of the subject's maintaining the same convergence but is, rather, the result of his maintaining attention for the same perceptual organization (depth plane).

In these tachistoscopic experiments, brief presentation of an unambiguous stereo pair (a pair having a center square with either a temporal or a nasal disparity) was followed by presentation of an ambiguous stereo pair (a pair having the same disparity but in both directions). The picture elements in the second stimulus differed from those in the first. Thus, the second stimulus erased the afterimages of the first stimulus, and therefore the real presentation time for the first stimulus was known. It was found that, when presentation time was adequate, the second, or ambiguous, stimulus was consistently perceived at the same depth as the first, or unambiguous, stimulus. (The unambiguous stereo pair was presented with temporal or nasal disparity, in mixed order.) Perception of the ambiguous stimulus was influenced by perception of the unambiguous stimulus even when the first stimulus was not consciously perceived. When the first stimulus was presented for a time shorter than this "perception time for stereopsis," or when the second stimulus was delayed by an interval longer than the "attention time," the second stimulus became independent of the first and could be perceived as having depth opposite to that of the first. This finding and the fact that perception and attention times were typically under 50 milliseconds (*17*) make it appear most unlikely that convergence motions might have been initiated. The subjects were unaware that the second stimulus was ambiguous. These facts imply that the first stimulus serves as a "depth marker" and determines which of the possible depth organizations should be attended to. Such an internal attention mechanism was nicely demonstrated by Pritchard when viewing the reversal of a Necker-cube under conditions of retinal stabilization (*18*). [The problem of whether this mechanism is a parallel or a sequential process is discussed in (*19*).]

Fig. 4. Stereo pair identical to that of Fig. 1 except for the fact that one field is expanded uniformly in both dimensions by 10 percent. Stereopis is easy to obtain.

Binocular Similarity

In the experiments summarized above, pattern-matching consisted of the relatively simple task of finding *identical* patterns in the two fields, differing only in their horizontal positions. In the experiments reported next the congruency of the corresponding patterns was perturbed to various extents by several manipulations. There are many ways to introduce such distortions. One way is to simulate real-life situations under more controlled conditions. In ordinary binocular vision the two retinal projections are generally quite different in brightness and shape, owing to reflections and perspective. Distortions which simulated such vision were introduced by blurring one of the fields, adding uncorrelated random noise, expanding one field uniformly, complementing certain points (by changing black to white and white to black), and so on. One of the many possible perturbations (*4*, *5*), the uniform expansion of one field, is illustrated in Fig. 4. Differences in the size of the retinal images for the two eyes (aniseikonia) are never as great as the size differences of Fig. 4; nevertheless, depth is easily perceived in Fig. 4, which is derived from Fig. 1 by uniform expansion of one of the fields (by 10 percent in both dimensions). Since in these computer-generated stimuli every point contributes to stereopsis, depth can be perceived even under tachistoscopic conditions if the centers of Fig. 4 are aligned. This means that, in addition to the horizontal disparity, some vertical shift can be tolerated. When random-dot stereo images are used, most quantitative findings on the limits of disparity as determined with simple line drawings (*3*) seem to be very conservative and can be extended.

In addition to expansions, rotations of one of the computer-generated stereo fields by 7 degrees of arc can give rise to stereopsis during brief exposures, a finding which is the more remarkable since the time of exposure is too brief to permit cyclotorsional eye movements. All these experiments show that the central nervous system has processing powers far beyond the requirements of common usage.

In the experiments described next I tried perturbations of a complexity which never occurs under ordinary conditions, in order to study the limits of pattern matching. Two corresponding patterns are called "binocularly

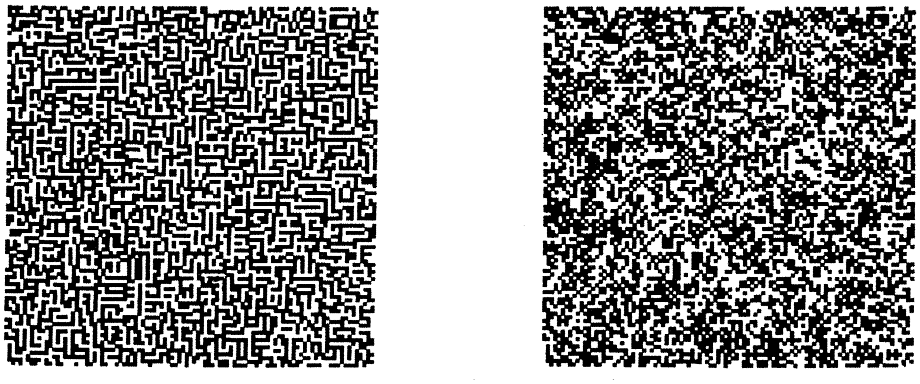

Fig. 5. Stereo pair identical to that of Fig. 1 except for the fact that in the left field the diagonal connectivity is broken; 75 percent of the picture elements of the stereo pair are identical. Stereopsis is easy to obtain.

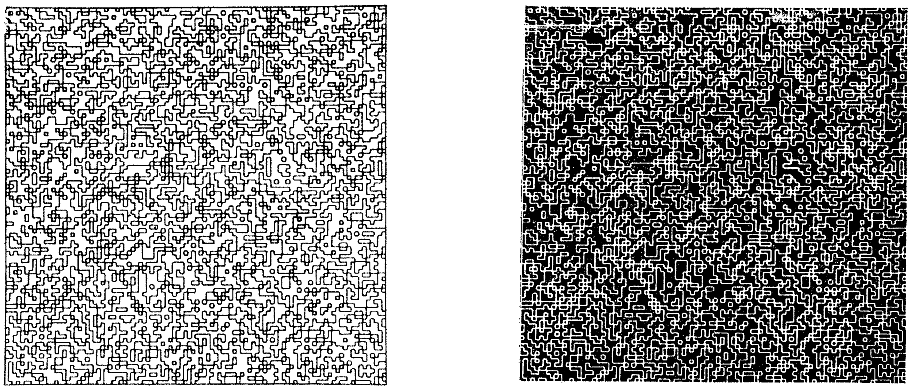

Fig. 6. Stereo pair generated by outlining the fields of Fig. 1 and complementing one of them. Stereopsis is very difficult to obtain.

similar" if they can be fused and perceived in depth. The quality of the percept may be regarded as an indicator of the similarity of the patterns.

One surprising finding was that the monocular similarity of two patterns can be quite different from the binocular similarity. This is illustrated in Fig. 5, which is derived from the basic stereo pair of Fig. 1 by breaking of the connectivity along the diagonals in the left field. If, along the +45-degree and −45-degree diagonals, three adjacent picture elements had identical brightness values, the middle one was complemented (that is, was removed from fusion). As a result of this procedure in Fig. 5 only 25 percent of the picture elements became complemented while 75 percent were kept identical in the two images. Although the two patterns appear exceedingly dissimilar when viewed monocularly, the binocular similarity is very high, inasmuch as stereopsis is easily obtained. This observation has another implication. It has already been proved that monocularly recognizable objects are not necessary for stereopsis. Nevertheless, one might object that, in Fig. 1, similar micropatterns can be perceived in the two fields, as viewed monocularly, and that these might serve as the basis for fusion. The fact that the patterns of Fig. 5 look so different on both a micro and a macro level, when viewed monocularly, and that the images can nevertheless be perceived in depth is strong evidence that the pattern processing occurs *after* the binocular combination of the stereo images has occurred. This pattern processing reveals that 75 percent of the picture elements of the two fields are identical, a fact disguised by the dissimilarity of the fields when viewed monocularly (*5*). This observation—that the processing has to occur after the binocular combination of the images—is in agreement with recent neurophysiological findings by Hubel and Wiesel (*20*).

It is interesting to note that binocular similarity cannot be described solely in terms of quantitative point-by-point identity between a pair of patterns. There are several ways of removing the same percentage of picture elements from fusion, and for these various ways the quality of depth perception may differ greatly. Thus, binocular similarity depends greatly on the topology of the perturbing configurations. One crucial factor in visual perception is the connectivity of adjacent elements. The perturbing configurations which destroy this connectivity to the greatest extent in the combined field produce the greatest perceptual degradation (*4, 5*).

With such techniques many inherent pattern organizations can be studied; one interesting class, involving contour dependencies, is discussed in the next section.

Role of Contours in Stereopsis

One of the most common beliefs concerning stereopsis is that contours are important (*3*). The usual definition of contours as boundaries between configurations that represent recognizable objects when viewed monocularly has to be modified, since the experiments described above illustrated that stereopsis can be achieved in the absence of such configurations. A contour may be alternatively defined as a boundary between white and black clusters. For real-life situations the two definitions coincide. Belief in the importance of contours is based on a classical experiment by Helmholtz (*21*). It is a belief which has never been questioned since his day. Helmholtz used a black line drawing of a simple object in a white surround as one stereo image and its complement (negative) as the other. In spite of some binocular rivalry the stereo pair could be fused. Because the two fields were everywhere different except for the location of the contours, it was inferred that contours are crucial for stereopsis. On the other hand, if one field of Fig. 1 is complemented, stereopsis is destroyed (*4*). Moreover, it is possible to perceive depth, without any binocular rivalry, for random stereo pairs which are identical everywhere *except* at the contours (*15*).

These findings seemingly contradict the results of Helmholtz's experiment. This apparent contradiction arises from the spatial complexity of the stimulus. This is illustrated by Fig. 6. To generate Fig. 6, the outline of the pattern of Fig. 1 was generated at the boundaries between black and white clusters, and one of the fields was complemented. These stereo fields have a great spatial density of outline, and stereopsis is very difficult. If one reduces this density by expanding a small area in each field, stereopsis is greatly facilitated, approximating that in Helmholtz's case.

Discussion

The techniques mentioned above make it possible to study stereopsis in its purest form. Nevertheless, the study is limited to problems concerning the sensation of relative depth in a small region around the convergence point (*22*). (How the entire visual space is built up from such regions by successive convergence motions and how these space samples are integrated in a unique percept are problems far beyond the scope of this research.)

Under these ideal conditions several of the observed phenomena can be explained by relatively simple statistical arguments. As an example, let us analyze the following finding: For a given disparity the corresponding point domains in the two fields (for example, the center square of Fig. 1) must possess a minimum number of picture elements (and thus be of a certain size) to be perceived in depth. This critical point-domain size increases with increased disparity and decreases with increased number of brightness levels in the stimuli. These experimental findings can be easily explained, as follows. Any two *uncorrelated* random images of black and white picture elements have 50 percent identical elements, by chance alone. With three or more brightness levels in the stimulus this chance identity is reduced to 33 percent or less. Thus, corresponding point domains in the left and right fields have to contain more correlated points than the cluster formed by chance correlation. Since with a smaller number of brightness levels the probability increases that noncorresponding *adjacent* dots will form correlated clusters (false clusters) of considerable size, the critical size of corresponding clusters has to be increased. Only then is the probability negligible that a false cluster will occur that is similar in size to a critical area. If the corresponding areas are above the critical size, then they need not be identical, only similar. But, to achieve stereopsis, this similarity has to be more than the chance correlation (see Fig. 5). The probability of finding large false clusters increases as the fields (which contain them) get larger. This corresponds to the observation that with increased disparity (that is, with increased image area to be searched for corresponding patterns) the size of the critical area has to be increased to obtain stereopsis.

In this analysis, clusters formed by *proximate* points of *similar* (correlated) brightness played a dominant role. This cluster formation (or connectivity detection) is basic for monocular texture discrimination too (*23*) and reminds one of figure and ground discrimination.

One can explain many of the observed phenomena by regarding them as a search for connected clusters in the combined binocular field (*4*). In order to test the validity and power of these notions, a computer program was written (called AUTOMAP-1) which complies a three-dimensional contour map from high-resolution stereo images (*24*). This computer simulation is a sort of active description, a model whose form reflects something of the structure of the phenomena represented, but which also has the character of a working machine (*25*). The results were satisfactory (the essentials of this heuristic model are given in *4, 23* and *24*). Some assumptions in the model were experimentally confirmed by White (*26*).

Random-dot stereo images are now used in fields other than that of stereopsis, for studying optical illusions (*27*), binocular rivalry (*28*), and perceptual learning (*16*); some findings might bear on subliminal perception. Possible applications range from automatic map compilation (*24*) to clinical uses [for example, x-ray stereofluoroscopy (*29*)].

The paradigm itself can be generalized, and analogue techniques might be used for studying apparent motion and skin localization (*30*). Such a generalization was recently applied in a study of auditory memory (*31*). These refined techniques may have some implications for auditory localization too, where work with correlated auditory noise was begun as early as 1948 and produced some interesting phenomena (*32*).

Summary

The reported phenomena were obtained through the use of special techniques. (i) All monocular depth and familiarity cues were removed from the stimuli (through the use of random-dot stereo patterns). (ii) The statistical and topological properties of the stimuli were precisely known (since they were generated according to a specific computer program). (iii) Convergence motions of the eye and proprioceptive cues were eliminated (through the use of tachistoscopic illumination). (iv) The time of presentation was under control (through erasure of the persistent afterimages). Under these conditions stereopsis could be studied in its purest form. It was shown that depth can be perceived in the absence of monocular depth and familiarity cues and of all binocular depth cues except for disparity. These findings have important implications for some existing theories of stereopsis and open up areas for further research. Some phenomena based on stereo erasure are reported here for the first time. It has been demonstrated that the perception of ambiguous depth organizations can be influenced, even subliminally, by a preceding unambiguous stimulus. Perhaps the most interesting result is the finding that the correspondence of objects and patterns in the two retinal projections can be established without actual recognition of the objects and patterns. This pattern matching is based on some relatively simple processes of finding connected clusters formed by adjacent points of similar brightness, and the processes seem to be amenable to rigorous analysis.

References and Notes

1. Stereopsis is the sense of relative depth in a limited region around the point of convergence, attributable to disparity of corresponding points on the two retinas. Stereopsis is more general than fusion, since with increased disparity (above the fusion threshold but within the limit of patent stereopsis) corresponding points can be seen as double (often with one image suppressed) but still perceived in depth.
2. In this article the term *disparity* is used in a generic sense for similar terms such as retinal disparity, binocular disparity, geometrical disparity, binocular parallax (shift), and so on.
3. For an up-to-date review on the traditional aspects of research in depth perception see K. N. Ogle, in *The Eye*, H. Davson, Ed. (Academic Press, New York, 1962), vol. 4, p. 209 [abstracted in *Science* **135**, 763 (1962)].
4. B. Julesz, *Bell System Tech. J.* **39**, 1125 (1960).
5. ———, in *Information Theory, 4th London Symposium*, C. Cherry, Ed. (Butterworths, London, 1961), p. 212.
6. J. J. Gibson, *Am. J. Psychol.* **63**, 367 (1950).
7. A concentrated solution of gelatin is prepared by dissolving the gelatin in hot water. It is then poured into a glass or plastic container which has at least one optically transparent and flat surface. The container is tilted by 15 to 20 degrees and is kept in this position until the gelatin sets. (The process can be speeded up by refrigeration.) The flat surface of the container and the hardened top surface of the gelatin form an optical wedge which can be used as a viewing prism.
8. B. Julesz and J. E. Miller, *Bell System Tech. J.* **41**, 663 (1962).
9. C. Wheatstone, *Phil. Trans. Roy. Soc. London* **371** (1838).
10. P. L. Panum, *Untersuchungen über das Sehen mit Zwei Augen* (Kiel, 1858).
11. The observed phenomena have important implications bearing on Gestalt psychology. According to a typical view of this school [E. Lau, *Psychol. Forsch.* **2**, 1 (1922)] stereopsis is not a result of disparity, but each eye works up its stimulus complex into a Gestalt, and it is the difference between these Gestalten which gives rise to an impression of depth. This argument is still debated, since some of the experiments (involving optical illusions) which were designed to illustrate Gestalt factors have given controversial results. The fact that stereopsis can be obtained with the random-dot images without any monocular cues decisively settles this question, since no Gestalten can be "worked up."

    It might still be argued that Gestalt factors may operate after the left and right images are fused. In this context it is important to observe what happens at the vertical boundaries of the center square of Fig. 1. The probabilities that the black-and-white picture elements will be perceived as belonging to the rectangle or perceived as belonging to the surround are equal. Indeed, when viewed stereoscopically, the vertical boundaries of the center square of Fig. 1 look fuzzy instead of being perceived as straight lines, as one would expect if some Gestalt organization had taken place (since a square has a "good Gestalt"). If the stimulus contains black, white, and gray picture elements of equal frequency of occurrence, then the probability that a dot at the boundary belongs only to the square increases to 2/3. This statistical argument is in agreement with the observed fact that a square looks less fuzzy at the boundaries when it is composed of random dots having three or more brightness levels. This comment is by no means to be interpreted as a critique on Gestalt psychology but merely as an implication that stereopsis operates on a primitive level where Gestalt considerations do not enter.

That some of the more complex Gestalt factors—such as goodness of form, symmetry, and closure—are not a prerequisite for stereopsis does not mean that some more basic factors, particularly proximity and similarity can be omitted. Their importance in perception was first stressed by Gestalt psychologists, especially by Koffka and Wertheimer. Similarly, throughout this article I stress the notion of connectivity, into clusters, of adjacent dots of similar brightness. But there is a difference between my approach and that of the Gestalt psychologists. They developed these powerful notions to show that perception of form was a more involved process than had been previously believed, while I am using these same notions, restricted to random-dot patterns, to show that certain processes in stereopsis (and in visual discrimination of texture) are simpler than had been expected and amenable to rigorous analysis.

12. H. W. Dove, *Ber. Preuss. Akad. Wiss.* **1841**, 251 (1841); *Ann. Physik.* **110**, 494 (1860).
13. N. M. S. Langlands, *Trans. Opt. Soc. London* **28**, 45 (1926).
14. L. von Karpinska, *Z. Psychol. Physiol. Sinnesorg.* **57**, 1 (1910).
15. B. Julesz, *J. Opt. Soc. Am.* **53**, 994 (1963).
16. ———, *ibid.* **54**, 576 (1964).
17. These findings were for a picture size of 6 degrees of arc (image size, 100 × 100 picture elements; size of center squares 48 × 48 picture elements); disparity, 7 minutes of arc; stimulus brightness, 5 footlamberts (55 lumens/m^2).
18. P. M. Pritchard, *Quart. J. Exptl. Psychol.* **10**, 77 (1958).
19. The ambiguous stereo pairs, when presented by themselves for a brief period, were usually perceived in only one way. When a slight (10 percent) bias was introduced (to counteract the subject's natural bias), it proved to be excessive and reversed the perceived depth. If the preferred depth level were the first level given attention and the other depth levels were searched sequentially only afterward, then a 90-percent match at the preferred depth level would be more than adequate for stopping the search. That, instead, the 100-percent match is perceived at the unpreferred depth level is strong evidence for the parallel process. Recently Dodwell and Engel came to the same conclusion, utilizing Efron's technique of presenting alternate stereo images with various time delays [see P. C. Dodwell and G. R. Engel, *Nature* **198**, 39 (1963); R. Efron, *Brit. J. Ophthalmol.* **41**, 709 (1963)]
20. Recent neurophysiological findings revealed binocular neural units in the striate cortex of the cat. These units were activated by simultaneous stimulation of corresponding regions in the left and right retinas. Both summation and antagonism between receptor fields of the two eyes were demonstrated [see D. H. Hubel and T. N. Wiesel, *J. Physiol.* **160**, 106 (1962)].
21. H. von Helmholtz, *Physiological Optics*, J. P. C. Southall, Ed. (Dover, New York, rev. ed., 1962), vol. 3, p. 512 and plate IV.
22. For details on this region of patent stereopsis and on the problem of the horopter, see K. N. Ogle, in *The Eye*, H. Davson, Ed. (Academic Press, New York, 1962), vol. 4.
23. B. Julesz, "Special Issue on Sensory Information Processing," *IRE PGIT* [Professional Group on Information Theory] *Publ. IT-8* (1962), p. 84.
24. ———, in *Proceedings IFIP* [International Federation of Information Processing] *Congress 1862*, M. Popklewell, Ed. (North-Holland, Amsterdam, 1963), p. 439. This computer program takes the point-by-point differences between the left and right fields with all possible shifts prior to subtraction. This produces an ordered set of "analog depth planes" in which adjacent points of minimum value are connected into clusters. The search for these clusters of points with the same disparity immediately gives the cross sections (contour lines) of objects in a natural way.
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30. For phenomena in skin localization see G. von Békésy, *Experiments in Hearing* (McGraw-Hill, New York, 1960), p. 567.
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32. J. C. R. Licklider, *ibid.* **20**, 150 (1948); E. M. Cramer and W. H. Huggins, *ibid.* **30**, 413 (1958).

Problems of Drug Development

The government, the drug industry, the universities, and the medical profession: partners or enemies?

Louis Lasagna

The past few years have been marked by acrimonious discussions about the problems of drug development. While some would like to believe that Congressional hearings such as those of the Blatnik and Kefauver committees stirred up previously calm waters, it is clear that the storm winds had been gathering force for a considerable period of time and that the explosive passion evident in the reaction to these events was not engendered *de novo*. That problems exist is clear; what is less evident is the willingness of the interested parties to define these problems with clarity and to solve them.

I should like to analyze the interactions of physicians, the medical schools, government, and business first by listing some *sources* of discontent, since an attack on primary causes seems preferable to a preoccupation with secondary manifestations. Then I shall suggest some approaches which might ameliorate the present state of affairs, in the optimistic belief that progress is possible and that Heraclitus was right. ("Everything comes about by way of strife and necessity.")

There are almost daily complaints about some aspect of drug usage in our society. The academicians are constantly berating industry for its motivations and promotional excesses. When not so engaged, they are lambasting Congress for inadequate support of clinical pharmacology or for adding to the headaches of researchers by passing "patient consent" laws. The personnel of the Food and Drug Administration (FDA) are rarely allowed to rest quietly in their foxholes: on one day they are bombed for pusillanimity, on the next for highhandedness. (If a specific issue is lacking, it is considered good form to brand them as generally inept.)

The drug industry, in its turn, is bitter about the unreasonableness and extravagance of the professional attacks. The pharmaceutical folk are understandably annoyed when their substantial scientific contributions are ignored, or when they are asked for funds to support research or scientific societies by the same academicians who have berated them. Government is constantly a threat to the industry, the nature of the danger ranging from possible patent restrictions to "arbitrariness" or "ignorance" on the part of specific FDA staffers determined to prevent a drug's being marketed or to snatch a profitable pharmaceutical off the market.

The government, for its part, must

The author is associate professor of medicine and associate professor of pharmacology and experimental therapeutics at Johns Hopkins University, Baltimore, Md. A frequent contributor to professional and popular publications, he is also the author of *The Doctors' Dilemmas*, a study of the medical profession, published by Harper in 1962.