Visual Pattern Discrimination*

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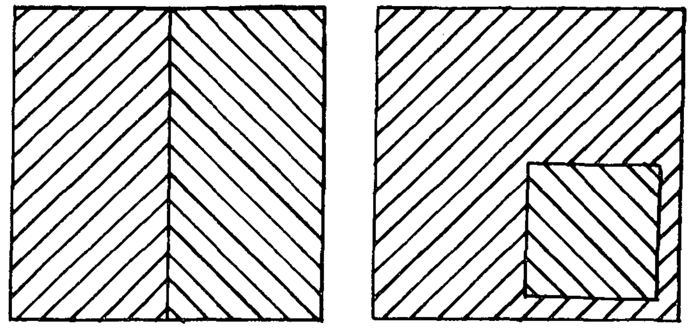
Summary—**Visual discrimination experiments were conducted using unfamiliar displays generated by a digital computer. The displays contained two side-by-side fields with different statistical, topological or heuristic properties. Discrimination was defined as that spontaneous visual process which gives the immediate impression of two distinct fields. The condition for such discrimination was found to be based primarily on clusters or lines formed by proximate points of uniform brightness. A similar rule of connectivity with hue replacing brightness was obtained by using varicolored dots of equal subjective brightness. The limitations in discriminating complex line structures were also investigated.**

I. Introduction

IN THE STUDY of perception, workers have long endeavored to control the effective amount of stimulus information. One method *impoverishes* the stimuli by adding noise, by presenting them for a limited time, by stabilizing them on the retina, or otherwise confronting the subject with impaired viewing or listening conditions. Another possibility utilizes subjects whose perceptual mechanisms are known to be deficient. Experiments on infants, on subjects with pathological defects, and on animals with surgically-introduced lesions are examples. Neither of these methods has been entirely satisfactory since they interfere with the *normal* perceptual processes to an unspecified extent. Recently a third alternative has been demonstrated. It utilizes computer-generated displays with controlled statistical, topological, or heuristic properties, but void of familiarity cues.[1-3] As stimuli these patterns deprive subjects of their life-long learned habits of recognition and make them rely on more primitive mechanisms. Thus these experiments are liable to reveal some basic organization principles of information processing in the sensory nervous system.

The experiments reported here investigate the discriminability of unfamiliar visual patterns. These experiments might also be described as studies in visual texture discrimination. Two visual fields were generated either side-by-side [Fig. 1(a)] or one contained in the other [Fig. 1(b)]. The first arrangement (Format A) of Fig. 1 was used when the fields differed along the horizontal dimension; the second display (Format B), whenever the fields differed in two dimensions. The problem posed was the following: If two visual fields are presented simultaneously, in what properties must they differ in order to be discriminated?



A B

Fig. 1—Format A and B used in discrimination experiments.

Discrimination as we will consider it involves a high degree of spontaneity. Obviously any difference between two fields can eventually be detected after long and careful analysis. But we will not concern ourselves with this conscious complex recognition and comparison process. We are interested in a more primitive and spontaneous process which organizes the two fields into two distinct entities. Fig. 2 illustrates this idea. Here the left field is composed of seven-letter English words, while the right field contains nonsense words of the same length (really they are the same English words written backwards). Although the English words are recognized as such by inspection, whereas the nonsense words are not; nevertheless, it is impossible to organize the left and right fields into two separate units with a distinct boundary between them.

On the other hand, Figs. 3–5 demonstrate cases which give the immediate impression of two distinct fields. This spontaneous process will be defined as visual discrimination. (This process might be thought of as a generalization of the classical *figure and ground* discrimination regarded basic in visual perception.[4])

II. Experimental Procedure

The visual displays were generated by the IBM 7090 digital computer with the aid of a digital-to-analog converter and a video transducer.[5-7] The display consists of 99 lines of 105 picture elements. Format A has a left field of 52×99 size, whereas the right field is 53×99.

* Received by the PGIT, August 15, 1961.
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[1] B. Julesz, "Binocular depth perception of computer-generated patterns," *Bell Sys. Tech. J.*, vol. 39, pp. 1125–1161; Sept., 1960.

[2] B. Julesz, "Binocular depth perception and pattern recognition," in "Information Theory," 4th London Symp., C. Cherry, Ed., Butterworths, London, Eng., pp. 212–224; 1961.

[3] B. F. Green, Jr., A. K. Wolf, and B. W. White, "The detection of statistically defined patterns in a matrix of dots," *Am. J. Psychol.*, vol. 72, pp. 503–520; December, 1959.

[4] D. O. Hebb, "The Organization of Behavior," John Wiley and Sons, New York, N. Y.; 1949.

[5] E. E. David, Jr., "Digital simulation in research on human communication," Proc. IRE, vol. 49, pp. 319–329; January, 1961.

[6] R. E. Graham and J. L. Kelly, Jr., "A computer simulation chain for research on picture coding," 1958 IRE WESCON Convention Record, pt. 4, pp. 41–46.

[7] B. Julesz, "A method of coding television signals based on edge detection, *Bell Sys. Tech. J.*, vol. 38, pp. 1001–1020; July, 1959.

CERTAIN	QUICKLY	PUNCHED	METHODS	SCIENCE	COLUMNS	NIATREC	YLKCIUQ	DEHCNUP	SDOHTEM	ECNEICS	SNMULOC
SCIENCE	SPECIFY	PRECISE	SUBJECT	MERCURY	GOVERNS	ECNEICS	YFICEPS	ESICERP	TCEJBUS	YRUCREM	SNREVOG
METHODS	RECORDS	OXIDIZE	COLUMNS	CERTAIN	QUICKLY	SDOHTEM	SDROCER	EZIDIXO	SNMULOC	NIATREC	YLKCIUQ
DEPICTS	ENGLISH	CERTAIN	RECORDS	EXAMPLE	SCIENCE	STCIPED	HSILGNE	NIATREC	SDROCER	ELPMAXE	ECNEICS
SUBJECT	PUNCHED	GOVERNS	MERCURY	SPECIFY	PRECISE	TCEJBUS	DEHCNUP	SNREVOG	YRUCREM	YFICEPS	ESICERP
EXAMPLE	QUICKLY	SPECIFY	METHODS	COLUMNS	MERCURY	ELPMAXE	YLKCIUQ	YFICEPS	SDOHTEM	SNMULOC	YRUCREM
SCIENCE	PRECISE	EXAMPLE	CERTAIN	DEPICTS	ENGLISH	ECNEICS	ESICERP	ELPMAXE	NIATREC	STCIPED	HSILGNE
SPECIFY	MERCURY	PUNCHED	QUICKLY	METHODS	EXAMPLE	YFICEPS	YRUCREM	DEHCNUP	YLKCIUQ	SDOHTEM	ELPMAXE
EXAMPLE	GOVERNS	OXIDIZE	ENGLISH	SUBJECT	RECORDS	ELPMAXE	SNREVOG	EZIDIXO	HSILGNE	TCEJBUS	SDROCER
COLUMNS	SUBJECT	PRECISE	MERCURY	PUNCHED	CERTAIN	SNMULOC	TCEJBUS	ESICERP	YRUCREM	DEHCNUP	NIATREC
ENGLISH	RECORDS	EXAMPLE	SUBJECT	OXIDIZE	GOVERNS	HSILGNE	SDROCER	ELPMAXE	TCEJBUS	EZIDIXO	SNREVOG
CERTAIN	PRECISE	PUNCHED	METHODS	ENGLISH	COLUMNS	NIATREC	ESICERP	DEHCNUP	SDOHTEM	HSILGNE	SNMULOC
OXIDIZE	QUICKLY	SCIENCE	DEPICTS	SPECIFY	PRECISE	EZIDIXO	YLKCIUQ	ECNEICS	STCIPED	YFICEPS	ESICERP
DEPICTS	EXAMPLE	ENGLISH	CERTAIN	RECORDS	SCIENCE	STCIPED	ELPMAXE	HSILGNE	NIATREC	SDROCER	ECNEICS
SPECIFY	MERCURY	GOVERNS	PRECISE	QUICKLY	METHODS	YFICEPS	YRUCREM	SNREVOG	ESICERP	YLKCIUQ	SKOHTEM

Fig. 2—Display to illustrate a case of discrimination solely based on pattern recognition.

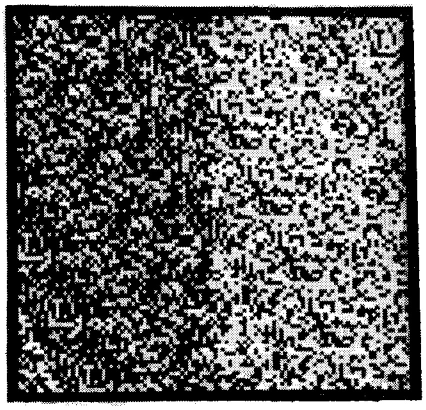

Fig. 3—Two random fields with different first-order probability distributions (two brightness levels).

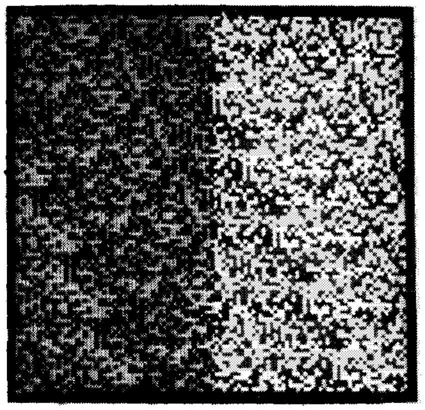

Fig. 4—Two random fields with different first-order probability distributions (four brightness levels).

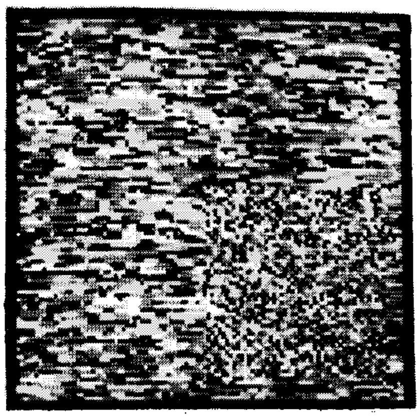

Fig. 5—Two random fields with different second-order probability distributions but identical first-order probability distributions.

Format B has a quadrant of 50 × 50 points in the right lower part such that its right and lower edge are 5 picture elements distant from the margin. The rest of the display constitutes the other field. The picture elements are quantized into 2, 3 or 4 brightness levels. The displays were given to subjects in the form of photographic prints of 2 × 2 inch for inspection. There was no limitation on the presentation time and it was assumed that the discrimination was performed under the most favorable viewing conditions. The subjects were asked to look for two fields and point at the boundaries if seen. The subjects were not told which format was used.

III. Discrimination of Random Patterns

One way to obtain patterns devoid of familiarity cues is to generate them from a stochastic process. Such processes can be specified by their Nth order joint probability distribution (which is the probability of N selected brightness points having certain values). The nomenclature N-variate probability distribution is also often used. The higher the order of the probability distribution, the better the process is specified. In the next two experiments the random fields are described by their first-order probability distributions and it will be demonstrated that slight differences in the first-order statistics can result in visual discrimination. Fig. 3 shows two random fields of Format A, where the picture elements of the left field have a 5/8 probability of being black and 3/8 probability of being white, while the right field has the inverse distribution. Discrimination is easy though the boundary between the distinct textures is somewhat fuzzy. Fig. 4 shows a similar experiment where the fields again differ in their first-order distribution. Here the left field has black and light gray dots of equal probability, while the right field contains equal number of random white and dark gray dots. Discrimination is even more distinctive, and there is a straight sharp boundary. If we try to describe the subjective difference between the two fields, we might characterize them as having different *tonal qualities*.

The next experiment results in two fields of Format B which have identical first order distributions (black, gray, and white dots of equal probability) but differ in their second order probability distribution. Fig. 5 shows this case. Any two points in the smaller field are statistically independent of each other in their brightness value, while the larger field is a Markov process having a second-order probability distribution which is given by the following transition probabilities:

$$P(\mu_{i-1}, \mu_i) = \begin{cases} \frac{3}{4}, & \text{if } \mu_{i-1} = \mu_i \\ \frac{1}{4}, & \text{if } \mu_{i-1} \neq \mu_i \end{cases} \quad \mu_i = 0, 1, \text{ or } 2, \tag{1}$$

where μ_i is the brightness value of the ith sample, $i - 1$ refers to the left adjacent element, and 0, 1, and 2 refer to black, gray and white. The first sample of a horizontal line is independent of the last sample of the previous line. Because the second-order distribution determines the power spectrum of the stochastic process, Fig. 5 compares a field with a flat power spectrum with a field which has a *low-pass* spectrum along the horizontal direction (it is flat in the vertical direction). It is easy to discriminate between the two patterns and the subjective impression might be regarded as a difference in *granularity*.

These experiments lead to the following question: Given two random visual patterns which are identical in their Nth order probability distribution (and thus identical in all their lower than Nth order distribution), but differ in their $(N + 1)$th order probability distribution, what is the greatest value of N for discrimination between them?

This question led to the following mathematical problem: For what values M and N do there exist stationary Nth order Markov chains with variables assuming M different values and such that any N variables of the process are independent while $N + 1$ adjacent variables of the process are not independent? It has been shown[8] that with $M = 2$ (*e.g.*, using only two brightness levels) such processes having $N \geq 2$ cannot exist, with $M \geq 3$ there are many such processes. Fig. 6 shows a process with $M = 4$ (*e.g.*, black, dark gray, light gray and white levels) and $N = 2$. The display has Format A. The left- and right-half fields have identical first- and second-order distributions, but differ in their third-order distribution. The first-order distribution is uniform (*e.g.*, the four brightness levels occur with equal probability) while the second-order distribution is described by the property that any two variables taken from the process are independent. $[P(\mu_m, \mu_n) = P(\mu_m) \cdot P(\mu_n)]$. The third-order probability distribution is given by the following transition probabilities $P(k \mid ij)$:

$$P(k \mid ij) = P[2k - i - j = s(\text{mod } 4)] = P(s), \tag{2}$$

where i, j and k are successive samples along the horizontal line from left to right, and for the left-half field,

$$P(s = 0) = P(s = 1) = 7/16$$

$$P(s = 2) = P(s = 3) = 1/16$$

while for the right-half field

$$P(s = 0) = P(s = 1) = 1/16$$

$$P(s = 2) = P(s = 3) = 7/16.$$

Here 0, 1, 2 and 3 correspond to black, dark gray, light gray and white. Thus, in the left-half field some of the highly probably adjacent triplets are 000, 111, 222, 333, 002, 331, etc., while in the right field 001, 003, 332, 330, etc., occur. According to this long uniform horizontal stripes of the 0000 . . . . type have a low probability in the right field and occur frequently in the left field. Despite this difference in the third-order distributions discrimination between the fields is very weak, and only by careful inspection is it noticed that the left field contains a few horizontal stripes of uniform brightness which are practically absent in the right field.

The above-mentioned results might give the impression that differences in the first- or second-order probability distributions yield pattern discrimination, but differences in the third- or higher-order statistics are irrelevant.

[8] M. Rosenblatt and D. Slepian, "Nth order Marhov chains with any set of N variables independent," *J. Soc. for Industrial and Appl. Math.*, to be published.

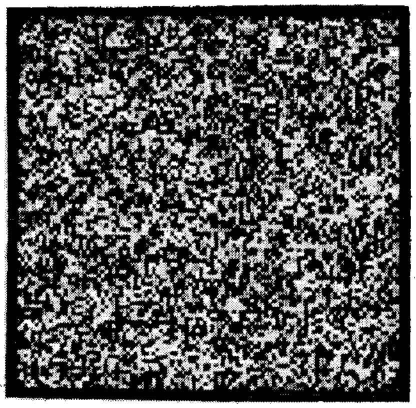

Fig. 6—Two random fields (Format A) with identical first-and second-order probability distributions but different third-order probability distributions.

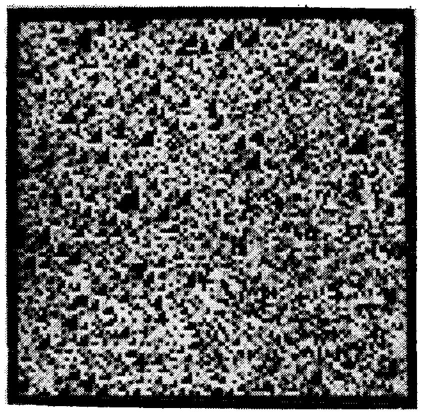

Fig. 7—Two random fields (Format B) to illustrate that of equally probably triangular structures; only the uniformly black ones can be seen.

```
      B         B         B         B         W
    B B       W W       W W       W W       B W
  B B B     W G B     B W G     G B W     B B W
 • • • •   • • • •   • • • •   • • • •   • • • •
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Fig. 8—Some triangular structures contained in the larger field of Fig. 7.

However, in Section IV several $N = 2$ examples in which discrimination is easy will be given. Thus visual discrimination cannot be predicted by N alone. Note in Fig. 6, however, that the presence or absence of *uniform* horizontal stripes were observed. Other combinations of adjacent horizontal brightness values of nonuniform brightness occurred with the same probability, but no attention was paid to them. This observation indicates that visual discrimination of random patterns depends primarily on psychological properties of the visual system.

The next experiment is intended to emphasize this observation. Fig. 7 shows a display of Format B where the small quadrant is entirely random, having 3 brightness levels of equal probability. The large field is also composed of 3 brightness levels of equal probability, but the brightness level of any given picture element $\mu_{i,j}$ depends on the adjacent $\mu_{i-1,j}$ to the left and the adjacent element $\mu_{i,j-1}$ above in the following way:

$$
\begin{aligned}
Pr\ \{\mu_{i-1,j} + \mu_{i,j-1} = \mu_{i,j} (\text{mod } 3)\} &= \tfrac{7}{8} \\
Pr\ \{\mu_{i-1,j} + \mu_{i,j-1} \neq \mu_{i,j} (\text{mod } 3)\} &= \tfrac{1}{8}.
\end{aligned}
\qquad (3)
$$

If B (black) = 0, W (white) = 2, G (gray) = 1, then the larger field will be filled with a great number of highly probable triangular micropatterns occurring with equal probability as shown in Fig. 8.

When viewing Fig. 7 the criterion of discrimination is not performed on the basis that the larger field is densely filled with these triangular patterns while the smaller field is uniformly random in structure. The only cue for discrimination is the presence of uniformly black triangles of different size in the larger field. The other triangular structures formed by points of nonuniform brightness values pass unnoticed. These uniform triangular clusters (similarly to the uniform lines in Fig. 6) do not occur frequently enough to be perceived as a distinct texture. But it is very plausible that by increasing the frequency of these clusters, the two fields can be discriminated similarly to Fig. 5. Discrimination in Fig. 5 can be attributed to the long uniform horizontal lines of black, gray and white levels which densely cover the larger field. On the other hand, the smaller field consists of random brightness dots which form only irregularly shaped clusters.

The previous experiments indicate that in visual discrimination, clusters or lines formed by proximate points of uniform brightness play a decisive role. These important notions of *proximity* and *uniformity* were originally emphasized by the Gestaltist school,[9,10] and later by many others.[11] In the next experiments, the importance of proximity and uniformity will be further illustrated and a more precise meaning will be attached to them. In the forthcoming, cluster and line detection will be called *connectivity detection.*

[9] M. Wertheimer, "Principles of perceptual organization," *Psychol. Forsh.*, vol. 4, pp. 301–350, April, 1923; also an abridged translation in "Readings in Perception," D. C. Beardslee and M. Wetheimer, Eds., D. Van Nostrand Co., New York, N. Y.; 1958.

[10] K. Koffka, "Points and lines as stimuli," in "Principles of Gestalt Psychology," Havacourt Brace, New York, N. Y., pp. 148–160; 1935.

[11] J. Hochberg and A. Silverstein, "A quantitative index of stimulus similarity: Proximity versus difference in brightness," *Am. J. Psychol.*, vol. 69, pp. 456–458; September, 1956.

IV. Connectivity Detection—A Clue to Pattern Discrimination

The next experiment is shown in Fig. 9 and uses Format B. Here the large field contains a periodic 4×4 matrix of 8 black and 8 white dots separated by gray lines and columns. The smaller quadrant is identical but complemented. This operation is equivalent in this case to a $90°$ rotation. The display can be regarded as a sample of a stochastic ensemble and statistically described. The two fields have the same first- and second-order distributions and differ only in higher-order statistics. The two fields can be discriminated easily, as a result of black and white rows and columns formed by repeating micropatterns. If the gray separating lines (every fifth row and column) are filled with random black and white dots, then these few points break up the formation of line structures and the discrimination is drastically reduced. (See Fig. 10). It is also interesting that the micropatterns (the black and

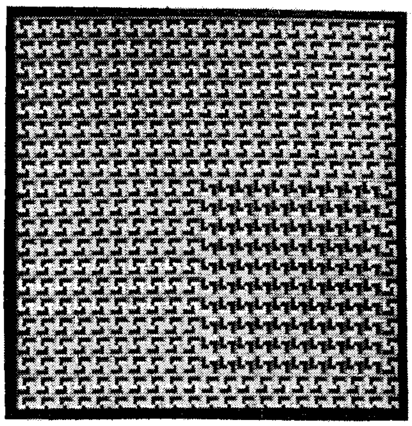

Fig. 9—Two fields which are each others complements. Discrimination is a result of different line structure seen.

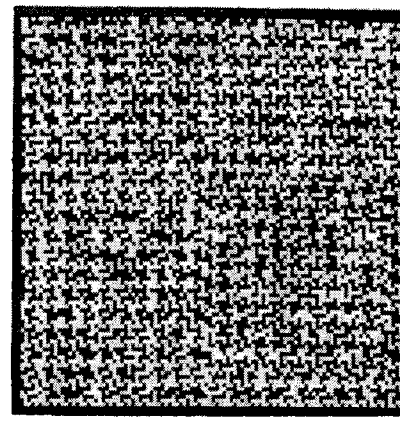

Fig. 10—Identical with Fig. 9 but every fifth gray row and column is changed to black and white random dots.

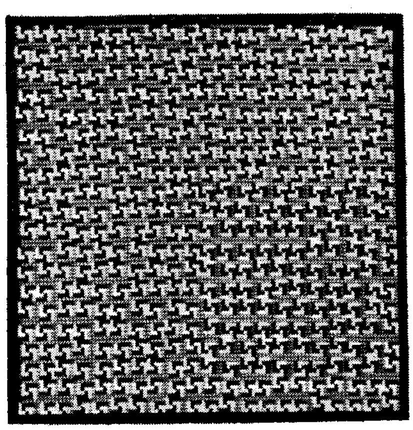

Fig. 11—Same as Fig. 9 but the micropatterns are randomly jittered.

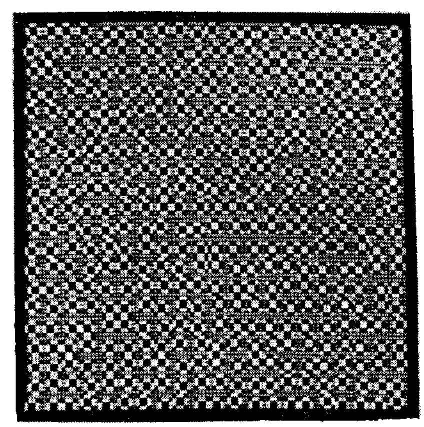

Fig. 12—Two fields which are each others complements. In the absence of line structures, discrimination is weak.

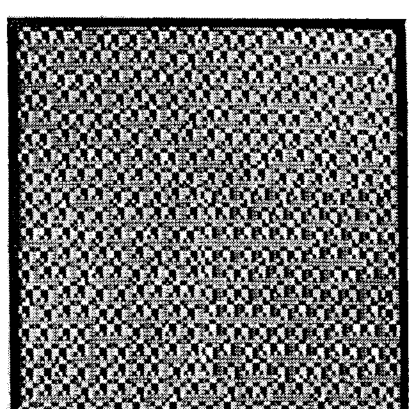

Fig. 13—Identical with Fig. 12 but one point out of 25 is changed. As a result line structures can be seen and discrimination is easier.

white S shapes) are completely hidden. When Fig. 10 is viewed at a very sharp angle, thus compressing the picture along one dimension, the dark and light lines reappear and discrimination is faciliated. This experiment implies that some isotropic spatial operation is taking place and only by minimizing the distance between like-brightness elements along a given direction can the interaction of adjacent points lead to uniform segments.

Fig. 11 is identical with Fig. 10 but the position of the micropatterns is jittered randomly around the regular grid points by one picture element. The discrimination is again due to the lines formed by the micropatterns. If we use a different 4×4 matrix, where the black and white dots are more homogeneously placed, the line structure is not apparent and discrimination is extremely difficult, although the two fields are again complements and have identical first and second order probability distributions. (See Fig. 12.) If only one point is changed in the micropattern (*e.g.*, 1 point out of 25), the line structure appears and discrimination is easier to perform. (See Fig. 13.)

V. Periodicity Detection as a Result of Connectivity Detection

The previous experiments indicated the importance of adjacent points of equal brightness. Classically, it is known that periodic structures attract the eye. The next experiments will show that this phenomenon can be attributed to connectivity detection.

If we take a random field and along one line introduce a sequence of alternating black and white dots, this periodicity cannot be detected by a cursory inspection. If several lines of the same periodicity are inserted in close proximity, then similar elements which are near each other are summated and a structure of parallel lines is seen. Fig. 14 indicates the geometry. The dotted lines show connected bright (or dark) dots. Every odd line is periodic while every even line is entirely random. Fig. 15 demonstrates that discrimination is due to the parallel vertical line structure formed in the left field and the diagonal line structure in the right field. Only in the top and bottom lines (which are bounded by a dark area) are the periodic sequences 0, 2, 0, 2, $\cdots$ and 1, 3, 1, 3, $\cdots$ observable. When one picture element phase shift is introduced in the periodic patterns in order to obtain diagonal stripes in the entire field (see Fig. 16) no discrimination is possible. (See Fig. 17.) At the boundary a sporadic faint line can be seen due to the fact that two dark or bright elements meet at the boundary (2, 3 or 1, 0).

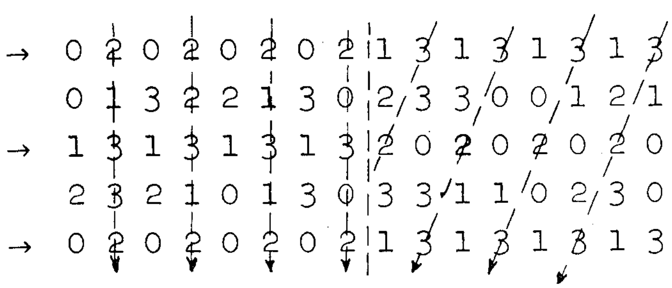

Fig. 14—Illustration of the method by which Fig. 15 was generated.

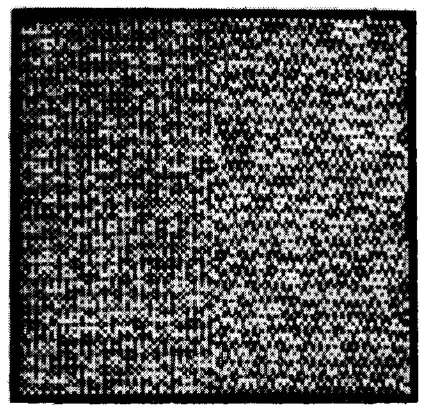

Fig. 15—Periodicity detection is a result of connectivity detection. The two fields can be discriminated as a result of differences in directivity of the stripes formed.

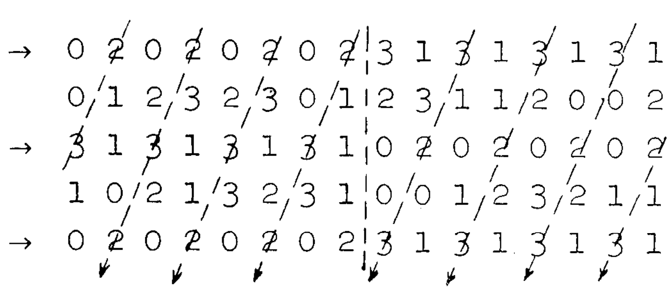

Fig. 16—Illustration of the method by which Fig. 16 was generated.

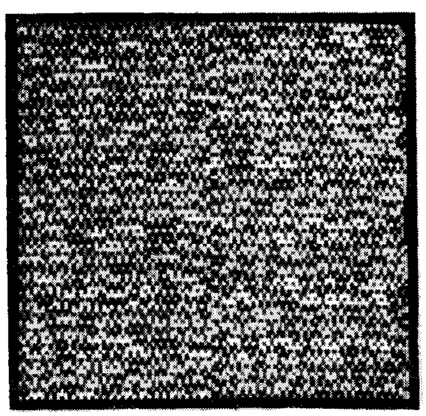

Fig. 17—Identical with Fig. 15 except for a phase shift. The two fields seem identical.

VI. Connectivity Rules of Quantized Brightness Levels

In the previous sections the importance of point domains of uniform brightness was observed. The meaning of *uniform brightness* in this context requires further elucidation. Particularly, the following problem was investigated. Can adjacent points of unequal brightness levels be perceived as forming a line? That is, can we shift our attention to clusters of unequal brightness points and connect them? Fig. 18 shows a display where every even line is random and contains four quantized brightness levels 0, 1, 2 and 3, while the odd lines are also random and contain only two brightness levels (0 and 1) and (2 and 3) in the left and right fields, respectively.

Fig. 19 was generated according to this principle and it is seen that the lines formed by 0, 1 and 2, 3 are perceived as connected dark or bright lines which can be easily discriminated. In these patterns, connectivity was between adjacent points with adjacent brightness values, (0 and 1) and (2 and 3). What would happen if adjacent points had nonadjacent brightness values such as (0 and 2) or (1 and 3)? A display of this kind is indicated in Fig. 20.

Fig. 21 demonstrates such a display in which no discrimination is possible. This finding implies that the visual mechansim operates like a slicer in separating brightness levels into dark and bright values. The range of brightness can be divided into two categories (dark and bright) by setting the slicer level at will, but it is impossible to quantize the brightness values into several levels and form categories which are not adjacent in values. (Fig. 22).

→ 0 1 0 0 1 0 1 1 | 2 2 3 2 3 3 2 3
  0 1 2 3 2 3 2 0 | 1 0 2 0 3 1 2 1
→ 2 3 3 2 3 2 3 3 | 1 1 0 0 0 1 0 1
  1 0 2 3 1 0 2 2 | 3 1 2 3 3 0 2 0
→ 1 0 1 0 0 1 1 1 | 2 3 2 2 3 2 3 3

Fig. 18—Illustration of the method by which Fig. 19 was generated.

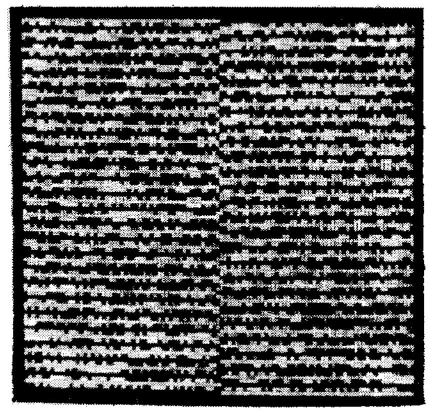

Fig. 19—Black and dark gray; and, white and light gray adjacent points can be connected into lines.

→ 0 2 0 0 2 0 2 2 | 1 1 3 1 3 3 1 3
  0 1 2 3 2 3 2 0 | 1 0 2 0 3 1 2 1
→ 1 3 3 1 3 1 3 3 | 2 2 0 0 0 2 0 2
  1 0 2 3 1 0 2 2 | 3 1 2 3 3 0 2 0
→ 2 0 2 0 0 2 2 2 | 1 3 1 1 3 1 3 3

Fig. 20—Illustration of the method by which Fig. 21 was generated.

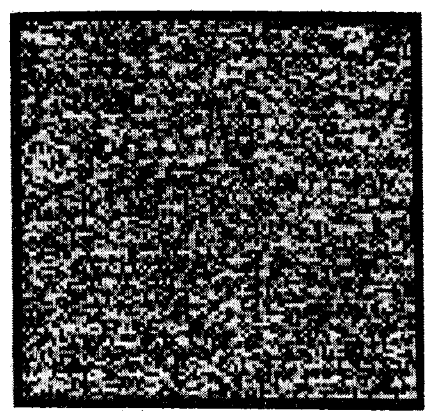

Fig. 21—Black and light gray; and, white and dark gray adjacent points cannot be connected into lines.

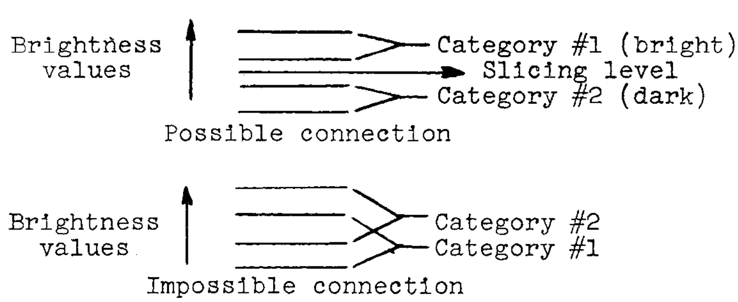

Fig. 22—Illustration of the connectivity rules of brightness levels

VII. Connectivity Rules of Colored Dots

In Section VI connectivity rules for different brightness values were established. The same experiments were repeated using picture elements having different colors with equal subjective brightness (similarly to the pseudo-isochromatic charts devised by Ishihara for testing color-blindness). The points could have four different hue values. Four transparencies were computer-generated for the four hues. Each slide was opaque except for the points having the hue value in question. When the four transparencies were projected in registration by four projectors having color filters, every point of the display had an assigned hue. The brightness of the four projected hues was set subjectively equal. (Several conventional methods of colorimetry were used.) The four hues used were red (R), yellow (Y), green (G), and blue (B) (or with more compressed hue separation orange, yellow, greenish yellow, and blue green). The experiments were identical to Fig. 18 and Fig. 20 but now $0 \rightarrow$ R, $1 \rightarrow$ Y, $2 \rightarrow$ G, and $3 \rightarrow$ B. The results were similar to these previous experiments, with hue separation replacing brightness separation. Red and yellow dots could be fused into lines, similarly blue and green dots could be connected. On the other hand, it was impossible to connect red and green dots or yellow and blue dots into lines.

VIII. The Limitations of Discrimination of Complex Line Structures

Though connectivity appears to be the main cue for discrimination, other properties of such regions, such as their size, their average length and width, their orientation, their density, etc., serve as further discrimination cues. The next experiments use complex line structures which have the same size, length, width, density and orientation (vertical, horizontal, etc.); but the sign of the orientation (up, down, left, right, etc.) is variable. A 3×3 matrix containing 4 black elements forming a *T*-like shape can occur in 4 different positions. (See Fig. 23.) Fig. 24 is composed of such adjacent *T* patterns according to Format B. The larger field is composed of *T* patterns of the four different positions at random, whereas the quadrant in the lower right region contains only *T* patterns of (a) and (c).

It can be noticed that discrimination at first sight is impossible. After careful inspection, it might be noticed that straight line structures formed by two adjacent white and black lines occur both in horizontal and vertical directions. The vertical structure has the white side to the left in the smaller field and to the right in the larger one; similarly, the horizontal structure has its white side down in the quadrant and up in the larger field. With

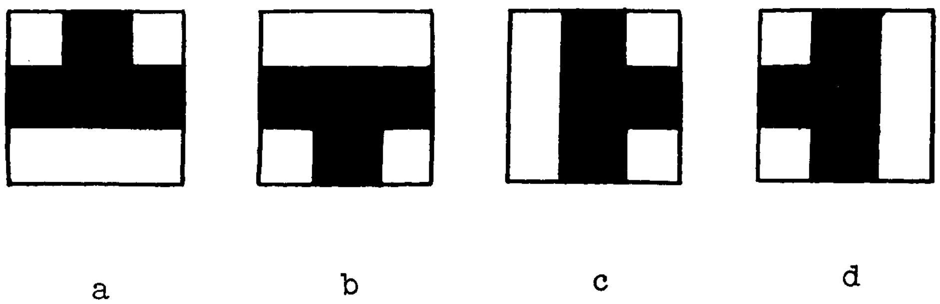

Fig. 23—Micropatterns of which Fig. 24 and 25 are composed.

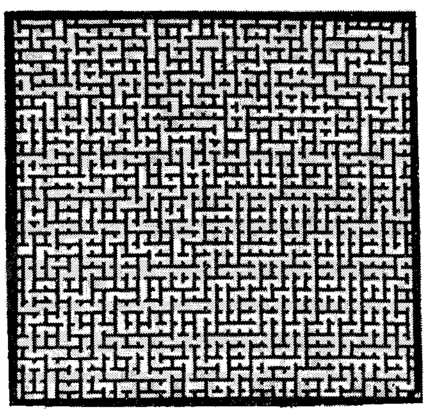

Fig. 24—Two fields (Format B) where the larger one contains (a) (b), (c), and (d) micropatterns of Fig. 23 at random, whereas the small field only (a) and (c).

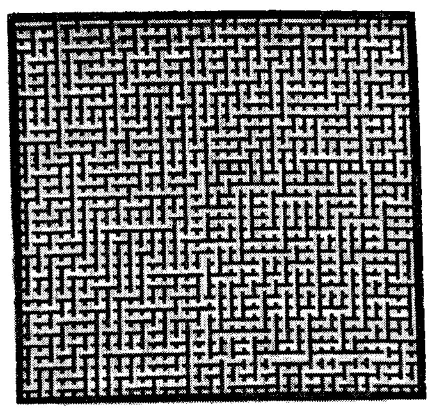

Fig. 25—Identical with Fig. 24 but the larger field contains (b) and (d) micropatterns at random.

even more conscious effort some different arborization structures might be detected, but all these observations result only in a weak discrimination. (Under certain rare conditions, the double lines can be seen in relief, the black side regarded as a shadow, and in one region the white sides are above the background, while in the other region behind.) Fig. 25 is similar to the previous one, but the large field contains T patterns of the (b) and (d) type, whereas the quadrant has again (a) and (c). Discrimination is even more difficult; although after careful inspection at the boundaries of the two fields certain unique structures can be seen (single $T - s$ and little squares).

These experiments indicate that the basic discrimination processes assign great importance to line structures, but if certain crude properties (width, brightness, orientasion) are similar, differences in the direction of connectivities cannot be perceived. Only by conscious efforts can discrimination be performed, but even on this level, the main cue is the recognition of differences in double lines.

IX. Conclusion

This study revealed the importance of clusters formed by proximate points of uniform brightness in visual discrimination. Embedded in random fields such clusters were immediately noticed. Clusters of points having unequal brightness passed unnoticed. The spontaneous process required to perceive clusters or lines might be called *connectivity detection*. Several rules of this connectivity detection have been established.

Several physiological models for connectivity detection can be proposed by considering spatial interaction of simple excitation and inhibition followed by nonlinear slicing. Recent neurophysiological findings[12–14] reveal that more complex spatial interactions are effective in the higher visual centers of animals. There are apparently specific neurons which respond selectively to various properties such as curvature, angles, etc. The psychological experiments reported here support such physiological findings and may suggest some other specific units which are important in visual perception.

Acknowledgment

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Kinesthetic-Tactile Communications*

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Summary—Machine aids to kinesthetic-tactile communication aim at maximizing the information-transfer rate from an external source to the human user. The display is the central problem. Source messages might be recoded into equal information units presented one at a time to the user, or a temporal or spatial display of the message may permit the user to recode the message perceptually into manageable units. The performance of these alternatives has been examined using a kinesthetic-tactile display for English text. This device consists of eight finger rests, each of which can move in 26 directions in three-dimensional space. Two methods of programming this device to present information were investigated. In the "traveling-wave" presentation, a three-dimensional traveling wave of finger movements moves across the display representing a sequence of symbols. This presentation is an example of the case in which the *user* recodes the source messages perceptually. In the "typewriter" presentation, the subject's fingers are moved corresponding to the way he would actively move them if he were typing. The latter proved to be the more effective, yielding a transmission rate of 4.5 bits/sec.

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Introduction

NORMALLY, most environmental information is supplied by our visual and auditory senses. These senses are effective receivers—capable of providing a continuous information intake of about 40 bits/sec. However, it is sometimes necessary to communicate through other sense modalities. For example, people handicapped by the loss of vision or audition, from either physical disability or environmental conditions, may want to compensate with their remaining senses. Also, for military purposes, surreptitious communication may be desirable. For example, a small