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THE EFFECT OF DEVIATIONS FROM LINEARITY ON THE DETECTION OF DOTTED LINE PATTERNS[1,2]

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IN RECENT years, important breakthroughs in neurophysiology (e.g. the work of HUBEL and WIESEL, 1959, 1962) have focused much attention in visual perception research on stimuli composed of straight lines or linear contours, and in psychobiological reductionistic theory on models in which line-sensitive neural feature detectors play an important role. In addition, recent experiments with dotted patterns have shown that straight lines are especially efficient in determining the recognizability of alphabetic characters (UTTAL, 1969) and geometric forms (UTTAL, 1971a), or even in judgments of figural "goodness" (GARNER and CLEMENT, 1963). An important related question thus arises: are separate straight lines more easily detected than curves or angles with identical local geometry?

The present paper explores the effect of changes in curvature and angulature on detectability for curves and angles of two different sizes. The general finding is that the overall or global pattern of a dotted stimulus does affect its detectability in the signal detection type of task used, even when local properties (in this case interdot spacing) are held constant.

In examining the question of straight line detectability in the modern context of techniques pioneered by such workers as Crook, Weisz and Green (see WULFECK and TAYLOR, 1957, for a summary of their developments), some notions introduced by the Gestalt school 30 or 40 yr ago are being reconsidered. However, we now do so from a researchable perspective. ZUSNE (1970) points out that even the most widely accepted Gestalt tenets have not been rigorously established. Although one may wish to reject the Gestalt *explanation* of the "good figure" rule, for example, an empirical test of the *rule* itself may be of some value in helping us toward an understanding of how we perceive patterns.

METHOD

Subjects

Undergraduate students at the University of Michigan were used as *S*s in these experiments. Each *S* served for 1 hr a day, after a 3-day training period. The target detection task was learned quickly and little additional improvement in standard performance occurred after this brief training period.

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Equipment

The entire experimental procedure was carried out under the control of a small digital computer programmed to present the stimuli, acquire responses and preanalyze the data. The *S* observed the stimuli on the face of an oscilloscope which was driven by a two-channel (*X* and *Y* axes) digital to analog output from the computer. Each dot was intensified by an 8 μsec pulse applied to the *Z* axis (beam unblanking) input of the oscilloscope. The cathode ray tube used in the oscilloscope was coated with an ultrashort persistence phosphor (P-15). Dots plotted on this surface faded to a subthreshold visual brightness (0·01 per cent of the initial brightness) in no more than 50 μsec. The display was limited to a square area measuring 6·5 by 6·5° at a distance of 33 cm from the bridge of the *S*'s nose. Overall target line breadth varied from about 4·5 to 2·75° of visual angle.

The *S* was seated in a sound- and light-attenuating cubicle in total darkness except for the display, with his head immobilized by a forehead rest. Responses were introduced into the computer system by depressing one of two hand-held pushbuttons to trigger the computer interrupt system. The response activated a subroutine which entered the response into the experimental protocol and initiated a new trial.

Procedure

Four separate experiments were carried out. The method in all four experiments entailed the random presentation of one of a set of 24 stimuli embedded in greater or lesser amounts of dotted visual noise. The general nature of the masking effect of dotted visual noise on dotted stimuli has been described in detail both for continuous dynamic visual noise (UTTAL, 1969) and for bursts plotted in a few milliseconds (UTTAL, 1971b). In brief, monotonic degradation of the recognizability and detectability of ordered stimuli occurs as noise density (or rate of noise dots) is increased, or as interval between stimulus and noise is decreased. One advantage of this procedure is that degradation in performance is controllable, from virtually perfect recognition to chance levels, simply by varying the number of noise dots. No change in focus, duration, brightness or any other physical parameter of the stimulus is required, nor any brightness difference between the stimulus and mask.

The experimental paradigm used was a two-alternative forced choice procedure in which the *S* indicated which of two sequential bursts of random dotted visual noise (separated from each other by a period of 1 sec) contained a dotted line signal. After one of the buttons was pushed a plus (+) or a minus (−) feedback sign appeared in the center of the stimulus field, indicating whether or not the correct interval was selected. This feedback sign also served as a rough fixation guide, but terminated 1 sec prior to the next trial. In each trial both the particular stimulus and which noise burst contained the stimulus were determined by random number algorithms.

The number of noise dots was kept constant for each daily session, but on sequential days each noise burst contained 40, 60, 80, 100, 120, 140 or 160 dots, respectively. This sequence was repeated twice. The number of dots in the signal was always deducted from the number of dots in the noise burst which did contain the signal, so that the two sequential stimulus bursts contained the same total number of dots. Therefore, such secondary cues as dot density or overall brightness were minimized.

Each of the four *S*s completed about 750 trials in each session. These data were summarized at the end of each session by a preprocessing program built into the experimental control program. Data from the eight runs (four *S*s on each of 2 days) were then summarized by a final analysis program. Because several conditions were explored each day, each point on each figure represents the accumulated results of approx. 1050 trials.

Stimuli

Although the general procedure described above was common to the four experiments, individual experiments used different stimulus sets. Two of the experiments were concerned with the effect on detectability when a straight line was deformed into curves, and two were concerned with the effect when a straight line was deformed into angles. In each of the four experiments there were six sequential steps of increasing curvature or angulature for each of four different initial straight line orientations—a total of 24 different stimuli. This was done in order to maintain uncertainty about specific dot locations. Figure 1 shows a sample of each of the four stimulus sets. In each case the six (of 24) stimuli produced by the downward deformation of a horizontal line have been chosen as the sample, but in other instances the orientation of the initial lines was vertical or oblique in either the left or right direction.

The first experiment utilized a line of nine dots separated by 33′ of visual angle, producing a total line length of 4° 24′. The stepwise increase in curvature shown in Fig. 1 was determined on an arbitrary basis for successive stimuli. Because earlier work (UTTAL, BUNNELL and CORWIN, 1970) had shown that the spacing of dots in straight lines is a strong determinant of their detectability and recognizability, experiment II used a family of curves in which dots were less densely placed to examine the effects of that variable. A line of seven dots, 4° 24′ in length, was used in this experiment, defining an interdot interval of 44′ of visual angle.

In experiments III and IV the straight lines were deformed into angles rather than curves. Increasing angulature was in 20° steps from 180° (a straight line) to an 80° angle. Since it is known that the detectability

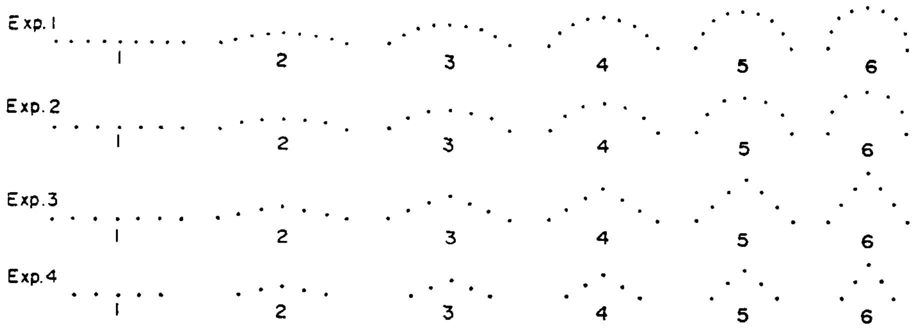

FIG. 1. Sample stimulus sets for the four experiments, showing the six patterns produced by downward deformation of a horizontal line. (Each experiment also contained 18 other similar patterns which were produced by deformation of differently oriented straight lines. Note differences in dot spacing and numerosity between experiments I and II and difference in numerosity between experiments III and IV.)

of straight lines is influenced by the number of dots in the line—the effects in some cases asymptoting at five dots (UTTAL *et al.*, 1970) or in some cases increasing without limit as the number of dots is increased (CHINNIS and UTTAL, in press)—experiments III and IV were composed of lines and angles which included seven and five dots, respectively, spaced at 44′ in each case for a total line length of 4° 34′ and 3° 6′.

Within each of the four experiments interdot spacing, total length and number of dots remained constant. Only the global pattern was varied.

RESULTS

The results of the four experiments are shown in Figs. 2, 3, 4 and 5. In each figure the percentage of correct response is plotted against curvature or angulature for the various noise levels. This data has been pooled for all noise levels and tabulated as an arithmetic mean for each experiment in Table 1.[5] The major finding of this study is apparent: there is a

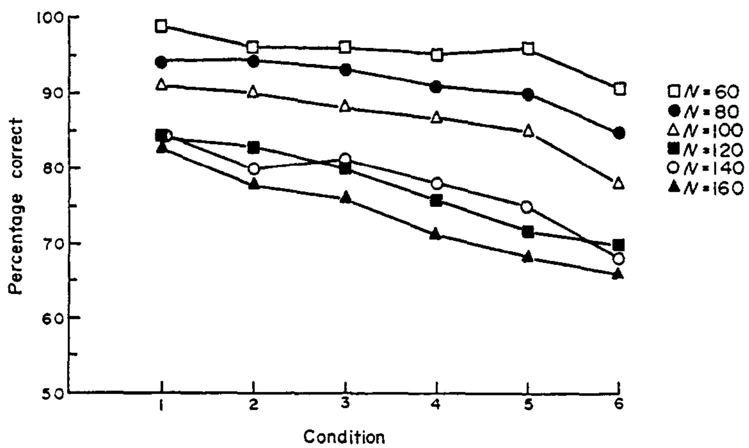

FIG. 2. Results of experiment I showing the decrease in detectability as 9-dot lines were deformed into curves.

[5] It should be noted that Table 1, in collapsing the data over the noise level parameter, does obscure some important aspects of our findings. For example, the range of the effect of noise in experiment II is 50 per cent greater than for the angles of experiments III and IV. Similarly, the range of the effect of noise in experiment I is considerably less than the range of experiment II, due to the resistance of the more densely spaced dots to masking.

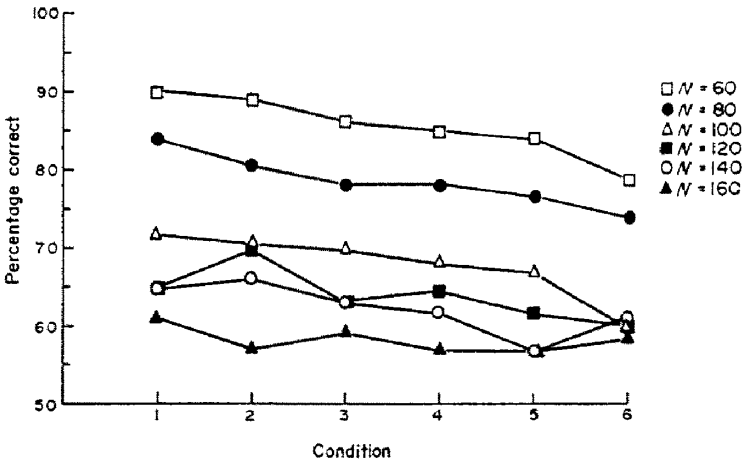

FIG. 3. Results of experiment II showing the decrease in detectability as 7-dot lines were deformed into curves.

gradual decline in the detectability of the line as deviation from linearity increases. This decline is most pronounced for the large curves of experiment I, due to their higher absolute level of initial detectability, but is also present to a lesser extent in experiments II, III and IV. There is, on the other hand, little suggestion that the decrease in detectability is sensitive in any strongly nonlinear manner to the increase in curvature or angulature. Furthermore, that there is no discontinuity or point of inflection on any of the curves seems to provide at least circumstantial support for the notion that no separate or distinct mechanisms are being called into play at different levels of geometrical deformation. Such a linear and continuous process is further indicated by the general parallel course of the family of curves in each figure, the only notable exception to this being a slight increase in spread as one passes from the straight line to the curves in experiment I.

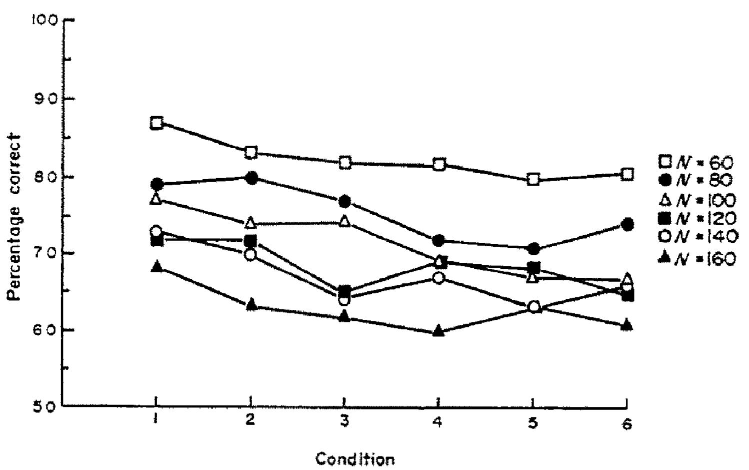

FIG. 4. Results of experiment III showing the decrease in detectability as 7-dot lines were deformed into angles.

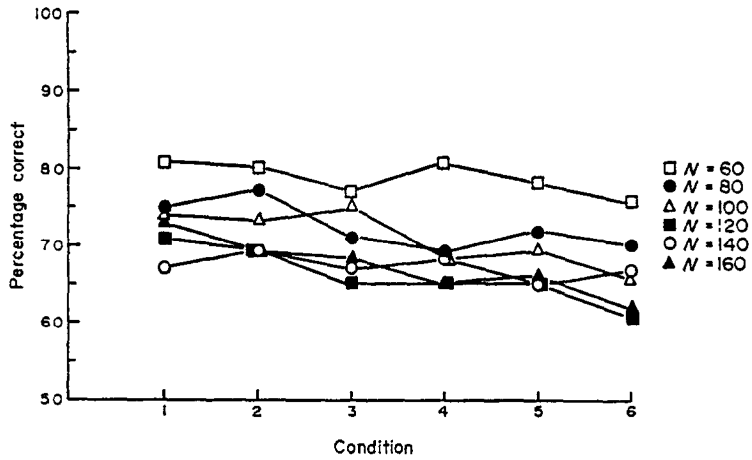

FIG. 5. Results of experiment IV showing the decrease in detectability as 5-dot lines were deformed into angles.

Comparisons between experiments I and II do show one expected difference. The absolute level of detectability of the more densely plotted dots in experiment I is greater than the less densely plotted dots of experiment II.

Table 1 also emphasizes another point. Allowing for the general decline in performance as angulature and curvature increase, there is little further difference between experiments II, III and IV, each of which possessed the same dot density.

TABLE 1. DECLINE IN DETECTABILITY AS A FUNCTION OF INCREASING CURVATURE OR ANGULATURE FOR THE FOUR EXPERIMENTS POOLED ACROSS ALL NOISE LEVELS

	Condition					
Experiment	1	2	3	4	5	6
1	89	86·8	85·6	83	81	76·3
2	72·8	72·3	69·8	69	67·6	65·3
3	76	73	70·7	69·8	69·3	69
4	73·5	72·8	70·5	69·3	69·2	67·0

DISCUSSION

The main finding of the experiments is that straight lines are more easily detected than curved or angled lines even when dot numerosity and interdot spacing are held nearly constant. The main question raised is why this should be the case.

Any explanation based on template matching or specific feature filtering leaves many unresolved problems. For example, it is necessary to explain the origin of sensitivity to specific forms. From this perspective, one would also be hard-pressed to explain how a figure which belonged to some general class but which had not yet been seen, or had not yet been seen in a specific orientation, could be recognized as easily as a familiar figure in a familiar orientation. As an exmple, one might consider KOLER's (1970) family of "random stimuli"—

in reality, an easily recognizable set of chairs. All template models of visual pattern perception, regardless of whether they are based on uni- or multicellular premises, fall victim to this criticism. Nor do template theories adequately model the insensitivity to magnification, rotation and translation which seems to characterize the recognition of dotted stimuli.

Clearly some sort of form recognition process sensitive to global rather than to local features and not requiring an internally stored template is called for. Such a process should probably be based on a multicellular network and should be characterized by a well-distributed mechanism, as focused upon in PRIBRAM's (1969) analogy of the "holographic brain" or JOHN's (1972) statistical theory of learning. Because of the results of the dot pattern experiments, it should also show special sensitivity to periodicity.

Is there such a process? Indeed there are many—the family of mathematical functions that includes averaging, cross-correlation, Fourier analysis and autocorrelation is just one possible source. All of these functions are sensitive to the overall form and periodic properties of the input pattern. In fact, each is formally identical to the other, but emphasizes one or another special feature.

Because of the nature of the current data, the particular importance of periodicity, and the desire to avoid any reference to an internal template or specific feature detection mechanism, autocorrelation is an especially attractive process. Though not a unique one, it is presented as one example of a transform that is sensitive to global geometry without sensitivity to specific features. Certainly exceptions will be found; however, it does represent one example of the sort of plausible transform which will ultimately prove capable of modeling these psychophysical findings. Most important of all, this illustrates an alternative manner in which specific sensitivity to particular forms, such as straight lines, can be produced even by a homogeneous and isotropic array of elements that individually display no directional or shape specificity.

Following specific suggestions by ENGEL (1969) and by DODWELL (1971), it is hypothesized that the detection of patterns in the present experiments is carried out by a neural correlate of the two-dimensional autocorrelation:

$$A(\Delta x,\Delta y) = K \iint f(x,y) \quad f(x + \Delta x,y + \Delta y)\mathrm{d}x,\mathrm{d}y,$$

in which $A(\Delta x,\Delta y)$ is the autocorrelation value of a function $f(x,y)$ at a given Δx and Δy (a shifted position), and K is merely a scaling constant.

Autocorrelations have the property of extracting those parts of signal patterns that are periodic in the X, Y space. Thus, signals composed of evenly spaced dots would be enhanced, sharpened or detected in a background of randomly placed dots even if all other physical properties of the signal and noise dots were constant.

An optical computer has been used to perform an autocorrelation on photographs of the stimulus patterns and thus to test the plausibility of this hypothesis. The procedure is based on a little-known technique that has been used to extract information about latice regularity in crystallography—the so-called Patterson plots (PHILLIPS and MCLACHLAN, 1954)—and more explicity, as an autocorrelator for photographed patterns by MEYER-EPPLER (1946), MEYER-EPPLER and DARIUS (1956), and MCLACHLAN (1962). The process essentially depends upon the overlap of multiple pinhole images in a way which specifically analogizes the autocorrelational mathematics described above.

Figure 6 shows the autocorrelation functions obtained with this simple optical computer for five different stimuli. The autocorrelograms shown are of a straight line (Condition 1 in experiments II and III), a slightly curved line (Condition 3 in experiment II), a maximally

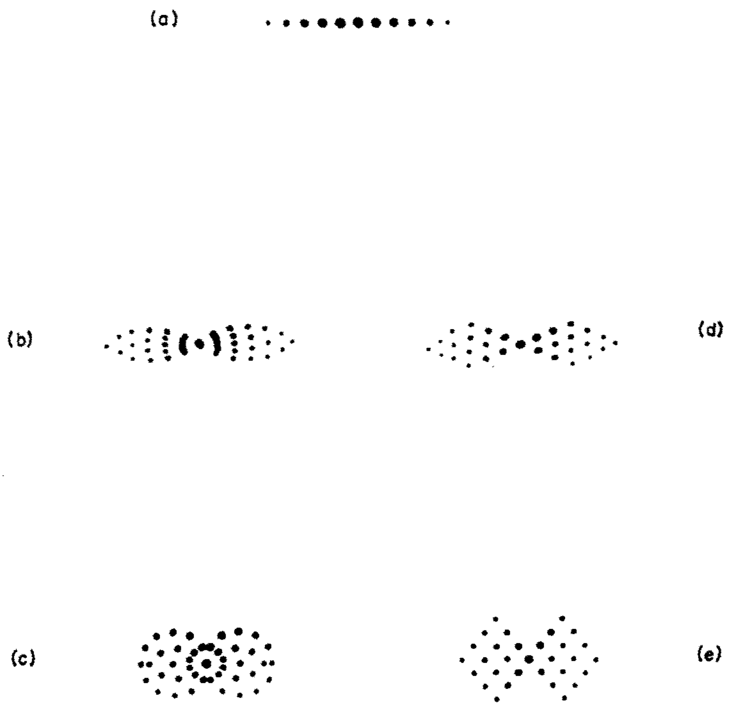

FIG. 6. Output of the optical correlator for: (a) a seven-dot straight line; (b) Stimulus Condition 3, experiment II; (c) Stimulus Condition 6, experiment II; (d) Stimulus Condition 3, experiment III; (e) Stimulus Condition 6, experiment III. (Some dots have been retouched to overcome the degrading effects of the quadruple photographic processing required.)

curved line (Condition 6 in experiment II), a slightly angled line (Condition 3 in experiment III), and a maximally angled line (Condition 6 in experiment III), each of which contains 7 dots separated by 44′ of visual angle.

An examination of these autocorrelograms suggests how the observed differences in detectability might be due to this sort of transform. The straight line is clearly a special case, for there are fewer visible dots in this correlogram than in any of the others, indicating that the same amount of energy must be distributed across a smaller number of dots. Thus the dots of the straight line correlogram will be brighter than those in any of the other autocorrelograms. Indeed, when the correlogram of a straight line embedded in a substantial amount of background noise was also photographed, the dots corresponding to the straight line were clearly visible, brightened above the lower level of the background noise dots. None of the other stimulus forms displayed this brightness differential to anywhere near the same degree.

What then can analogize the contained decrement in detectability of the stimuli as they become more curved or angled? An answer is also apparent in these correlograms. As angle or curvature becomes greater, the dots of the correlogram move increasingly far apart from each other even though the stimulus dots are all equally spaced. Since we know that dot spacing is perhaps the strongest determinant of the detectability of a dotted straight line (UTTAL *et al.*, 1970), and since the autocorrelation reproduces these spacings, we may assume that a similar increase in dot spacing in the autocorrelograms of curves and angles could be associated with a reduction in their detectability in dotted visual noise.

The notion of a neural autocorrelator has another advantage. It is a global process in which the overall pattern of the stimulus can play an important role in the extraction process. Models utilizing local processes (usually average density sorts of calculations) are typically insensitive to the form of a line. The autocorrelational process, on the other hand, reflects the differential advantage of global straightness, just as human observers do.

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Abstract—Four experiments were carried out to determine the detectability of dotted line stimulus patterns embedded in backgrounds of randomly dotted visual noise. The results indicate that straight lines are more easily detected than curves or angles. This finding holds robustly even though interdot spacings (local geometry) are held constant in each experiment. The global organization of the stimulus, therefore, is a strong determinant of the ease of visual pattern detection. The implications of these findings for pattern recognition theory are considered using an optical computer.

Résumé—On détermine par quatre expériences la possibilité de détecter un stimulus dessiné en lignes ponctuées, noyé dans des fonds de bruit visuel obtenu par des points au hasard. Les lignes droites sont détectées plus facilement que les courbes ou les angles. Ce résultat résiste solidement bien que les espaces entre points (géométrie locale) restent constants dans chaque expérience. L'organisation globale du stimulus détermine donc fortement la facilité de détection du dessin. On considère au moyen d'un calculateur optique les implications de ces résultats pour la théorie de reconnaissance des figures.

Zusammenfassung—In vier Experimenten wurde die Erkennbarkeit einer punktierten Linie auf einem Rauschmuster untersucht. Die Orgebnisse zeigen, dass gerade Linien leichter erkannt werden als Kurven oder Winkel. Dieses Ergebnis bleibt bestehen, auch wenn der Abstand zwischen den Punkten (die lokale Geometrie) bei jedem Versuch konstant gehalten wird. Die Erkennbarkeit eines Testreizes wird also entscheidend durch seine globale Organisation bestimmt. Die Folgerungen dieser Ergebnisse für die Mustererkennung werden mit einem optischen Rechner untersucht.

Резюме—Было произведено четыре эксперимента для определения обнаружения паттернов, состоящих из линий образованных точками, включенных с фоны состоящие из точек, расположенных в случайном порядке (зрительный шум). Результаты показывают, что прямые линии обнаруживаются легче, чем кривые и линии представленные под углами по отношению друг к другу. Эта закономерность ясно сохраняется даже тогда, когда расстояния между точками (локальная геометрия) сохраняются постоянными в каждом из экспериментов. Глобальная организация стимула, поэтому, существенно определяет легкость обнаружения зрительного паттерна. Выводы из этих фактов для теории распознавания образов рассмотрены с помощью оптического компьютера.