On the detectability of straight lines in visual noise:

An extension of French's paradigm into the millisecond domain^{1,2}

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We report the results of a study that investigated the effects of four experimental parameters on the tachistoscopic detectability of dotted lines in a noisy background consisting of dynamic patterns of identical dots. Characteristics of the lines that were explored included dot spacing, dot numerosity, and line orientation. Dot spacing was shown to be the most powerful parameter in determining the masking effect: the closer the dots, the more easily the line was detected. Increasing the number of the dots was also effective in increasing the detectability of a line, but only up to a limit of five dots. The orientation of the line, on the other hand, did not alter its detectability. Increasing the density of the visual masking noise monotonically reduced the detectability of the line. These studies are an extension of French's (1953, 1954) work, differing mainly in the fact that the stimulus material was presented tachistoscopically rather than in a mode that allowed prolonged (up to 5 sec) examination of the figures. Thus, they put the results in a domain in which physiological interpretations may be more critically evaluated. A comparison of the results suggests that essentially the same sorts of cognitive mechanisms are operating in the millisecond domain as in the longer exposures. This suggests that simple neurological models utilizing the concept of feature filters or detectors may be being prematurely applied to relatively complex perceptual processes.

How do we recognize geometric forms? This question has arisen in many different areas of psychology, biology, and engineering in the last two decades, particularly since modern computer developments offered the possibility of imitating recognition processes with electronic mimics. The development of artificial pattern recognizers for both acoustic and visual signals, however, turned out to be a most refractory problem, and no machine yet designed is able to approximate the highly successful and general-purpose recognition processes of the human cognitive system. A major reason for this lack of engineering success may be attributed to the fact that there is

yet no fully adequate theory of human form recognition. A wide variety of experiments (see Wathen-Dunn, 1967, for a compendium of recent experimental and theoretical developments) have been used to study the parameters of form recognition, but few satisfactory general statements have been forthcoming. Individual experiments seem to be characterized mostly by the manipulation of specific features or dimensions, whereas the cognitive functions of man seem often to be concerned with relations that are almost independent of specific features. Where Es manipulate corners and sides in visual form recognition or frequency domains of auditory signals—the parts of the stimulus—there is a strong presumption that the human pattern recognizer is more concerned with relations among the parts than with the parts themselves. Thus, type font has relatively little influence on the recognizability of printed alphabetic characters for humans, but all artificial pattern recognizers are highly sensitive to slight changes in font. In sum, template fitting by correlational techniques or specific feature extraction does not seem, in many cases, adequately to mimic human pattern recognition.

One of the major intellectual foundations on which much recent work in pattern recognition is based is the knowledge emerging from the neurophysiological laboratory. Many workers have shown that neural mechanisms capable of extracting specific geometrical features of stimulus patterns seem to be common at many levels of the afferent pathways. Hubel and Wiesel (1959) have demonstrated directionally specific receptors in the visual system of the cat; Lettvin, Maturana, McCulloch, and Pitts (1959) have shown feature-geometry sensitivity in the frog; Barlow and Hill (1963) have made similar demonstrations for the rabbit; while Evans and Whitfield (1964) have extended many of these concepts to the auditory system.

But what of stimuli made up of component parts that are not connected, in which the "features" that might be extracted are nothing more than the statistical relations among the parts? Figures made of tachistoscopically presented dot patterns are examples of

such stimuli. It is hard to imagine how such a dot pattern might lead to the activation of a specific feature detector at any level of the nervous system. Physical features such as a line or corner simply do not exist in a continuous form. In other words, there is a set of relations that defines a pattern but specific features of the stimulus have no physical continuity or feature or temporal sequence that could conceivably activate a specific feature extractor. That small dots do not interact via lateral inhibitory interaction has been particularly emphasized by the recent work of von Békésy (1969).

We have recently been studying a visual pattern-recognition task, using a paradigm in which such dotted characters had to be detected in dynamic visual noise (DVN), a particularly controllable form of mask. One of the initial results (Uttal, 1969a) was that all characters were not equally easily identified. At very high noise levels, at which most characters could not be detected with any greater success than chance levels, the four characters I, K, L, and X were still surprisingly recognizable. The character X was on this list because of a rather curious artifact. In the font used in that experiment, X, unlike all other characters of our special alphabet, had no long straight lines and was, therefore, almost invisible even at moderate DVN levels. The Ss learned quite early that when they saw nothing at all they had probably been presented with, and thus they reported, an X. Quite artifactually, therefore, the "recognition" score for X was elevated. The characters I, K, and L, however, were recognized at supernormal levels for two different reasons. First, their confusion with other members of the alphabetic stimulus set was lower than that of the other characters; second, they contained long and straight dotted lines which uniquely defined the three characters. Long lines of dots appeared to be more easily detected than the shorter fragments which provided the distinguishing criteria for many of the other characters. When other members of the character set containing long lines of dots received low recognition scores, it was usually due to the difficulty of detecting shorter line segments, which were critically necessary to define which of several

confusable characters was actually presented.

The parameters of line detectability were thus of considerable interest in relation to this specific problem of alphabetic character recognition. But these measures are also of importance to the more general problem of how lines are detected. In the present paper, we report the results of a study in which the parameters of line density, orientation, and dot numerosity were varied to determine what effect, if any, these parameters had on line detectability. DVN was used to degrade the dotted line stimulus, which otherwise would have been almost perfectly detectable at all brightness levels above the threshold for the individual dots.

The experimental paradigm for line detection used in the present experiment turns out to be very similar to one used a number of years ago by French (1954) in studies of the recognition of more complex dot patterns embedded in dotted noise. The main methodological difference between those earlier studies and the present one is that French allowed his S to examine the displays for what seemed to us to be very long periods, ranging from 2 to 5 sec. Thus, all sorts of search, eye movement, and examination processes not possible in the brief presentations of our experiment were allowed. A further procedural difference was that French used a very small number of noise dots (1-8) rather than the relatively dense DVN patterns (10 to several hundred) used in the present study. Nevertheless, the results of these two studies are similar, a development which in itself is of some interest, as we shall see below.

METHOD

Subjects

Four Ss (students at The University of Michigan), inexperienced in previous psychophysical experiments, were used in this experiment. The task was of sufficient simplicity so that few effects of training could be discerned after 2 days of preparatory practice.

Procedure

The task of the S in this experiment was to identify the orientation of a dotted line embedded at the center of a 2-sec-long burst of DVN. The entire experimental procedure was under the control of a small digital computer (a PDP-5 with a 6-microsec core memory cycle). The stimuli and the DVN were constructed from dot arrays and plotted on the face of an oscilloscope (Tektronix 561), the face of which was coated with an ultrashort-persistence P-15 phosphor (brightness reduced to 0.1% after

50 microsec). The experiment was designed to evaluate the effects of orientation, dot numerosity, and dot spacing in varying amounts of DVN. The DVN density was specified by the interflash interval (IFI) between randomly located points in an area 6 deg wide x 9 deg high, which, as we shall see, was somewhat larger than the length of most of the lines. During each daily session, the stimuli were drawn from a set of 24 lines in which the four orientations and six dot numerosities were presented. Each day, the DVN level and the dot spacing were held constant, but from day to day one of five DVN levels and one of four dot spacings were jointly specified. The entire experiment was thus run in 20 daily sessions for each S.

The length of the line to be detected thus varied from trial to trial as well as from day to day, depending upon the specific number of dots and the dot spacing selected. In some of the cases in which a large number of dots was combined with wide dot spacing, the line could extend out of the region covered by the DVN. In these cases, the extra dots were simply masked off by a black paper shield. All such conditions occurred in data regions that were essentially plateau-like and thus did not affect the results of the study.

The values of the various parameters were as follows: The four orientations included horizontal, vertical, left oblique, and right oblique alignment; the six dot numerosities included 3, 4, 5, 6, 7, and 8 dots; the five DVN levels were specified by IFIs of 2, 4, 6, 8, and 10 msec; and the dot spacings were defined by the visual angle in minutes of arc (min) between dots (as measured along the axis of the line of dots) and could have the values 17.5, 35, 52.5, and 70 min. These latter measures can be converted to linear measures by noting that the face of the oscilloscope was 14 in. in front of the bridge of the S's nose, which was constrained by a forehead rest.

Each S served for a ½ h in a sound- and light-shielded cubicle. He responded, indicating the apparent direction of the line of dots, by speaking the words "horizontal," "vertical," "left," or "right" into an intercommunication system. A transcriber keyed this information into the input teletypewriter for the computer and then fed back error information, if a mistake was indicated by the computer, to the S.

Data were analyzed immediately by the computer at the end of each session.

RESULTS

The results of the entire experiment are shown in Figs. 1, 2, and 3. In each of these figures, the data have been analyzed in a different fashion.

Fig. 1. The data of the experiment factored according to the spacing of the dots composing the signal line. X = dot spacings of 17.5 min; O = 35 min; * = 52.5 min; and + = 70 min. The horizontal axis indicates the interflash interval between dots in the DVN while the vertical coordinate represents the percentage of the total number of lines presented which were correctly oriented by the S.

In Fig. 1, the data have been separated into four curves parametric as a function of the spacing between the dots that make up the straight line. The variation in the recognizability of the various patterns is shown as an effect of various levels of masking DVN by plotting the percentage of the total number of dotted lines that were correctly oriented against the noise level. It is clear from this rendition of the data that the spacing of the dots is a key factor in the detection and correct orientation of the straight lines. It should be noted that pure chance for this experiment is the 25% level, since there are only four alternatives with which the S might respond.

In Fig. 2, the same data are replotted, but this time parametric in the number of

Fig. 2. The data of the experiment factored according to the number of dots composing the signal line. X = 3 dots; O = 4 dots; * = 5 dots; + = 6 dots; # = 7 dots; and \$ = 8 dots. Coordinates are the same as in Fig. 1.

Fig. 3. The data of the experiment factored according to the orientation of the signal line. X = horizontal; O = right oblique; * = left oblique; and + = vertical. As indicated in the text, the difference between the curve for the horizontal lines and the other three curves is not considered to be significant. Coordinates are the same as in Fig. 1.

dots in the dotted line. The data in this case indicate that the performance of the S is increased by the addition of dots to the straight line, but only up to a limit. Adding dots beyond five does not increase the detectability of the line in the DVN used in the present experiment.

In Fig. 3, the data have been replotted parametric in the orientation of the dotted lines. Three of the data lines, those corresponding to the vertical, left oblique, and right oblique orientations, are virtually superimposed. The curve presenting the data for the horizontal orientation is slightly displaced, but this is known to result from the use of a rectangular rather than a square display area and is not believed to represent a real difference between this curve and the other three of Fig. 3.

These results may be compared with those of French (1954). In spite of the fact that French's Ss were allowed periods of several seconds to examine the stimulus materials, he obtained effects very similar to those reported above. Increasing the number of dots increased the performance of the S, but only up to a limit. His data curves appear to flatten out when there are seven dots in the stimulus pattern. On the other hand, increasing the noise dots continues to decrease performance progressively, just as in our present study. Furthermore, in an earlier study (French, 1953) not involving masking with visual noise, he found pattern recognition was very strongly affected by spacing of the dots, as was seen in the present experiment.

In connection with our current interest in the physiological foundations of this kind of pattern perception, this similarity

in results, even though obtained in quite different time domains, is striking. Considering the longer observation periods during which eye movements, scanning, search, "hypothesis formation," and a variety of other complex information processing functions were allowed, there would have been little reason to suggest that relatively simple neural feature filters or detectors were likely to be involved. In the tachistoscopic case of the present experiment, however, and particularly in light of the schema of much current physiologizing among experimental psychologists, such reductive explanations seem far more likely to emerge. In the discussion that follows, we shall mainly consider this epistemological point.

DISCUSSION

The results of this paper and the similarity of French's (1953, 1954) data suggest that some current popular ideas about pattern recognition may have to be modified or reformulated. First, it is difficult to see how a theory of straightness based upon a "functional geometry" or "congruence under displacement" (Platt, 1958, 1960) could explain these data. The main notion of the Platt theory is that line straightness is based on invariance of the retinal image as the image is translated across the retina. Since, in the present experiment, the stimuli were dot patterns in which each dot was 50 microsec in duration, and the presentation of the entire dotted line lasted less than 1 msec, displacement, the sine qua non of Platt's theory, is prohibited. Mechanisms other than self-congruence must thus be invoked. Platt also places the locus of this straightness-detecting mechanism in the retina itself, but previous experiments with dichoptic mixing of dot patterns (Uttal, 1970) strongly suggest that rows of dots from each retina could be mixed and interpreted as a straight line in the same way that Eriksen and Collins (1967) mixed dot patterns to form nonsense syllables. Thus, both the notions of displacement and uniretinal congruence seem to be violated in experiments of the present sort, and Platt's theory and others like it can no longer be considered tenable.

It is also extremely important to remember that the geometrical properties of the stimulus need not be maintained at all possible levels of the neurological coding schema for that neurological information to be interpreted appropriately. "Straightness" may not be encoded by linear representations any place beyond the optical distortions of the cornea and yet a stimulus pattern may still be interpreted as a straight line. The

topologically constant, though highly distorted, representations of the body in the somato-sensory region of the cortex (Penfield & Rasmussen, 1950) are examples of just such representation distortions without corresponding perceptual distortion. The classic prism adaptation experiments (starting with Stratton, 1897) suggest that it may even be possible to modify such nonlinear representations so that what once had encoded a straight line might no longer be so after sufficient and appropriate experience.

Similarly, the existence of the Hering, Zöllner, and Poggendorf illusions in which the perceived straightness of a line can be wildly distorted, even though optical linearity is maintained, suggests that the key to the problem of how straight lines are recognized may lie in considering this perceptual task in terms of a problem to be solved or a task in the interpretation of a set of organizational relations, rather than by referring to the properties of a hypothetical retinal analyzer.

In the present experiment, the problem-solving task requires that the S select from a number of isolated point stimuli a particular set, which is, in some statistical manner, aligned along a common axis. The fact that the dots of the line are no more interconnected with each other than they are with the dots of the noise, in fact in some cases less so, makes it hard to understand how a peripheral spatial filter or feature-extracting mechanism sensitive to this form of organization could operate. Quite to the contrary, we would have to hypothesize some very elaborate set of receptor signal analyzers that would have to operate on statistical distributions in a way that comes very close to modern discussions of decision making and other cognitive interpretative functions.

In conclusion, it is felt that perhaps too much emphasis may have been placed on explanations of highly complex perceptual phenomena based on the startling and exciting neurophysiological findings in filtering, feature-extraction, and directional sensitivity. The relational analyses that seem to be required to explain the present data imply that psychology once again may have become fixated on a new fad: the conceptually limited technology of the single-cell, microelectrode experimental paradigm (see Uttal, 1969b, for a complete discussion of this point). Some examples of discrepancies between the molar properties of the human sensory system and single-cell results are now beginning to appear in the literature (Julesz & Hesse, 1970). This perspective was, perhaps, best summed up by Harris (1969), who said, "We must not forget that physiological

data become physiological *models* when used to explain psychological phenomena." This is not to say that there is no physiological basis of this sort of perceptual behavior. Rather, the point we make is that the simple pattern-processing effects based on simple feature filtering may represent an oversimplified model of a far more complex neural mechanism—one that actually does the sort of statistical processing the results of the present experiment imply must be necessary.

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NOTES

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3. The figures presented in this paper were plotted on an oscilloscope under the control of a PDP-9 computer. This program, written by one of us (Stuart Corwin), allowed the user to specify coordinate titles and units and then accepted the coordinates of individual points to be plotted on the coordinate axes. These dots could be connected by line segments or not, as desired. Photographs were initially recorded on Polaroid Type 107 film and then photographically reversed to give black curves on white backgrounds. A considerable savings in drafting time and expense has resulted from the use of this program.

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