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HUMAN PATTERN RECOGNITION PROCEDURES  
AS RELATED TO MILITARY RECOGNITION PROBLEMS

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Contract No. AF19(604)-6632

Project No. 4691

Task No. 46912

FINAL REPORT

15 June 1962

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AIR FORCE CAMBRIDGE RESEARCH LABORATORIES  
OFFICE OF AEROSPACE RESEARCH  
UNITED STATES AIR FORCE  
BEDFORD, MASSACHUSETTS

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## Foreword

This is the final report of work performed under Contract AF 19(604)6632. It concerns application of what we know about human pattern recognition to the solution of certain military problems that involve pattern recognition and related activities in the processing of information. Efforts under this program were concerned with the following objectives:

1. To collocate, interrelate, and further develop hypothesis and theories concerning pattern recognition in general.
2. To organize relevant experimental data within the theoretical frameworks.
3. To examine the relation of military problems involving pattern recognition to the theoretical frameworks and to the organized facts as a basis for setting design criteria for military man-machine pattern recognition systems.
4. To formulate tests and experiments to further understanding of human pattern recognition and the application of human processing principles to military systems.

## I. PATTERN AND OBJECT RECOGNITION, IDENTIFICATION AND CLASSIFICATION

The root meaning of recognition is knowing again, but the term is used in several senses. It will be helpful, at the outset, to examine the most relevant ones, to define or delimit the field of our inquiry. We may do this with the aid of rather simple paradigms or schemas.

### A TWO-CATEGORY CLASSIFICATION

The root sense of recognition corresponds to classification into the two categories, (1) "perceived before" and (2) "not perceived before." The object of the classification is a stimulus, either the whole stimulus complex corresponding to an "experience" or a part of such a complex -- a figure or a pattern.

### Distinction Between Class and Particular Pattern

It is worthwhile to note that the question is not whether the particular stimulus was previously perceived. The particular, present stimulus is an individual event in space and time; another stimulus like it but not it, itself, could have been presented on an earlier occasion.

In the schema under discussion, as in others of greater importance to which we shall shortly turn, the stimulus is best regarded as being a member of a class, or as being generated by a source. The question can be formulated, "Was a stimulus of the same class, or from the same source, previously presented?"

Objective Formulation vs. Subjective Formulation

If there is an external agency (such as an experimenter) that knows from what class or source the stimulus actually originated, the question just stated is an objective question, and the recognition response ("YES, it was presented before." or "No, it was not presented before.") is scoreable. The recognition is correct if the criterion category is the same as the response category; otherwise the recognition is incorrect.

Note that the objective, scoreable question is not the only question that might be of interest. One might conceivably want to know, not whether the stimulus was presented previously to the recognizer, but whether the recognizer perceives the stimulus as familiar. Almost everyone has had the experience of "recognizing" a person or a place he could not possibly have seen before. In psychiatry, an abnormal condition ("deja vu") is well known in which the patient feels that everything he sees he has already seen and everything he starts to do he has already done. Evidently, his mechanism for solving the objective recognition problem is out of order.

MULTI-CATEGORY CLASSIFICATION

Because our interest is aimed at applications, we shall focus upon the objectively formulated question, and we shall speak of correct and incorrect recognitions. Our main concern, however, will not be with classification into the categories, "presented before" and "not presented before." It will be with

a finer classification in which patterns or figures from various sources are assigned to categories corresponding to those sources. The relevance of the word recognition in this formulation stems from the fact that the bases for the classification lie in direct prior experience.

#### Direct vs. Artificially Abstracted Experience

By saying direct prior experience, we mean to separate pattern recognition from the "thinking" kind of problem solving and concept formation. In general schema, pattern recognition, problem solving, and concept formation are very similar. One must go to some length, in fact, to establish distinctions. It appears, however, that the process of recognizing a 1961 Ford from previous inspection of new models in dealers' showrooms is different from figuring out that it is a 1961 Ford from symbolic data about its size and shape -- or, for that matter, its engine displacement, wheel-base, radiator capacity, and manufacturer's suggested retail price. Either basis may support classification. But human beings are superb at classifying on the one basis and relatively poor at classifying on the other.\* Evidently, the classification problem is made difficult for men by artificial abstraction, by the substitution of symbols for direct sensory patterns.

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\* There is much truth, we believe, in the ancient adage:  
"It is more important for women to be beautiful than to be bright because men can see much better than they can think."

Main Paradigm for Multi-Category Classification

Although we shall distinguish several variations of the schema that contains the essentials of this "finer" classification problem -- variations corresponding to various experimental arrangements or sequences of events in ordinary life -- we may focus our attention mainly on one version. There are several or many classes (sources) of patterns. On each "trial," a source is selected, and one of its appearances (patterns) is presented to the recognizer. On certain trials, called "training" trials, criterion information accompanies the pattern: the recognizer is told from which source the pattern actually came, to which class it actually belongs. On other trials, "test" trials, criterion information is not given, and the recognizer is required to assign the presented pattern to a source or class.

The general paradigm does not in itself distinguish pattern recognition from problem solving, concept formation, learning or hypothesis testing. Indeed, pattern recognition is related to, or involves elements of, all those things. However, we emphasize the involvement of "patterns," of direct presentation of the stimuli, and thus hope to some extent to delimit the field.

Variations of the Paradigm

The schema just described may be varied, as we have acknowledged, in several ways. Criterion information may be presented on every trial -- after the recognizer has made his classification. The criterion information may be uncertain; the parameter values

of the probabilities (or probability densities) may or may not be statistically stationary. The recognizer may not be required merely to assign each pattern to a class; he may have to rank the various classes in order of likelihood, or he may have to assign a posteriori probabilities. Some of these variations are more frequently encountered than others in every day life. Their variety has made difficult both the conducting of an experimental analysis and the development of a comprehensive theory. Nevertheless, at least some of what is known appears to apply at least to several of the variations.

#### PATTERN AND OBJECT, RECOGNITION AND IDENTIFICATION

Finally, in this examination of the scope of our inquiry, we may ask whether it is the pattern or the source that is recognized, and whether it is recognized or identified. Certainly it is the pattern -- the stimulus actually presented, as we are using the term -- that is classified. The class is intended to correspond to the source of the pattern. If the classification is correct, the source is identified.

That circumstance accounts, we believe, for the confusion that is prevalent in discussions of target classification. If the target is a class, a source of patterns, and the class is designated, it is in a sense truly identified. If, on the other hand, the target is just considered to be a pattern, it is merely classified, or perhaps recognized. But the target is usually neither simply a class or simply a pattern. It is a class (source) that is a member of a higher class that is a member of a still

higher class -- say, Explorer VIII, a definite satellite, but also a member of the Explcrer class, which is itself a member of the class of American satellites -- and the signal or pattern received from the source is thus but a member of a sub-subclass. Obviously, there is bound to be confusion unless problems and conclusions are carefully formulated.

Examination of the matter has led us to see that almost all the prevalent terminologies have reasonable bases. Confusion arises mainly because the bases are not always made explicit, and one man's "identification" is not "true identification" to another.

In this report, we shall use the term pattern recognition in the sense of pattern classification on the basis of direct prior experience with patterns of the same and alternative classes. We shall occasionally speak of object recognition or object identification or object classification to make a point: Recognizers often ascribe actuality to a class (source) or patterns and call the source an object. If most or all of us agree in defining the class, we ("naive realists") shorten the language process to match the thought process and say that it is an object, a real (solid, red, heavy, etc.) object, out there, thus avoiding many long words and much confusing cerebration. Nevertheless, to learn what is going on in the recognition (or classification, or identification) process, we must accept the longer, slower approach, from which one sees that the "object" is not out there, at all, but "constructed" by information-processing activities in our nervous systems. Thus viewed, an object is the solution to a problem, to the problem of accounting for redundancies, correlations, coherences, etc., in the space-time pattern of stimulation that impinges upon our receptors.

## II. A DEFINITION OF THE PROBLEM FROM THE PSYCHOLOGICAL STANDPOINT

The main trend in the experimental psychology of perception during the last decade has been to analyze perception as a kind of problem solving. From this approach, one sees the perceiver as an epistemological system, the task of which is to develop and maintain a simple, consistent, informationally economical representation of the world. The perceptual mechanism is continually working -- not on the problem: "What picture is on my retina? What pattern is in my cochlea?" -- but on the problem: "What must I assume about the world in order to make a simple, coherent story of what I know plus what I am now sensing?"

Stated in that way, the aim of perception is not greatly different from the aim of science. It is, in the large, very much the same as the aim of the over-all cognitive process. Perception is the first main event in the cognitive process, and its main distinction from thinking and implicit problem solving is that it works more directly with, and therefore gives somewhat greater weight to, immediate sensory data. The perceptual mechanism seeks to develop and maintain a model of the world, as was just said, and it should not be surprising that the perceptual model, being closer to sensory data, sometimes comes to solutions that diverge from the solutions achieved by the over-all cognitive process.

Ordinarily, "seeing is believing," but sometimes we see things we know not to be true. On those occasions, it may be evident to us that our perceptual mechanisms have come up with neat solutions, but that giving heavier weighting to data from sources other than the immediate sensory one leads to a different solution. We may conclude, under such circumstances, that the different solution is the correct one.

#### TWO EXAMPLES

To illustrate the idea of the preceding paragraph, we may use an experiment of Ames (1). The observer looks along a dark tunnel. Half-way down the tunnel is a balloon, attached to a tube through which it is inflated and deflated periodically. The balloon is illuminated; its surroundings are not. The observer "sees" a bright sphere that moves back and forth, toward him and away from him, in the tunnel. That perception is obviously a neat, though (we conclude on the basis of additional information) incorrect, solution. It accounts for the sensory data quite well. If the experimenter takes the observer down the tunnel and shows him the arrangement, then repeats the experiment, the perceptual process may -- but does not always -- take the newly gained knowledge adequately into account. In fact, the observer may see the balloon grow and shrink, grow and shrink, for a while, then go back to seeing the to-and-fro motion.

We may take a second example from observations made by Johansson (29). The subject views two lights in a darkened field. One is stationary. The other moves around the first, in a circle in a plane normal to the line of regard. The circle is gradually changed into an ellipse, and the ellipse into a straight line. The subject "sees" the moving light move in a circle, the plane of which tilts just enough to account for the eccentricity of the actually elliptical orbit.

In the two examples, the perceptual solutions corresponded to hypotheses that were reasonable, and in an ecological sense probable, under the circumstances. The hypotheses were wrong. It is notable that illusory perceptions may persist despite the observer's knowledge that they are illusory. We must keep in mind that the perceptual process is better connected to sensory data and to the store of perceptual experience than it is to the more general cognitive conception of the world. With that qualification, however, it is little short of obvious that perception deals with hypotheses.

#### HYPOTHESES IN PERCEPTION

The concept of hypotheses is of central importance to the understanding of the perceptual process. A review of the experimental methods that have served to delineate the concept, of the principal manifestations of hypotheses in perception, and of the general theoretical accounts of their function, will bring into focus an aspect of human perception that is of direct and immediate relevance to an attempt to simulate the human perceptual process.

Such a review will also establish that the ideas about hypotheses that have been developed in the psychology of perception are, despite their centrality, not clearly defined. There is an important opportunity to relate these ideas to the much more sharply defined and well-developed system of ideas concerning hypothesis-testing that exists in the fields of statistical decision theory, artificial intelligence, and documentation.

Students of perception regard the concept of hypotheses as basic to a description of the perceptual process. This is attested to by the age and durability of the several terms that they have introduced to characterize the concept. Thus, at one time or another, they have spoken of set, determining tendency, unconscious inference, structure or stricture, direction, expectancy, attitude, assumption, tuning, readiness, and so forth. As this listing makes clear, the concept developed as a means of dealing with the dependence of any particular percept on information acquired prior to it.

The existence of so many near-synonyms suggests not only that the concept is of central importance, but also that it is only hazily defined. We shall attempt to reduce the haze somewhat by a critical review of the empirical and theoretical work on hypotheses or categories that has been undertaken within the psychology of perception. We shall begin with a statement of the problem of perception and then present a very general outline of the perceptual process. Following this, we shall examine the experimental methods that have been employed to disclose the role of perceptual hypotheses, the chief examples of the functioning of hypotheses, and the general theories of perception in which they have figured prominently.

THE PROBLEM OF PERCEPTION

The problem of perception has been aptly stated by Koffka (32): "why do things appear as they do?" All of us, at one time, would have answered impatiently "because they are what they are." The world is so obviously real and stable and solid, our perceptions are so reliable, the information we obtain from different senses is in such harmony, that it is difficult to understand why the question is raised. The simple fact, however, is that we do not observe our environment directly in the way we naively tend to think that we do, for we are isolated and disconnected from the outside world by our sense organs and our nervous systems. We cannot accept the Greek notion of eidola, of images cast off by objects that travel up hollow tubes to the sensorium. In fact, a great deal intervenes between the outside world and our impressions of it, and many of the properties of the things that we see, hear, smell, taste, and touch are due to events internal to us. So things appear as they do, not because they are what they are, but because we are what we are. We have very specialized ways of receiving and comprehending information flowing into us from our environment.

As Osgood (52) puts it, the only environment of which we are aware is the pattern of physical energies that impinges on our receptors. In a real sense, he says, our environments are literally plastered upon our body surfaces, for this surface houses the receptors that react to energy in the physical world. Our common belief that the environment is "out there," although a rational one to be sure, is founded upon an elaborate system of inferences developed through a lifetime of experiencing.

It is impressive, with our present sophistication, to stop and to think how tremendous is the gap that exists between the spotty data that come from our sense organs and the beautifully organized world of our experience. As theorists, we are prone to fill this gap with several "perceptual processes" that we understand only partially, such as filtering, sharpening, organizing, prediction, satiation, and so forth. Our problem is to describe adequately these processes that somehow construct the properties of objects and events in our experience, that transform the apparently inadequate sense data into a smooth and orderly world. We must come to understand how impressions can vary when the underlying sensory events are constant, and how impressions can remain constant when these sensory events vary, or, in the terminology of psychology, we must come to understand the departures from the "constancy hypothesis."

So, to belabor the point, sensory information feeds into an on-going system. Sensory information is not passively recorded in the brain. Perception does not simply mirror objects and events in our environments. Perception, we suggest, depends in large part upon hypotheses about the causes of sensory experience, upon inferences about the nature of the environment, upon a process of working back from the "proximal" stimulus at the sense organ to the "distal" stimulus in the real world.

Although we are emphasizing here the role that hypotheses based on past experience play in perception we must keep in mind, as the Gestalt psychologists (24) have long contended, that some perceptual phenomena that tempt one to invoke the concept of learning (e.g., failures of the constancy hypothesis) may be due to innate factors, or to interactions between stimuli in the

present and the structural features of the nervous system. The controversy of nativism vs empiricism has raged for a long time, and, although we have reached the point of seeing the good in both sides of the issue, we have not succeeded in dissecting perception so that we can confidently attribute its various aspects to one or the other of the two factors. Hebb (19) has dealt most recently with the problem. His position, largely based on people who see for the first time as adults because of cataract removal and on chimps raised in darkness, is that the perception of "primitive unity," which is practically identical to figure-ground segregation, is innate, whereas the perception of "identity," or the distinctiveness of different figures, is learned. It may be helpful to translate Hebb and say that detection, of strong signals, is innate, and that recognition and identification of patterns depend upon, or are modified by, experience. (We use the qualifier "of strong signals" with respect to detection, for we shall indicate later that the detection of weak signals, of signals obscured by noise, is highly dependent upon learned modes of adjusting to situational parameters.) In any case, Hebb's position is typical of most modern theorists in the field of perception in ascribing a very large role to learned factors. We shall be concerned here with any significant failures of the constancy hypothesis -- it may be that some of them are determined by present stimuli, but we assert our belief (counter to the Gestalt belief) that, in general, hypotheses based on prior experience are heavily involved. We shall also be concerned with other perceptual phenomena that seem to illuminate the role of hypotheses that are not, strictly speaking, departures from the constancy hypothesis.

AN OUTLINE OF THE PERCEPTUAL PROCESS

In stating the problem of perception, we asked: "Why do things appear as they do?" Implicit in this statement is the fact that human perception is organized, to a large extent, in terms of objects. It is often assumed that the process of object perception is one of matching an incoming pattern to a set of standard patterns. That is to say, physical energy that is initiated by, or reflected from, objects in the surround impinges on sense receptors; the receptors transform the physical energy into spatiotemporal patterns of neural firing; these neural patterns are compared with a set of standards; the best match determines the percept.

We have spoken several times of "hypotheses or categories." These terms are used almost synonymously in the psychology of perception. It will be clear that, for most purposes, we could think of the standard patterns as constituting categories (representations of physical categories) into which the incoming patterns are selectively placed, or we could think of the standard patterns as hypotheses about the probable significance of the incoming pattern, and of the process of comparison as one of testing various hypotheses. The translation from one of these descriptions to the other is usually very direct -- we shall see, for example, when we consider the theoretical formulations, that "the strength of a perceptual hypothesis" can be taken as equivalent to "the accessibility of a perceptual category."

When psychologists add to the general outline of the perceptual process as a matching process such terms as hypotheses and categories, they suggest a way to particularize the general outline -- for these same terms are used in a stricter sense in some fields outside of psychology, where they form a part of a quantitative system of related ideas. We can, therefore, in anticipation of a later section of this report extend the general outline of perception further along these lines. We may presume, for example, that the incoming pattern is analyzed, prior to the comparison with the standard pattern, in terms of attributes. We can think of the attributes as categorical descriptors (brown, hot, vibrating) or as quantities expressed on continuous scales. The analysis may then reduce the incoming pattern to a pattern of descriptors or dimensions. We may also use the more specific term correlation to describe the process of comparison of input and standard. And we may represent the correlation by means of a space that is defined by the descriptors or dimensions, in which the inputs have variable distances from the regions that define a standard. To continue, we may think of the incoming pattern as identified with the standard that is nearest it in the space. We may, alternatively, allow a priori probabilities and values and costs to determine criteria, or the boundaries of the regions corresponding to various standards; in this case the identification is not always the same as would be made on the simpler basis of the "nearest standard." It is this sort of elaboration of the description of the perceptual process -- an elaboration in which we use in a stricter sense terms as hypothesis, category, analysis, attribute, reduction, descriptor, dimension, correlation, space, distances and regions in a space, probabilities, values, costs and

criteria -- an elaboration that begins to borrow from the fields of statistical decision theory, artificial intelligence, and documentation -- that suggest that a more detailed consideration of ideas in these fields will help us to sharpen further our ideas about the perceptual process. As indicated above, we have some other topics to discuss before we consider the possibilities of such fertilization; we are simply taking this early opportunity to emphasize an important aspect of the motivation for a review of the role of hypotheses and categories in the psychology of perception.

EXPERIMENTAL METHODS IN THE STUDY OF PERCEPTUAL HYPOTHESES

It will be well to review very briefly the general techniques used to study hypotheses in perception before examining the principal experimental results and the systematic formulations of these results. There are two basic techniques. Both consist in fabricating a situation in which a "strong" hypothesis or a "highly available" category (in short, a favored standard) dominates the stimulus information (the incoming pattern) in the determination of the percept. In one of these, the relevant stimulus information is greatly attenuated, or absent altogether and we find that the percept is less ambiguous than might be expected because whatever stimulus information exists is identified with a favored standard. Hypotheses operate here without the benefit of external checks on their appropriateness. We speak, in this case, of an impoverished situation. The other technique consists simply in preparing an illusion. The situation is such that a particular hypothesis or standard will be favored, i.e., will be most likely to be identified with the incoming pattern, but inappropriately so. A strong hypothesis, perhaps one that has become habitual through a lifetime of experience, is invalidated through trickery and thus exposes itself. In this case, the hypothesis does not merely act in the absence of relevant input as in the previous case; rather, the hypothesis actually deforms the stimulus information.

These are the principal techniques. We have found it helpful in describing them to use the concept of hypothesis strength. We used it loosely and in a way, we hope, that is intuitively clear. We shall examine the concept more fully, including the supposed determinants and consequences of hypothesis strength, in a later section of this report.

SOME EXAMPLES OF HYPOTHESES IN PERCEPTION

We begin now a highly condensed, but still extensive, account of some of the perceptual phenomena in which hypotheses or inferences appear to be involved. It will span many of the major topics in perception, including visual space perception, auditory localization, movement perception, the visual constancies, color perception, perceptual organization, word recognition, and the detection and recognition of signals in noise. Although no attempt will be made to provide a complete list of the phenomena that exhibit the role of perceptual hypotheses, still the great range of this account should provide a rather impressive demonstration of the importance of the concept -- especially impressive in connection with the problem of specifying the data to be stored and the manner of correlating incoming and stored data in an automatic recognition device. (A verbal description of an illusion, of course, is less compelling than an actual demonstration, but we shall have to proceed within the restrictions of the printed page; in most cases references are given that will enable the reader to duplicate for himself the effects described here.)

Visual Space Perception

Consider first perception of the third dimension, of solidity and distance. It is commonplace that perception of the solidity of near objects is largely, if not entirely, dependent upon binocular parallax (or retinal disparity), the fact that the two eyes are presented slightly disparate images of an object. It is also well known that an illusion of solidity where it does not exist can be achieved by means of a stereoscope. The creation of impressions in

depth on the basis of binocular parallax led Helmholtz to speak of "unbewusste Schluss," of "immediate unconscious inference," and there is, indeed, a reasonable basis for implicating learning in this process. It is with respect to depth perception, however, that the controversy between nativism and empiricism raged the hottest, and the issue has not been resolved to the satisfaction of all concerned.

The perception of distance on the basis of monocular cues presents a clearer picture. There is little doubt that we learn to use a variety of cues, that we set up hypotheses, and infer distances, on the basis of our past experience with these cues. The familiar examples include linear perspective (the fact of a smaller distance between far objects, perhaps best illustrated by the apparent convergence of parallel lines) and aerial perspective (or the clearness of outline). With regard to the latter, the reader will no doubt recall anecdotes about Eastern-bred acquaintances who, deluded by the clear air on their first trip West, attempt to walk to a mountain 25 miles off before breakfast.

The way in which light and shadow indicate depth can be illustrated by coloring one circular patch a uniform gray, and another with a bright spot in the center and a gradient of decreasing brightness to the edges. The latter will exhibit the effect of shining a light on a sphere, and, if viewed through a tube to eliminate other distance cues, will appear to be a sphere. Superposition (the partial obliteration of one object by another) is perhaps the most powerful monocular cue, probably because it has been the most reliable in our experience.

Ames (1)\* has shown neatly that this cue will dominate the one provided by the apparent size of a familiar object. (He has achieved this by mounting two ordinary-size playing cards so that Card B, which is further away, is seen as closer than the nearer Card A. Card B is seen as nearer because what is actually a corner cutout of Card A that makes visible all of Card B, appears to be a portion of A blocked out by B.) We complete the list of monocular cues by mentioning movement parallax (far objects show less relative movement than near objects, or, when the head is moved, far objects appear to move in the same direction as the head whereas near objects appear to move in the opposite direction) and the gradient of texture. The use of the cue provided by movement parallax perhaps illustrates best (considering the discussion so far) that although inferences are made on the basis of past experience, they can be "immediate" and "unconscious," in Helmholtz's terms -- and not at all deliberate. This will be demonstrated more amply later in this discussion. We should also note that we will have reason to consider further the cues to distance, and the interdependency of apparent size and apparent distance, when we discuss size constancy.

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\* We shall discuss in the following several perceptual demonstrations constructed at the Perception Demonstration Center, Princeton University. Many of these demonstrations, and the Center, were inspired by Adelbert Ames, Jr. For brevity in the text, we shall simply acknowledge "Ames" in all cases; the accompanying reference numbers will be more specific.

It seems very unlikely, when we consider the several monocular cues to distance, that the utilization of these cues is wired into the nervous system. Their significance is linked in an obvious way to prior experience with them. The role of experience in space perception is dramatically demonstrated by the familiar experiments conducted by Stratton (65), Kohler (33), and others, that use inverted lenses to turn the world upside down and right to left. Wearing these lenses causes considerable confusion at first, but after a period of weeks the subject's visual world is stable again, and his behavior in relation to it is adequate. The subject learns to attach a new significance to the cues of spatial position. Another, shorter, learning period is required when the lenses are removed. Thus, although certain hypotheses about the causes of sensory experience can become very strong if their reliability over a long time is very great, it is possible to arrange circumstances that ultimately lead to their rejection and set up new hypotheses which are again highly automatic. The reader will observe that a much shorter period of exposure is needed to adapt to the distortions of images on our television screens or on motion-picture screens as viewed from a front, side seat. We might note that whereas the visual world does not "appear normal" to the subject wearing inverted lenses for a period of weeks, the adaptation to distorted television or movie images involves a change in appearance -- after a time the distorted images are accepted as undistorted. We shall have more to say later about the distinction between cases in which the perception itself seems to be affected and the cases in which the responses to stimulation rather than the percepts themselves are adjusted.

Auditory Space Perception

The perception of the direction of a sound source utilizes the binaural cues of time, intensity, and phase. A sound emanating from the side will reach one ear slightly before the other; the sound shadow cast by the head will make it slightly less intense in the far ear; the phase difference between the two ears provides a reliable cue at low frequencies. The accuracy of about  $20^\circ$  usually achieved when both the sound source and the head are stationary can be considerably improved if either is allowed to move, and for this reason people learn to move their heads when attempting to judge the location of a sound.

An illusory location may be produced by a pseudophone, simply a pair of tubes that carry sounds from one side of the head to the opposite ear, and vice versa. Wearing such a device creates no problems for a blind-folded person; sound sources are located, although with a predictable error, with no more ambiguity than before. Confusion results, of course, if the subject is allowed to see, for then sounds that are clearly linked to given objects (as, e.g., voices) appear to originate elsewhere. As in the case of inverted lenses, however, learning takes place, and after a few days sounds are again correctly localized. The cues of time, intensity, and phase are reinterpreted.

The perception of the distance of a sound source is also dependent on prior experience. The monaural cues of intensity and frequency composition (the latter based on greater absorption of high frequency by intervening objects and air) can be effective, clearly, only in the case of familiar sounds.

The Perceptual Constancies

The constancy of perception refers to the fact that objects are appropriately identified under widely varying conditions of sensory stimulation. Perception is in accord with the physical rather than the physiological stimulus. Thus, we see the world as stable although its images move across our retinas. A man is seen as man size though the size of his image on our retinas may differ by a factor of a thousand. A window is seen as rectangular in spite of the fact that its retinal image is usually trapezoidal. A wall is seen as the same color or brightness throughout its extent although some of it is in shadow. And so forth. The fact that unifies these phenomena is that corrections are made in the interpretations of sensory cues, on the basis of past experience. We shall describe a few experiments that disclose some of the complex assumptions or hypotheses that come into play in the interaction of the human perceiver and his environment.

Size Constancy. A perceived constant size, of an unfamiliar object, depends upon corrections made for its distance, and the corrections in turn depend upon adequate cues of distance. Holway and Boring (25) asked their subjects to adjust a circular patch of light, at a constant distance down one corridor, to match a second circular patch of light, located at varying distances in a corridor at a right angle to the first. The size of the second patch was adjusted by the experimenters so that it maintained a constant visual angle, independent of its distance from the observer. They found almost perfect constancy (the observer made the adjustable patch progressively and correspondingly larger as the test patch moved farther away and became larger in fact)

when the observer used both eyes in a well-illuminated environment. They then found that the observer underestimated the true size of the test patch more and more as they successively eliminated more distance cues. This they achieved by dimming the illumination, permitting the observer the use of only one eye, using an artificial pupil, and finally by using reduction screen or tube to cut out the surround of the test patch. When all distance cues were eliminated, the observer set the adjustable patch in accordance with the visual angle -- he set it at the same size independent of the true size of the test patch.

The familiar moon illusion has recently been explained on a similar basis (30). When a prism arrangement was used so that the moon overhead could be made to appear on the horizon, and vice versa, it became evident that the other objects played a role in the greater apparent size of the moon there. It is now thought that the intervening objects made the horizon moon appear farther away, and that a correction is automatically applied for the greater distance. On the basis of past experience, the more distant of two objects having the same retinal size is seen as larger. It is perhaps the same phenomenon as that involved when the perceived after image of a given spot of light is developed on fields at different distances. The retinal image is of fixed size but the apparent size of the after image increases with the distance of the after-field -- a fact known as Emmert's Law.

As might be expected, experiments have shown that not only is apparent size a function of apparent distance, but the reverse is also true. We mentioned earlier the experiment in which Ames arranged conditions so that a sphere at a fixed distance is

seen as swinging to and fro, toward and away from the observer. The observer looks down a dark tunnel, and the sphere, which is actually a balloon, is slowly and rhythmically expanded and contracted. The observer apparently assumes a fixed size of the sphere, and interprets actual changes in size as changes in distance. (The same effect is achieved when the intensity of the beam of light illuminating the sphere is successively increased and decreased.) Ames (1) has also shown that, in a dark tunnel, a double-sized card at four feet appears to be a normal-sized card at two feet, and conversely, a half-sized card is seen to be of normal size at eight feet. When objects are used that come normally in varying sizes, the perception of size and distance vary from one subject to another, but each subject sees the object as being of a definite size and at a distance. The inherent ambiguity in the situation is not reflected in perception -- the subject makes an "immediate, unconscious inference."

Brightness Constancy. In perceiving the brightness, or whiteness of an object, corrections are made for the general level of illumination. This is best illustrated by the experiments of Gelb and Kardos (71).

Gelb hung a black disc in a dimly illuminated doorway, and projected from a concealed projector a beam of intense light that illuminated all of the disc and no more. The disc appeared to be white. The projector was then turned off so that the subject could see that the disc was black. When it was turned on again, the disc again appeared to be white. When a piece of white paper was held up in front of the disc, the disc appeared to change from white to black; when the white paper was removed,

the disc flipped back to white again. Kardos performed the reverse experiment. He concealed an object that cast a shadow on a white disc in a well-illuminated room, and the disc appeared to be black. Thus the perception of brightness depends upon the albedo of an object, upon the ratio of reflected to incident light. A correction is made for the incident light, and devious distortion of the incident light will disclose this basis of inference. Katz's (71) subjects revealed almost perfect constancy when adjusting the whiteness of a circular patch of light to match one that was visibly in shadow. When they viewed the two through a tube that illuminated the source of the shadow, the resultant setting was distinctly more gray.

Color Constancy. Color perception depends also on the relation of the reflected to the incident light, and it too involves various corrections and adjustments made on the basis of past experience.

It is reported in several secondary sources (71) that an amorphous patch of blue light cast on a yellow screen will appear gray, in accordance with the familiar laws of color mixture, but that an identifiable object will retain its blueness. This is consistent with Land's finding (34) that achieving a wide range of colors from a two-color mixture depends upon the use of highly articulated fields of familiar objects. A similar result is reported by Bruner, Postman, and Rodrigues (7) who induced a brownish-orange color into a number of gray figures by presenting them on a blue-green background. Subjects asked to match the colors on a color mixer were affected by the shape of the figure; thus they required more red to match a figure

shaped like a lobster claw and more yellow to match a figure shaped like a banana. This effect was maintained even when the figures were superimposed on the color mixer, and the subject was asked to produce a setting that made the figures disappear.

Form Constancy. Perhaps the best-known demonstration of form constancy is the rotating trapezoidal window developed by Ames<sup>1</sup> (2). A rotating object, having the appearance of a window, but distinctly trapezoidal in form, is viewed monocularly from ten feet, or binocularly at distances greater than 25 feet. It is seen as oscillating rather than as rotating. The effect of oscillation is maintained even after the observer knows full well that the window is actually rotating. The explanation appears to be that the observer automatically assumes, in accordance with past experience, that the window is rectangular. If the window were rectangular, then the short side could never be seen as nearer than the long side, and the observer never sees it as nearer. This explanation can be developed in much more detail, and the assumption of rectangularity can also be used to account for other perceived characteristics of the window, including changing shape, changing size, and changing speed of rotation.

It is possible to put several cues or hypotheses in conflict in this situation, and to make thus some crude estimates of their relative strengths. For example, a cube may be attached to a corner on the short side of the window, or a tube inserted through the window. When the window reverses direction, the cube is seen as continuing its circular motion -- the cube is

seen as becoming detached from the window and floating around in front of it. We can guess that observer assumes a fixed size of the cube, and sees it as coming nearer (as it actually does) as its retinal image becomes larger. This perception is not effectively countered by the observer's knowledge that the cube is firmly attached. When the window reverses and the tube continues to rotate, they will shortly meet. It is reported that observers actually see the tube as breaking through the window, or, alternatively, as curving around the window in an S-shape, depending upon whether they have just handled a piece of lead pipe or a piece of rubber hose reputed to be the tube used in the demonstration.

The assumption of rectangularity is also made for floors, walls, and ceilings as Ames (1) has shown in a number of grotesquely misshapen rooms. The perception of such a room as being normal holds even though men standing in different corners must then be seen as vastly different in size.

#### Adaptation Level

We have reviewed several instances in which a long period of learning has set up hypotheses that are very strong, as indicated, for example, by the time required for relearning. We have also discussed a number of instances involving more labile hypotheses. Helson's concept of "adaptation level" (20) is an example of the second type; it refers to effects of short duration due to immediately preceding stimulation. Thus, judgments of the weight of a stimulus depend upon whether the preceding stimuli were heavier or lighter, and judgments of the pitch of a stimulus depend

upon whether the preceding stimuli were higher or lower in pitch. The same effect occurs in judgments of temperature and in a number of other perceptual tasks.

### Perceptual Tuning

A variety of studies have shown that immediately preceding stimuli affect the sensitivity of the observer attempting to detect or recognize weak signals in noise. In many cases, the result makes most sense if we think of the preceding stimuli as providing cues to the nature of the stimulus, cues which may enable the observer to tune his receptive apparatus, or which may enable him to establish a more adequate internal standard. Shipley (60) has shown, for example, in an experiment in which the observer is attempting to detect relatively weak and strong tone bursts in noise, that a correct detection is more likely to follow a correct response to a strong stimulus than a correct response to a weak stimulus. She has also shown (66), in an experiment in which two different frequencies were presented in random order, that a correct response to a given frequency is more likely after a correct response to the same frequency than after a correct response to a different frequency. Tanner (68) has explained these results by pointing out that the observer's memory for the characteristics of the signal (in this case frequency, phase, amplitude, starting time, and duration) is inadequate; he has supported this explanation by showing that the observer approaches more and more closely to the mathematically ideal detection performance as more information about these characteristics is supplied him in connection with each observation he makes. That the adequacy of discrimination

is related to the adequacy of the observer's knowledge about the stimulus is apparent apart from perceptual experiments proper; we need only recall the great difference that training makes to the student of bacteriology or pathology attempting to determine the significance of a slide in his microscope. Again, the newspaper headline at a distance too great to discern a single word is easily perceived once its contents are known.

### Meaningfulness

The material that we have just discussed reminds us that the meaning of a stimulus affects its perception. The story of the doctor who is awakened by the telephone ring but not by his baby's cry and his wife who reacts oppositely reminds us that this topic could occupy us for quite some time if we considered only examples from everyday life. We could go on as long discussing experimental results. Perhaps one or two examples will suffice to renew our conviction that the meaning of objects in terms of personal experience is of immeasurable aid in their identification.

Some of the more interesting examples involve the effect of meaning on perceptual organization or grouping. They are interesting because many of the factors involved in grouping are apparently innate. Some of the best evidence for innate factors in grouping (factors such as proximity, similarity, and continuity) comes from the fact that adults who are given sight by cataract removal immediately see objects as objects apart from their backgrounds. The other side of the coin is that these people require months of training to identify the

objects visually though tactual recognition is prompt. Hebb (19) in describing Senden's results, related that arduous learning is required to identify visually a triangle or square, that for many weeks identification of these figures depends upon counting their corners.

Osgood (52) gives several demonstrations of meaningful factors in grouping. He shows, for example, that we can group properly and

#### READWORDSWITHOUTSPACES

if the words involved are English words. He also points out that these two figures are a meaningless jumble of lines



until we are told that the first represents "a soldier and his dog passing a gap in a picket fence" and the second is "a washwoman scrubbing the floor" -- from that point on they will be organized in a particular way. Other examples come from homonyms in different languages. Thus

O SIBILE SI ERGO  
 FORTIBUS ES IN ERO  
 O NOBILE DEMIS TRUX  
 SI VADE SINEM CAUSEN DUX

can be interpreted with ease, and acquire a different intonation, if we read aloud and listen to the sounds as if they comprised English words.

### Word Recognition

The major results in the study of word recognition, for our purposes, are that word thresholds depend upon frequency of usage and upon the size of the ensemble from which the stimulus words are drawn.

It has been shown that the duration threshold in vision (27) and the intensity threshold in audition (26) depend upon the frequency with which the stimulus word in question occurs in a sample of popular English text. The same effect of frequency is found if the frequency of exposure to nonsense words is manipulated experimentally (61). The role of experience is clear.

The role of hypotheses is also amply demonstrated in several studies reported by Miller (45). He shows that the intelligibility of a nonsense syllable depends on the size of the list (the entire list being known by the observer) from which they are drawn. Intelligibility is also dependent upon context in another way: words which appear as a part of connected discourse are considerably more intelligible than the same words in isolation. It is clear from these studies that word perception does not depend solely on the physical characteristics of the words that were presented, which can be held constant, but also on the subject's expectancies, or on what words might have been presented.

Signal Detection and Recognition

We can discuss very briefly at this point the involvement of perceptual hypotheses in the detection and recognition of signals in noise. Here, too, the observer's behavior is critically dependent upon his foreknowledge of certain situational parameters. Thus, for example, an observer is more likely to report that an observation represented Signal as opposed to Noise, or Signal 1 as opposed to Signals 2...n, the higher the a priori probability of occurrence of Signal, or of Signal 1. We might say that if the hypotheses that a signal (vs noise) will be presented is strong, then the evidence from a given observation will be more likely to confirm it. Further, an observer will be more likely to report the presence of a signal if the value of correctly reporting its existence is relatively great, and if the cost of incorrectly reporting its existence is relatively small, than he will be if the values and costs associated with signal and with noise are equal (67).

THEORETICAL FORMULATIONS OF THE ROLE OF HYPOTHESES

We shall review very briefly the theories of perception developed by Ames and by Brunswick, and by Bruner and Postman. The reader should be warned that these theories are not theories in the sense that we know them in the harder sciences -- they do not enable quantitative predictions of effects. The first two, as a matter of fact, are little more than statements of a position on the nature of perception. The third attempts to isolate some of the relevant variables.

Ames and his colleagues (1) begin with the fact that any stimulus pattern on the retina could have resulted from a very large number of objects. In one demonstration, for example, a subject looks down a dark tunnel and sees three similar rectilinear, three-dimensional chairs of a particular size and at a particular distance. The three corresponding physical configurations bear little resemblance to one another -- two are neither rectilinear nor three-dimensional, and no two of them are of the same size or at the same distance. Reception is thus restricted -- the actual perception is one of many possibilities -- and this restriction is apparently due to very automatic assumptions or hypotheses based on past experience. The position taken goes beyond an implication of "a sub-conscious integration of past experience," however, as perception is presumed to be based also on what the perceiver is trying to accomplish at the moment, and the anticipated future results of his present "transaction" with his environment. The assumptive system the observer carries within him involves the future because his assumptions are only guesses, his transactions are only probabilistic. The function of perception is to provide a basis for action, to indicate the action most probably successful. So perception depends upon purposes and values, as well as on expectancy.

Brunswick's (8) position is quite similar. He too is impressed that the correspondence between the physical stimulus and physiological stimulus is imperfect, that the relationship is equivocal, and that, therefore, ambiguity is inherent. By experience, the observer learns the probable significance of various physiological stimuli, or cues; he learns, by a sampling

of his environment, the probability that a given cue indicates a given physical object or attribute of an object. The perceiver is thought to engage in two types of probability learning: correlation learning, or the reliability of a cue as a correlate of an object, and distribution learning, or the a priori probability of occurrence of various objects. In short, he learns the a priori probabilities of objects (e.g. hanging objects are rare), and the conditional probability of particular cues given the existence of particular objects. Brunswick's position, expressed by Hochberg (24), is that "perception is a reasoning-like process much faster to respond than is reasoning, but slower to change what has been learned; it is a speeded-up, conservative, stereotyping, reasoning-like function."

For Bruner and Postman (6) the principal concept is that of the "strength of an hypothesis." The strength of an hypothesis determines the probability that it will be evoked, and also the amount of stimulus information required to confirm it or to deny it. Our strong hypotheses are more likely to come to the fore, and once they have, the slightest bit of consistent stimulus information, or the slightest bit of ambiguous stimulus information that can be twisted to appear consistent, will confirm the hypothesis, and perception will be in terms of it. Conversely, a strong hypothesis is dislodged only by a large amount of inconsistent stimulus information.

Bruner and Postman listed four determinates of hypothesis strength. These are: (a) the frequency with which the hypothesis has been confirmed in the past, (b) the number of alternative hypotheses available (c) the motivational support for the hypotheses

(whether the truth of a particular hypothesis would result in satisfying other needs of the organism), and (d) the cognitive support (whether the truth of an hypothesis is consistent with other knowledge of the situation or attitudes toward the situation).

In later writings of Bruner (5), "hypothesis strength" becomes "accessibility of category." The accessibility of a category is seen as determining (a) the amount of input necessary for categorization in terms of the category, (b) the range of cues accepted as fitting the category, and (c) the amount of masking of other categories that would provide a better fit. He sees the sequence of events in perception as first a primitive categorization, then a cue search, then a confirmation check of the primitive categorization, and finally a completion of the confirmation. This theory, it is clear, is much like that proposed by Ames and Brunswick in its involvement of values, purposes, and probabilities, and in its characterization of perception as a reasoning-like process.

### III. PATTERN RECOGNITION BY MATHEMATICAL TECHNIQUES AND AUTOMATA

In part, the purpose of our work on pattern recognition has been that of extracting from the psychological and physiological literature relevant facts and principles that will be of value in the information-processing technology. Because there are many more unrelated data than broad principles in these areas, we have sought to develop frameworks drawn from other fields to aid in relating the items to one another and to the areas of possible application. Concepts drawn from the body of theory relating to pattern recognition in general, particularly that portion concerning self-organizing automata, have been useful in organizing the material on human pattern recognition. This section presents two such frameworks drawn from fields of great current interest and rapid development.

#### STATISTICAL DECISION THEORY AS A FRAMEWORK

Statistical decision theory, or the theory of testing statistical hypotheses is, in and of itself, a broad, general structure that is useful as a framework. It is normative, indicating how one should proceed in order to maximize utility through the making of decisions in a probabilistic world described by distribution functions and parameters, and its normativeness creates a rather awkward situation when one tries to use it as the skeleton of a description: He finds himself always saying how the actuality deviates from the theory. Nevertheless, statistical decision theory makes a place for almost every idea in the field of human pattern recognition.

We have used the statistical decision framework extensively. It has focused our attention on the important role of hypotheses in human pattern recognition. We believe that it will be very important to let hypotheses play important roles, also in mechanical\* pattern-recognizing systems.

### Two-Alternative Paradigm

Most of the elements of statistical decision theory are to be seen in the simplest paradigm, the schema for making two-alternative decisions, shown in Fig. 1. The points of the Input Space represent the various patterns that may be presented. In this simple version, there are only two sources of patterns,  $S_1$  and  $S_2$ .

A Priori and Conditional Probabilities. Each source has an a priori probability of being active on a given trial. Let the probabilities be  $p_1$  for  $S_1$ , and  $p_2$  for  $S_2$ . Each pattern has a conditional probability of arising from  $S_1$  and (in general) a different conditional probability of arising from  $S_2$ . Let the conditional probabilities for pattern  $i$  be  $p_{1i}$  and  $p_{2i}$ .

Responses. The decision process has only two responses,  $R_1$  (meaning, "I say that a pattern from  $S_1$  was presented.") and  $R_2$  (meaning, "I say that a pattern from  $S_2$  was presented."), and it must make one of them on each trial, under demand from a trigger pulse along the lowermost (dotted) line of the diagram. The Decision Computer, the box of which the response is demanded, can signal to the Distribution Computer and the Criterion Computer (along rising, dotted lines) for information.

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\* We use mechanical here as a generic term, roughly equivalent to artificial as opposed to natural, and specifically including electronic.

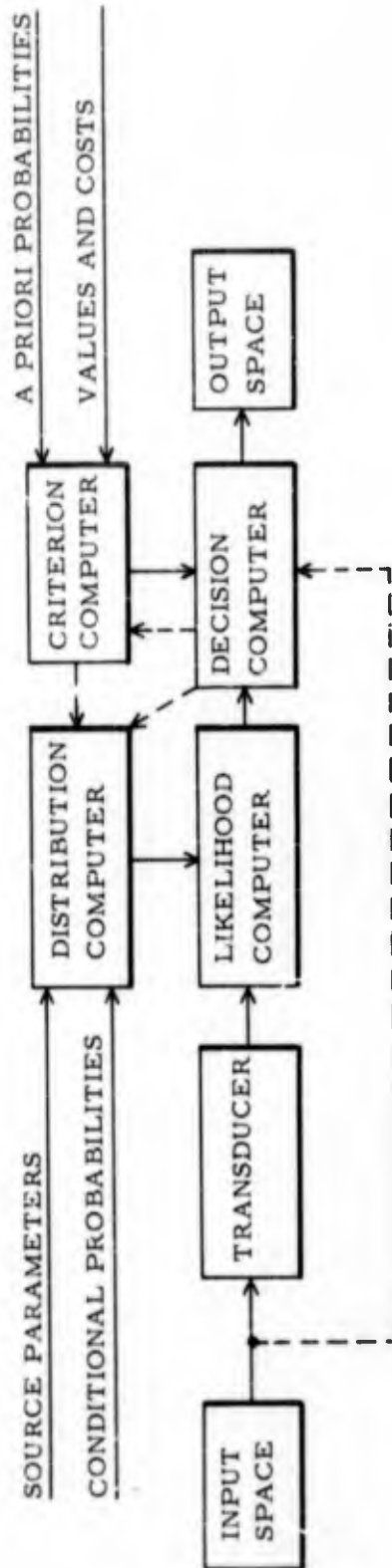


FIG. 1 STATISTICAL DECISION THEORY FRAMEWORK

Basic Operating Information. Finally, information concerning the source parameters (i.e., descriptions of the patterns generated by the sources) and concerning the conditional probabilities  $p_{11}$  and  $p_{12}$  is provided by an external agency to the Distribution Computer, and information concerning the a priori probabilities  $p_1$  and  $p_2$  and concerning "payoff" is provided by an external agency to the Criterion Computer. One form the "external agency" may take is that of the administrator of the criterion information during the training trials of our main pattern-recognition schema. From that information, plus the assumption of statistical equilibrium, the decision process (the "recognizer") may build up estimates of the a priori probabilities and the conditional probabilities and pictures of the various patterns. The "value structure" of the process must arise, however, either from within the recognizer (internal satisfaction or inherent cost of processing information) or from externally administered rewards or punishments. These are particularly clear in a version of the schema in which each trial, after the recognizer has made his response, he is given the "correct" category, together with a reward or a punishment that defines (at least in part) the value or cost of making response  $R_j$  to a stimulus from source  $S_i$ .

Processing the Signals. The foregoing sets the problem for the decision process. What the decision process does about it depends upon the nature of that process. We have been working with the implicit assumption that the decision process is an ideal process that maximizes utility. As mentioned earlier, that is a good starting point, even though human pattern recognizers are by no means ideal processors, and even though their value structures seem to work with oddly-behaved utility.

The operations performed by the decision process of Fig. 1 are the following:

1. Transducer: Transduce the received pattern into a form upon which the likelihood computer can operate. A general form, conceptually convenient, is provided by the concept of dimensionality: Let the transducer convert the pattern into a point in an n-dimensional space, for which n is the number of independently variable pattern characteristics.

2. Likelihood Computer: From the values of  $p_{11}$  and  $p_{12}$  supplied by the Distribution Computer, determine the likelihood ratio  $L = p_{11}/p_{12}$  for the pattern i of the present trial.

3. Decision Computer: Compare L with the critical value  $\alpha$  supplied by the Criterion Computer.

$$\alpha = \frac{p_2}{p_1} \cdot \frac{V_{22} - V_{21}}{V_{11} - V_{12}}$$

where  $p_1$  and  $p_2$  are the a priori probabilities and four V's are the values of making the response  $R_1$  to a pattern from  $S_1$ , the response  $R_2$  to a pattern from  $S_1$ , the response  $R_1$  to a pattern from  $S_2$ , and the response  $R_2$  to a pattern from  $S_2$ . (A negative value is a cost.) If  $L \geq \alpha$ , the Decision Computer emits  $R_1=S_1$ ; if  $L < \alpha$ , it emits  $R_1=S_2$ .

That simple procedure, it is well established and well known, maximizes utility over statistically homogeneous trials. It is applicable, of course, to all forms of decision, but to pattern recognition no less than others.

More Than Two Alternatives

To extend the model to handle several or many alternatives it is necessary only to substitute vectors or matrixes for the simpler quantities we have discussed and to expand the payoff matrix to provide a value (or cost) for each possible response to each pattern source. In the extended model, the decision axis (on which  $L$  was compared to  $\alpha$ ) becomes a region of dimensionality one less than the number of alternatives. For  $N$  alternatives, there are  $N$  a priori probabilities in all and  $N$  conditional probabilities for each possible pattern.

Continuous Variables

When we work with spatial or temporal patterns, it is natural to think of them as being continuously variable and to suppose that the patterns we actually present or experience are drawn from a nondenumerable infinity of possible patterns. That need cause no practical difficulty, however, and perhaps no conceptual difficulty, either.

It is reasonable in any practical case to introduce a "fidelity criterion" and to assume that all the patterns that differ by less than a given small amount from a given pattern are identical with that pattern. In this way, we can subdivide the input space into a finite number of regions, to each of which one pattern corresponds.

Alternatively, we may regard the patterns as being band limited in inverse-spatial frequency or inverse-temporal frequency or both. The subtleties of band-limitation assumptions are still under active discussion, but it seems likely that, in due course, something similar to Shannon's sampling theorem (or "2WT theorem") will be found to hold rigorously for mathematical models that line up well with experimental and practical requirements. The sampling theorem has the effect of reducing the apparently infinite ensembles of continuous domains to finite ensembles in discrete domains. It thus brings patterns in space and time into the paradigm of the decision process we have discussed.

#### Use of Statistical Decision Theory as a Framework

As indicated earlier, when we start to use statistical decision theory as a framework, we see that it focuses our attention on features that are desirable but out of reach. The thing that takes shape, then, is a picture of the engineering compromise that nature has made in designing recognizers that must get along with limited memories, noisy transducers, and slow processing components. Before trying to develop such a picture, however, we should examine an alternative framework.

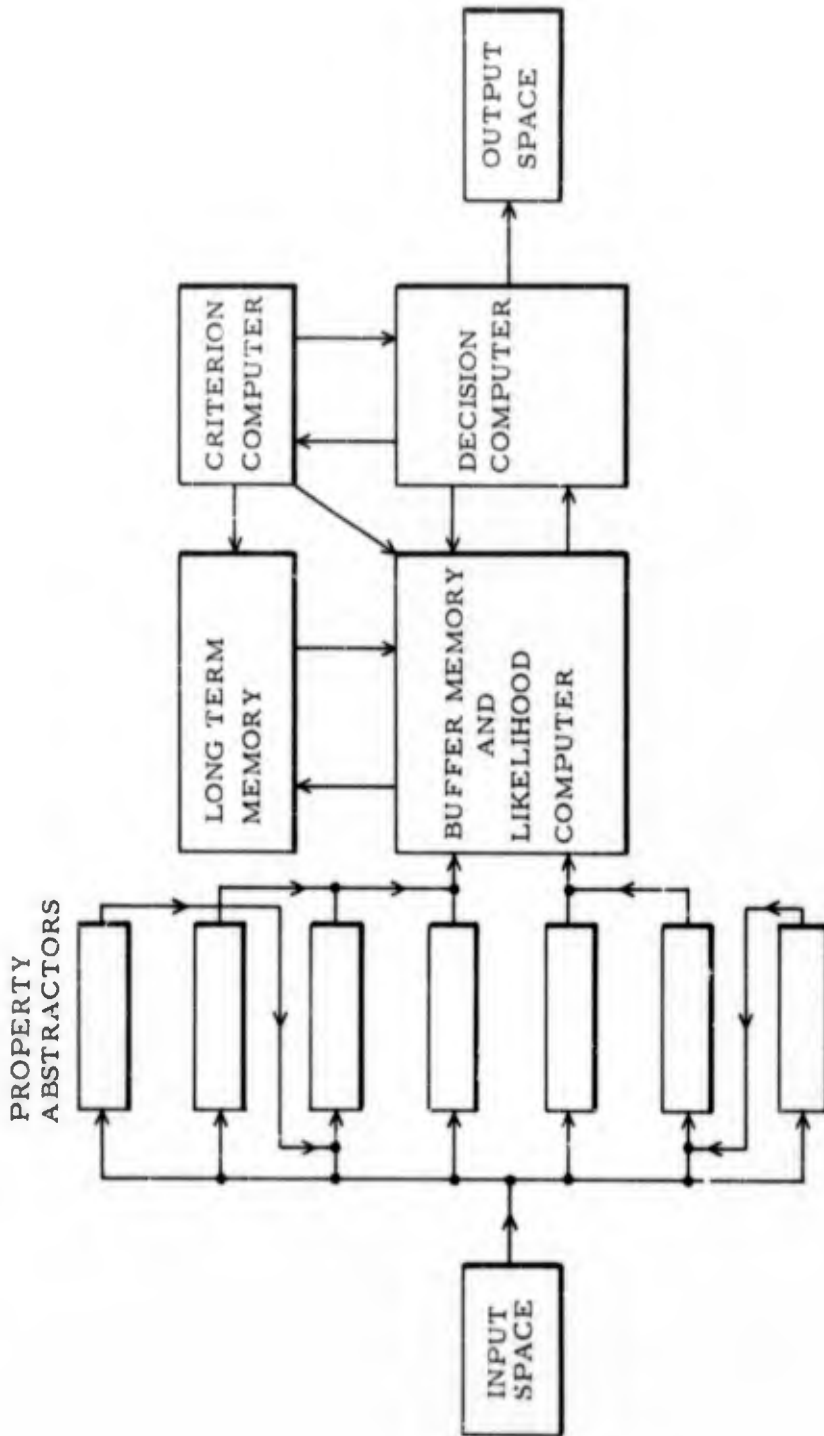


FIG. 2 PROPERTY-LIST CLASSIFICATION FRAMEWORK

PROPERTY-LIST CLASSIFICATION AS A FRAMEWORK

In the field of artificial intelligence, several efforts have been made to automate decision processes. Minsky (48) recently reviewed the most interesting of the published papers in this area and, in part under the present contract, prepared an extensive bibliography. From Minsky's analysis and our own study of the problem, it appears that the most promising methods use what we shall call property abstractors where our statistical-decision-theory paradigm had an information lossless transducer.

Property-List Classification Model

In Fig. 2, we have retained as much of the structure of Fig. 1 as we could without interfering with illustration of the property-abstraction idea. The Input Space, the Output Space, the Criterion Computer, and the Decision Computer are preserved. The Transducer and the Distribution Computer, however, are replaced by the Property Abstractors and the Memories, and the Likelihood Computer is placed in the same box as the Buffer Memory to emphasize that there is no clear distinction, either functional or spatial, between mnemonic and processing aspects in certain models of brain processes. (It is understood, of course, that any present effort to break the human decision down into labeled blocks is bound to be artificial and distorting, but artificiality and distortion may be acceptable costs if the diagram facilitates our interaction with the problem.) Lines run from the Criterion Computer to all the other main blocks to indicate that the value structure affects not only the response decision but also the activity of the storage and processing units.

Property Abstractors

The property abstractors simply perform measurements or transformations on the presented patterns. Each measurement or transformation loses information, but, in combination, the property abstractors retain the essential information. Except that the measurements be performable upon the signals (patterns), there are essentially no restrictions upon the kinds of measurement property abstractors may perform. In a brain-wave classification program on which we are working, for example, property abstracting subroutines find (1) the frequency band with the greatest momentary signal strength, (3) the relative change between the present maximum and the most recent past maximum, (4) the over-all signal strength smoothed over the recent past, and so on to 30 or 40 properties. It may be possible to work effectively with fewer measurements. A character recognizer constructed by Selfridge and his colleagues (56) used only five or six, such as counting, edging, and local smoothing. Another character recognizer constructed by Sherman (59) used fewer than 10 properties, all of them topological.

Hierarchical and Recursive Arrangement of Abstractors

An important feature of the property-abstraction system is the hierarchical and recursive arrangement of the abstractors. This is only suggested in Fig. 2, which in two places shows connections from the output of one box to the input of another. In principle, it is unimportant whether recursive processing is accomplished by repeated use of one measuring device or by

cascading several devices of the same type. The important thing is to provide for the determination of derived measures by applying the measuring transformations to elementary measures and/or other derived measures.

#### Selection of Property Abstractors

We may have spoken, thus far, as though the selection of measures or transformations were a matter of little moment, but that is certainly not the case. Effective selection is a problem upon which every available source must be brought to bear. It may be that, in the evolutionary process, random variation and natural selection were enough. It seems more likely that, if they were ever enough, they were enough only until those blind processes could develop heuristic principles and so incorporate them into the genetic structure that viable variations would be increased in probability. In any event, the measuring transformations that we can see operating in human and animal perception have been well selected. It is sufficient to mention here the phase-advancing stretch receptors in the human motor-kinesthetic servomechanism (13), the moving-fly and stationary-fly receptors found by Lettvin (35) in the retina of the frog, the contour-enhancing space-weighting networks examined by Hartline (18) in the eye of Limulus, and the superb system of wave filters analyzed by Bekesy (3) in the cochleas of mammals.

"Pandemonium"

The best-developed system of pattern recognition based on property abstraction is Selfridge's (57) Pandemonium. Selfridge refers to the devices that make the measurements or transformations as demons.

In Pandemonium, there are several levels of demons. The most peripheral, or lowermost, level is responsible for making the basic measurements, for abstracting properties of the stimulus patterns. On the second level, there is a demon for each source or class of patterns. The second-level demons receive linearly weighted outputs from the peripheral demons. The weights are adjusted through a hill-climbing procedure until greatest weight is given to the most discriminating elementary measures.

Each second-level demon signals upward with a strength proportional to the sum of its weighted inputs. When the input pattern is an "A", the A demon gets a greater total input than any other demon on the second level, and his signal to the head demon on the third level is therefore the strongest -- whereupon the head demon concludes that the input pattern is an "A". It will go similarly, if all works well, for the other pattern classes.

There are more sophisticated versions of Pandemonium with more levels, but the three-level version illustrates the basic ideas. The nonlinear processing steps are carried out at the lowermost and uppermost levels. The low-level demons make measurements; they are the property abstractors.

The head demon counts votes or selects the strongest signal. In between, there is little more than linear superposition.

An important feature of Selfridge's concept is the development of improved measuring demons. If any demon is found to have the same weight with all the second-level demons, and to persist for some time in being indiscriminate, that ineffectual demon is dropped. Its place is assigned to a new demon. The new one may be selected at random, or it may be designed by combining features of discriminating demons. Selfridge speaks colorfully of intermarrying demons and breeding extremely discriminating offspring. The essential idea is that the first-level measurements have definite logical or mathematical structures, that one measurement has a determinable degree of similarity or closeness of relation to each other measurement, and that measurements can be interpolated or extrapolated in much the same way as organic chemical compounds. In our opinion, that is a valuable concept, and the basis for a useful heuristic in selecting property abstractors.

The decision process of Pandemonium consists essentially in (1) linear superposition of weighted measures and (2) selection of the strongest signal or the largest sum. Property-list classification methods are of course not limited to those procedures.

#### Decision Processes

Recent work of Marill and Green (43, 44) and others has made it clear that the process of deciding among response alternatives can be separated clearly from the selection of measures.

Only heuristic and evolutionary methods are available for the latter. Given a set of measures, however, there is often an algorithmic procedure for arriving at a decision that will meet some criterion of optimality. Of equal practical importance, there are often approximation procedures or procedures that involve reasonable supporting assumptions -- feasible procedures that lead to statistically near-optimal decisions. One way of rounding out the property-list classification model is to employ such a procedure, literally to calculate a decision. The term Likelihood Computer is included in Fig. 2 to suggest that approach.

At the other extreme, we may use a hill-climbing procedure. By hill climbing, of course, we refer to procedures for achieving elevated position or improved performance by (1) making a change, (2) evaluating the change, (3) going farther in the same direction if the change resulted in an increment, (4) reversing direction if the change resulted in a decrement, (5) trying a new direction (new dimension) if the present position is a local maximum in the dimension that was being explored, and (6) going far away and starting over if the present position is an unsatisfactory local maximum in all dimensions. Obviously, blind and memoryless hill climbing is slow and tedious. Introducing memory and subtler strategy improves its efficiency greatly. It is very helpful to find the direction of steepest ascent and to follow it to a maximum. (Memory is required in finding it.) Limited look-ahead features improve performance, also. But the main advantage of hill climbing as an improvement procedure is that it places very little demand on storage and processing facilities. Any embellishment of the procedure is essentially a compromise in which something is gained at the cost of increased information processing and storage.

Between hill climbing and algorithmic decision processes is a wide territory. The main developed areas are indeed only partially developed, but they are areas of great interest. Nearest the algorithmic end, perhaps, are sequential decision procedures in which definite calculational methods are employed in the primary decision process, but in which informal or heuristic methods are employed in determining a compromise between the pressure of time and the need for additional data. There is a large area in which heuristic methods are applicable, methods similar to those used by Newell, Shaw, and Simon (51) in their work on a "general problem solver," by Gelernter (12) in his work on theorem proving, and by Shannon (58) and others on game playing. These methods have not been spelled out in detail in relation to pattern recognition, and it may be that, because of the differences in time scale and probably also in neural locus, they are not used in pattern recognition. On a priori grounds, however, they are quite as acceptable for use in models and frameworks as are the more formal techniques of algorithmic decision theory.

#### Hierarchical Decision Processes

A final concept that we want to incorporate in the property-list classification framework is that of the hierarchical nature of the decision process. The process is viewed as the result of compromise in the interest of maximizing utility. A cost is associated with the process itself, with the use of the information-processing facilities of the recognizers. An additional cost may be associated simply with the use of time in making the recognition. Upon entering

a classification act, the process has only knowledge from past experience on which to base estimates of processing costs, of the time and facilities required to reach each discriminable level of solution. It would be very expensive to calculate precisely just what decision procedure to use. A compromise must be made even to get started.

Once the decision process is under way, the basis for extrapolating it improves. The question may arise, is it worthwhile to continue processing data in the present way, or would it be better to shift to another (faster and less accurate or slower and more accurate) procedure. That may raise the question whether to consider the procedural question. And so on ad infinitum.

#### Use of Property-List Classification as a Framework

Because property-list classification is itself a compromise procedure, designed to provide effective classification despite limitations of processing and storage facilities, it is capable of serving more directly than normative decision theory as a framework for a study of pattern recognition. We can see at once what some of the human abstracting transformations are. We can find physiological mechanisms that look as though they were designed to carry out the transformations.

Insofar as the decision part of the process is concerned, the property-list-classification framework is scarcely different from the algorithmic-decision-theory framework. In both cases, we must depart from the maximum-likelihood assumption as we put the framework to use.

#### IV. A COMPOSITE MODEL OF HUMAN PATTERN RECOGNITION

This section presents a model of pattern recognition built by selection and interweaving of concepts from a number of diverse fields. It stands in sharp contrast to the schemes presented in the preceding section. Although many of the operations we attribute to human pattern recognition are similar to those described earlier, the overall organization of the hypothesized system and the flow of information in the model are very different.

##### "What Frog's Eye Tells the Frog's Brain"

Let us begin with a biological pattern recognition system which recent analysis has shown to possess some similarities to the descriptor-list model described in Section III. Lettvin et. al. (35) have elucidated a complex system of coding in the retina of the frog. Four types of ganglion cells were observed, each cell connected via bipolars to at least several hundreds or several thousands of photoreceptors, so that it responds to visual events occurring in a receptive field extending over an area of several degrees on the retina. These cells abstract from the visual image the following four complex qualities: 1) local sharp edges and contrast; 2) the curvature of edge of a dark object ("bug perception"); 3) the movement of edges; and 4) the local dimming produced by movement or rapid general darkening. The "bug preceivers" are most interesting since they respond best when a dark object smaller than the receptive field enters, stops, and then moves about intermittently within the field.

These four stimulus attributes are thus the only kinds of visual information transmitted to the frog brain. Detailed pattern vision apparently cannot be achieved by the frog. Filtering of information at the periphery of the system restricts the variety of sensory patterns to these four attributes plus those achieved by further processing of the filtered information at higher centers (36).

The limited number of classes of property abstractors found in the eye of the frog indicate that a great deal of information is discarded and never enters into the central nervous system. As pointed out by Minsky (49) in evaluating automatic pattern recognition techniques, descriptor-list schemes are critically limited, because of their fixed size, in the detail of the distinctions that can be made. It appears that in the evolutionary process mechanisms were developed in the frog to abstract sufficient visual information from the environment to guarantee survival while minimizing requirements for complex processing and integration at higher center.

In higher animals far more information is available for transmission to the central nervous system. Higher organisms are therefore capable of far richer and more varied visual experiences, but at the cost of providing more complex central processing capabilities to abstract particular stimulus attributes from the welter of stimulus information. Hubel and Wiesel (28) have shown that in the cat and monkey similar descriptor-abstracting functions are carried out at higher levels in the optic pathway.

Central Control of Sensory Input Patterns

There is a growing body of evidence indicating that in the higher animals and man the central nervous system is incapable of dealing with all of the impinging sensory information available at receptor systems at any given moment. Recent psychological and physiological studies of the mechanisms and limitations of attention have shown that only a limited amount of the information available within any single receptor system can be handled adequately at any time. In order to deal effectively with this limited portion, it is necessary to selectively filter certain classes of stimuli to protect the nervous system against overload.

Let us first consider the mechanisms involved, since we have here clear demonstrations that the central nervous system possesses an important sensory control mechanism which contributes to perceptual content by selecting and modifying sensory messages both at the receptor and in higher portions of the ascending sensory pathway. The importance of these brainstem reticular formation functions to our understanding of perceptual processing is indicated by Livingston (39):

"The nervous system appears to be made up less of independent linear pathways than of mutually interdependent loop circuits which stitch together the various parts of the brain into a functional whole. Along ascending as well as descending projections, the brain-stem reticular formation and the cerebral and cerebellar systems linked closely with it seem to modulate impulse traffic in a continuous action that modifies the composition of perceptive as well as projective neural patterns. The losses and distortions of signals brought about by this mechanism is at work; this appears to be designed to diminish

the involvement of higher centers with signals that have little immediate significance for the animal. Thus, sensory signals appear to be subject not only to error, in the sense projected by Descartes, but also to some purposive central control." (39, p. 759)

The relationship between reticular mechanisms and shifts of attention is clearly shown in several studies. Recording from electrodes implanted in the dorsal cochlear nucleus of the cat. Hernández-Peón et. al. (22) tested the effects on auditory-evoked potentials of distraction by visual and olfactory stimuli. When mice in a jar were placed before the experimental animals, or when fish odors were blown into the cage, the formerly high amplitude auditory responses to click stimuli were immediately and markedly reduced in amplitude. When the mice were removed, or the odor blowing stopped, and the cats were again relaxed, the evoked auditory potentials returned to their initial high-amplitude level, so that the reduced auditory potentials were closely correlated with the period when the animals were distracted by non-acoustic signals. In visual studies using electrodes implanted in the reticular formation, optic tract, lateral geniculate body, and optic radiation, Hernández-Peón et. al. (23) demonstrated that both stimulation of the reticular formation and distraction by nonvisual stimuli are associated with a reduction in amplitude of the photic response at each point along the visual pathway.

Earlier concepts of transmission in the nervous system based on studies of anesthetized animals, held that sensory nerves and the ascending paths of the central nervous system passively and reliably convey to the cortex the information

processed by sensory transducers. The selection and modification of perceptual messages by the sensory control mechanisms revealed in modern studies of unanesthetized animals implies that incoming signals are identified, given significance, and that subsequent transmission or modification of the signal is based upon the results of this preliminary identification. The active selection and organization of sensory information demonstrated here is, thus, congruent with our earlier discussion of perception as a process that constructs the properties of objects and events in our experience, that does not simply mirror objects and events in our environment.

#### An Information-Flow Model

Broadbent (4) has constructed a model of the nervous system as an information-handling mechanism. His view of the nervous system as a single communication channel exhibiting a limited capacity for which sensory events must compete, is based upon psychological data derived largely from experiments on selective listening in which several messages arrive at the ears simultaneously or in close temporal proximity. We shall see that these data fit well with the neurophysiological findings presented above.

Broadbent's information-flow model for the organism incorporates the following principles derived from his study:

1) A nervous system acts to some extent as a single communication channel, so that it is meaningful to regard it as having a limited capacity.

2) A selective operation is performed upon the input to this channel, the operation taking the form of selecting information from all sensory events having some features in common. Physical features identified as able to act as a basis for this selection include the intensity, pitch, and spatial localization of sounds.

3) The selection is not completely random, and the probability of a particular class of events being selected is increased by certain properties of the events and by certain states of the organism.

4) Properties of the events which increase the probability of the information, conveyed by them, passing the limited capacity channel include the following: physical intensity, time since the last information from that class of events entered the limited capacity channel, high frequency of sounds as opposed to low (in man), sounds as opposed to visual stimuli or touch as opposed to heat (in dogs).

5) Given that two signals have been selected one after another, the conditional probability of the second given the detected occurrence of the first is stored within the nervous system in a long-term (relatively slowly decaying) store.

6) Incoming information may be held in a temporary store at a stage previous to the limited capacity channel: it will then pass through the channel when the class of events to which it belongs is next selected. The maximum time of storage possible in this way is of the order of seconds.

7) To evade the limitations of (6) it is possible for information to return to temporary store after passage through the limited capacity channel: this provides storage of unlimited time at the cost of reducing the capacity of the channel still further and possibly to zero. (Long-term storage does not affect the capacity of the channel, but rather is the means for adjusting the internal coding to the probabilities of external events; so that the limit on the channel is an informational one and not simply one of a number of simultaneous stimuli.)

8) A shift of the selective process from one class of events to another takes a time which is not negligible compared with the minimum time spent on any one class.

Sperling (62) has shown that in the visual system there is an equivalent short term storage mechanism at the retina. Utilizing a variation of the tachistoscopic flash procedure in which the instruction for selective reproduction from the stimulus complex followed after the stimulus, he was able to show that for approximately a quarter of a second after the flash more information is available at the retina than can be processed at higher levels.

The data of Broadbent and Sperling make it a likely assumption that filtering of signals by the reticular formation is a mechanism developed to match information input to the limited channel capacity of the nervous system. Moreover, they demonstrate the selection of information within, as well as between, individual receptor channels, as has been shown in studies of habituation to repeated stimulation (11, 21, 22).

#### Orthogonal Categories

Viewing the nervous system as a communication channel of limited capacity capable to selective filtering, and considering

the magnitude of the information-processing task, implies that the necessary information for pattern recognition must be processed to some extent in serial fashion rather than on a completely parallel basis.

This leads directly to consideration of the technique of orthogonal categories for characterizing an object or pattern, known most widely through the game of Twenty Questions. In this procedure an effort is made at each stage to bisect the space in which the object or pattern conceptually resides. The bisection is, of course, a bisection on the basis of probability; each question should, for maximum efficiency, have a 0.5 probability of eliciting a "yes" or "no" response.

The main feature of the procedure of orthogonal dichotomies is that the number of questions grows only as the logarithm to the base 2 of the number of possible objects or patterns.

We can compare this technique with simple parallel and sequential processing techniques. In parallel processing the time required to reach a decision is independent of the size of the ensemble of possible patterns. In simple serial processing, the time required is linearly proportional to the ensemble size. The method of orthogonal categories is like the serial procedure in making relatively modest demands for equipment, yet it is much more efficient in its use of time and questions.

There is nothing new in the concept of the nervous system as a mixed serial and parallel processing device. Equivalent notions are implicit or fully expressed in diverse areas such as "span of apprehension" in psychology, anatomical and functional descriptions in neurophysiology, and concepts of self-organizing automata.

#### THE PATTERN RECOGNITION SCHEMA

We can now describe our final model of human pattern recognition. The process is hypothesized as a step-wise, hierarchial one in which hypotheses based upon conditional probabilities stored in the organism determine the information to be selected for processing at that stage, the transformations to be performed upon that information, and the standard or template against which the processed signal is compared. A single yes-no discrimination is not made at each stage, rather a pattern of processed information is compared against a standard and the mis-match information leads to the selection of both the next pattern of stimulus information to feed into the system and the related standard against which it is to be evaluated. The whole process then is one of successively making hypotheses concerning the external source, selecting the data providing the most efficient test at that stage, and proceeding with successively finer discriminations until an unequivocal identification is possible. What must be stored within the organism, through learning or evolutionary organization, then, are sequences of operations well suited to the conditional probabilities between sets of descriptors. The

object or pattern is defined by, and recognized in terms of, the series of operations carried out in the processing sequence giving rise to a final mis-match value small enough to fall within criterion limits.

### Role of Motor Adjustment

In coming to write this report, we have found several areas in which similar approaches are developed. They provide significant contributions, derived from very different theoretical approaches, toward understanding of the origin and development of such a hierarchical organization of perceptual processing operations. Representative of the first area, is the work of MacKay (41, 42) who has constructed a number of hypothetical models of statistically self-organizing information-flow systems which can be compared with human information handling in perception. MacKay (41) suggests that the correlate of perception is activity which organizes an outwardly directed internal matching response to signals from receptors. Perception is concerned with the statistically stable or quasi-stable features of the environment. Percepts are essentially recurrent regularities or compounds of regularities capable to being reflected in the adaptive organizing system.

In his schema, the core of the organism is an active system of organizers whose statistical pattern of interconnections implicitly depicts the organism's world of activity, as so far discovered by it. They form an "internal department" of the effector system, framing internal representations of percepts by generating matching responses under the guidance of a comparator, and at the same time organizing appropriate external

effector activity. The relative probabilities of different trial activities in the core system of organizers are weighted by a detector system, which filters from the receptor such clues as they provide to the choice of an appropriate organizing routine to match a given sensory input.

Of particular interest is MacKay's treatment of a central problem of perception -- that of the stability of the perceived world or the perception of change in space (42). The problem he deals with is seen in simplest form in the situation where the visual field does not seem to move when the line of gaze is changed through a voluntary eye movement, although the visual image moves across the retina. When the eye is moved by pressing on the corner of the open eyelid, however, violent movement of the visual field is seen. The explanation usually offered for this effect is that the innervation of oculomotor muscles provides "compensation" which is absent when rotation of the eyeball is due to other causes.

MacKay shows that the simplest and most efficient information-flow implementation of such a system is one in which the signals to be transformed are outwardly-directly matching-responses, rather than one requiring transformation of sensory inputs. In the diagram of the model shown in Figure 3, the transformation in the control system, setting the conditional controls of effectors is realized as well in inverse form in the abstracting system which breaks down receptor information into terms of universals and their particular qualifying properties; this is accomplished by using the same network in a feedback loop.

It should be noted that MacKay's general formulation is embodied in current efforts toward development of automatic speech recognition techniques, an area in which such progress can arise because of our ability to specify conditional probabilities between phonemes based on language structure and the speech-producing apparatus (37, 55, 64).

A similar point of view is developed by Sperry (63) in proposing that the avenue to better understanding of brain functions lies in further insight into the relationship between the perceptual and motor functions of the brain. From phylogenetic and structural evidence the vertebrate brain was designed for the regulation of every behavior rather than for mental performance -- "the entire output of our thinking machine consists of nothing but patterns of motor coordination." Perception and ideas have their factual significance and meaning in terms ultimately of overt operation, where the interrelation of motor and mental activity is one of cyclic and reciprocal interdependence. The encoding of neural correlates of perceptual experience must of necessity be so designed that they intermesh in intimate fashion with the motor and premotor patterns.

The congruence of Sperry's viewpoint with that of our model is well illustrated in the following:

"We may arrive at a better conception of the neural events in visual perception if we imagine our sample triangle as being constructed gradually in time out of dots and dashes that are passed successively into the brain to produce each its individual vertical effect. This may seem contradictory to demonstrated Gestalt principles in perception but actually it is

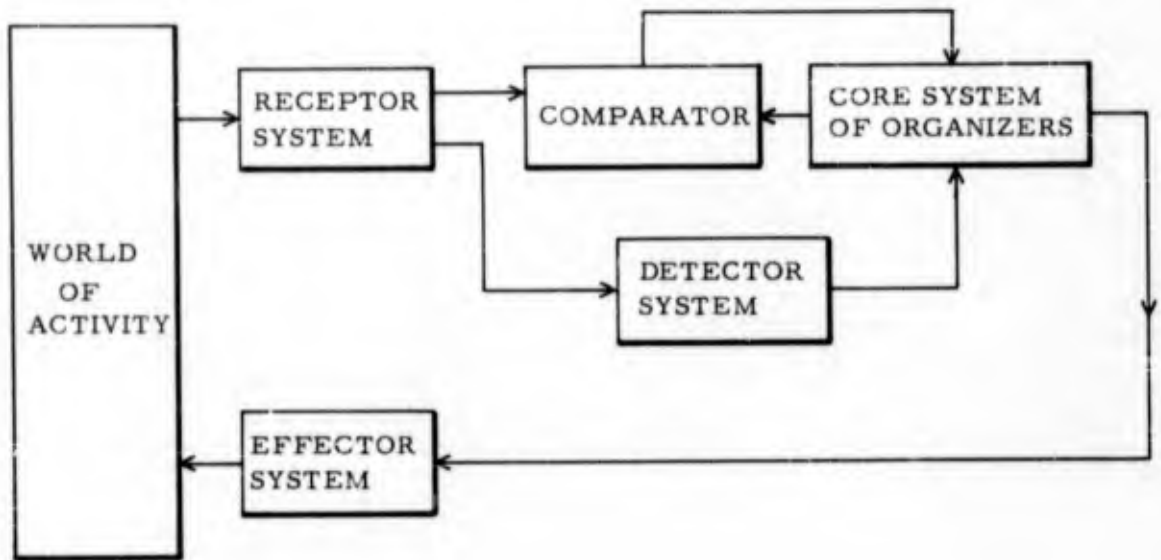


FIG. 3 MacKAY'S INFORMATION - FLOW MODEL

contradictory only to some of the secondary inferences drawn therefrom regarding brain physiology. It is well established by tachistoscopic studies that a complicated pattern is not perceived in full detail with the initial projection of the pattern into the brain. The total picture comes gradually; at first the broader and bolder features are seen and then, by steps, further details. The perception of simultaneous spatial relations thus commonly depends upon temporal organization in the brain processes.

"Consider the neural adjustments involved in perceiving a single dot on the wall before you. The stream of impulses entering the midbrain and cortex will first set up responses that tend to center the eye on the dot. This may involve head as well as eye movements and possibly the entire musculature. Immediately with perception of the dot comes readiness to locate it and to respond to it. Widespread facilitating and inhibiting effects are invoked in many parts of the brain. The cerebral mechanisms have become set for a certain class of reactions. This particular set will automatically exclude an infinite number of other reaction possibilities. Probably your eyes will not remain fixed upon the dot but will stray around the wall in its vicinity. As a result the stream of excitations in the brain will drift about the visual cortex. Nevertheless the dot appears to stay fixed meanwhile, and you remain oriented with reference to it.

"Now suppose another dot is added in the neighborhood of the first. This sets up another stream of impulses which in turn arouses responses somewhat similar to those of the first dot. The adjustments from the first largely remain, however, and essentially the result is an additional adjustment superimposed upon the first.

"The addition of a third dot sets up other reactions that further modify the adjustments already present. There are now three streams of impulses passing through the striate cortex. As the eyes move about

from one dot to another and to neighboring points on the wall, the spatial patterning of the three streams of impulses through the cortex varies greatly. Not only do the three foci of excitation flash about in different positions in the cortical field, but the number projected in each hemisphere will fluctuate from none to three. The simultaneous spatial inter-relationships thus undergo continuous variation in the cortex so that it is impossible to think of any type of horizontal "field" force binding these streams of impulses together in the constant pattern that is perceived.

"To the three dots may be added two more, and so on. Then the dots can be closed gradually by dashes and more dots until the triangle is completed. The cerebral adjustment to a single dot meanwhile will have been built upon and modified into an adjustment to respond to a partial and finally a whole triangle. The sensory input must be pictured throughout as influencing and modifying premotor and motor patterns of excitation that are already present. One may say that the sensory input is perceived and acquires conscious meaning only in so far as it modifies preceding patterns of central activity. The foregoing approach to the perceptual process is suggested merely to aid in visualizing the neural events as an active meaningful adjustment, rather than as simply an impression or passive registration in brain tissue of a pattern of sensory excitation.

"By the same procedure one might build a square or a hexagon. Although the first several dots in each case might be identical and arouse the same response, the final adjustment will differ according to the pattern completed." (63, pp. 305-306)

If we turn to consideration of the functional organization of the central nervous system, it becomes apparent how well our model, together with the extensions drawn from the work of MacKay and Sperry, fits with the information provided by recent studies.

Livingston (39) points out that it is now possible to identify six mutually interacting neural systems: two parallel ascending sensory pathways; two parallel descending motor pathways; the brain-stem reticular formation; and the descending sensory control mechanisms. The interdependence of these six systems is obvious. Evidently they are all knit together by the brain-stem reticular formation.

It should be noted that the formulations that have been described in this section lead toward understanding of an extremely knotty problem that has long troubled psychological and neurophysiological theorists: Where and how is past experience stored in memory and how does it make contact with the processing of current sensory input to add meaning to sensory information? Although the topic is too complex to allow for further discussion in this report, it appears that, in juxtaposition, these formulations clear away the underbrush so that, at the conceptual level, an adequate solution is in sight.

## V. APPLICATIONS TO TWO FIELDS OF PSYCHOLOGICAL RESEARCH

This section presents interpretations and re-evaluations of data drawn from several psychological areas of current interest and importance. Together with the extensive body of material presented in other sections of this report, they represent an effort to explicate from our frameworks principles useful in organizing the sprawling, unrelated facts relevant to pattern recognition.

### Informational Measures of Pattern Recognition Capabilities

A large body of experimental data has been gathered through application of the theory of information of Wiener and Shannon in estimating the capacity of people to transmit information. Rates of information transfer, in bits per second or bits per stimulus, have been measured in diverse experimental situations testing reaction time, visual thresholds, absolute judgements, communication channel intelligibility, and immediate memory.

An interesting aspect of these data which we should like to interpret in the light of the composite model is the range of differences in channel capacity or rates of information transfer found in experiments employing different perceptual tasks.

Miller (46) has summarized the results of a number of experiments involving absolute judgements (identifications) of single-dimensional stimuli. Channel capacities measured for these uni-dimensional variables range from 1.6 bits for curvature of a line to 3.9 bits for pointer position, with intermediate values for pitch, loudness, size, hue, area, and angle of inclination clustering closely about a mean of 2.6 bits (6.5 perfectly identifiable categories).

When we turn to estimates of channel capacity in situations requiring judgements of multi-dimensional stimuli which differ from one another in several ways, we find that transmitted information increases with the number of dimensions. While Hake and Garner (17) found a maximum transmission of 3.1 bits for the uni-dimensional location of a point on a line, Klemmer and Frick's (31) finding that 7.8 bits were transmitted for locating 1 to 4 dots in a two-dimensional grid suggests that the maximum increases with number of dimensions. This is confirmed by Pollack and Ficks (53) who used an interrupted tone containing six coding dimensions and found 7.2 bits transmitted. They also demonstrated that increasing the number of classification steps within each dimension improves information transmittal far less than increasing the number of dimensions.

These data have been interpreted as demonstrating that the span of absolute judgement imposes severe limitations on the amount of information which the human can process (46).

There are several comments to be made in regard to these data and their interpretation. First, there is an implicit assumption that the central nervous system is a relatively static system with fixed capabilities imposed by its organization and structure. This report has stressed another view -- the capability of perceiving organisms to select and organize information in order to make the relevant, necessary discriminations to structure and deal with their environment. If it is found that a relatively few, coarse discriminations characterize discrimination within a single dimension, there is a strong possibility that finer discriminations would be superfluous or inefficient in the overall information-processing system developed in interaction with the environment.

The fact that more information can be handled with multi-dimensional coding fits well with our model and seems to be due to the fact that the results for multi-dimensional data were derived from experimental situations approximating more closely natural perceptual conditions.

Estimates of human channel capacity are appreciably higher when we turn from these bare laboratory tasks to well-practiced tasks in which the experimental subjects can be expected to have developed through extended learning the capability of handling a large ensemble of (source) classes. One student identified (i.e. read aloud clearly enough for scorers to find them in the dictionary) almost 2 items per second from a vocabulary of 500,000. Over half of the items were individually meaningful to him; they were not just collections of syllables. It is difficult to find comparable examples outside the field of language, but informal observation suggest that a person can apprehend in some way, given a few seconds for each object, one object after another from a class that, as judged from efforts to designate the objects with binary descriptors, includes about a million members.

The discrepancy between the low informational measures reported earlier and these more impressive informal observations of human information transmittal is understandable if we consider some facts concerning information encoded in language. Miller (47) points out that if vowels and consonants are considered equi-probable and independently selected, speech would convey information at a rate of 67 bits per second. If we take account of the various sources of redundancy in the language, however, it appears that from 10 to 20 bits per second is an average rate of transmission (40).

The point to be made here is that a person completely naive concerning the structure of the language would undertake a most formidable information-processing task in conversing with his neighbor, since he would have to identify any one of about 100,000,000,000,000,000,000 sequences of sounds each second. If he has developed an adequate knowledge of the statistical dependencies within the language, and can frame hypotheses based on this knowledge, his task (at 10 bits per second) is reduced to a selection from a total ensemble of  $10^{24}$  possible sound sequences. What is remarkable in this process is not the limitations of channel capacity found in studies of uni-dimensional absolute judgements, but rather the efficiency with which the redundancy of the stimulus pattern has been exploited to perform a complex information-processing task with inefficient equipment.

A strong argument can be made that speech perception shows an almost perfect fit with our composite model of pattern recognition. A verbal message is a temporal pattern which is analyzed in serial fashion. The structure of the vocal tract and of the language impose strong dependant probabilities between units in the pattern, so that it is possible to form hypotheses about probabilities of occurrence at each point in the series based on the identification of the preceding units. The extensive involvement of motor acts in speech communication is self-evident.

#### Display/Control Design

It appears to us that the composite model of the perceptual process offers a new conceptual approach in an area of military importance -- the design of information-processing displays. In the twenty-year span since the beginnings of human engineering

during World War II a substantial research effort has been devoted to elucidating data and principles relating to display design. The result of this work is a large body of empirical data concerning legibility of scales and pointers, the size, shape, and orientation of displays and controls, and related topics. At the same time there is a paucity of organizing principles which can serve as guides in design efforts to relate and combine information in complex displays.

The composite theory described in Section III provides a conceptual base for pulling together into a coherent picture diverse and unconnected items of information such as population stereotypes in display/control motion (50, 69, 70) the shortcomings of multiple-pointer dial displays (53) and the greater intelligibility of graphical representation over tables of numbers. In each case we can attribute the difficulty or difference revealed in the data to different and conflicting spatial frames of reference within the display which preclude the use of a single type of transformation of the outwardly-directed matching responses. Or, stated differently, we can say that analyzing one aspect of the display requires a particular motor set, which must be replaced by a second different motor set for analysis of another aspect of the encoding scheme. Encoding within such mixed frames of reference may preclude the development of optimal sets of descriptor-processing routines by the human operator.

The argument can be illustrated in the case of the dial-type three pointer altimeter, on which three concentric pointers of different sizes represent hundreds, thousands, and tens of thousands of feet, respectively. Grether (16) found that instrument

designs of this type gave rise to the longest interpretation time and highest percentages of interpretation errors among nine display designs tested. Our interpretation is that each of the three pointers on the dial calls for the same implicit motor response in interpreting angular position, but the implicit motor response then requires a very different transformation or scaling in translating to a numerical value. In other words a shift of 90 degrees of the hundreds pointer results in a very small change in quantity as compared to the same rotation of the small pointer representing tens of thousands. Pointer size, the only cue denoting scale change, is represented in motor terms as a linear radial movement unrelated to the rotational dimension. An altitude reading thus calls for rapid alternation among three scales with the shifts among scales signalled by an unrelated or conflicting coding dimension.

This appears to be an interesting new approach which may be developed to allow prediction of display interpretability, rather than explanation after the fact. The fields of greatest potential application appear to be in display/control compatibility, display of spatial relations, and situations where rate estimation is required in addition to read-out of momentary values.

## VI. APPLICATIONS TO THE DESIGN OF INFORMATION PROCESSING SYSTEMS

We can now look back over body of theory and data that has been presented in this report and attempt to assess its value in pointing to interesting and promising approaches to the design of military information processing systems requiring complex pattern recognition and object identification. Although our interest is focused primarily on the short term goal of defining optimum use of human and automatic capabilities in system design efforts undertaken within the next five or ten years, some recommendations geared to long term goals are also included.

### Human Operator Functions

It appears that within the next five or ten years, automatic recognition techniques despite recent advances will not be developed sufficiently to rival the capabilities of the human perceiver, at least for those tasks in which evolution and extended learning and training have combined to produce the remarkably skilled and flexible performance characteristics, of object recognition, the perceptual constancies, and visual space perception. In fact, it appears to be an extremely laborious and costly procedure, for many applications, to design automatic techniques which simulate imperfectly these biological skills. The problem, of course, is that the human operator can be expected to perform considerably less effectively in situations where the information provided by radar, other advanced sensor systems, and complex information processing techniques provides displays and quantitative information in a form and within a framework totally unsuited to these well-practiced data-processing techniques of the human perceiver.

If, however, it were possible to transform sensor and computer information so as to present it in a form in which the human operator could utilize his perceptual processing capabilities more naturally and without extensive learning, the requirement for automatic techniques to guarantee adequate system performance might be reduced considerably.

The point of the argument and the direction in which it appears that the greatest potential lies is well demonstrated by recent developments in aircraft instrument design. The contact analogue displays currently being developed under the Army/Navy Instrumentation Program are a complete departure from traditional means of displaying information for vehicle control. Rather than presenting individual quantitative dial read-outs of such control parameters as speed, heading, altitude, and vehicle orientation, these sensor inputs are utilized to generate a single integrated information source, a computer-generated surface that responds to the six degrees of freedom of aircraft motion as does the earth's surface seen from the aircraft. The essential point is that it has been deemed worth while to transform straightforward, precise values and intermix them to create a very complex display as a means of insuring easier, faster, error-free interpretation by the pilot. Although these contact analogue displays are complex judged from mathematical, computational or electronic standpoints, they are simple, straightforward, and easy to interpret for the pilot because they allow him to bring to bear more efficient information-processing techniques than he can utilize in deriving information from dial-type displays.

A similar example germane to the problem at hand is provided by observation of a Cinerama film in which one sequence was photographed during a roller coaster ride. The information processing load of the observer is very great as he interprets the constantly-changing visual pattern on the large screen to re-create, without vestibular or kinesthetic cues, the very compelling illusion of riding the roller coaster. What is extremely interesting is that the slight distortions in the picture caused by lens aberrations at the edges of the fields of view of the three projectors are immediately apparent. In other words, not only are the complex distortions and image changes due to three dimensional movement instantly and easily analyzed, but very minor imperfections in the complex pattern of change are apparent as an "unlawful" twisting or bending of objects as they pass through particular locations on the screen.

Let us look at some ways in which such transformation or recoding of information can be utilized in astrosurveillance systems to utilize human perceptual skills in complex pattern recognition and object identification. There are a number of variations of this general approach which appear feasible and interesting. In each case, however, the problem is to isolate important dimensions or attributes of the sensed data, define the probable or potential relationships between dimensions, and find an equivalent, more natural perceptual framework into which the information can be coded for greater ease of interpretation. An important consideration is that the recoding scheme must not hide or prevent the finding of unsuspected or new patterns of relationship within the data.

The simplest illustration of what we have in mind is a static, three-dimensional plot of a family of curves, as shown in Figure 4 in which interactions among variables are more easily discerned than in a series of individual curves.

As an extension of this approach we can consider a hypothetical situation in which it is necessary to monitor 40 separate information channels consisting of 4 types of information derived from each of 10 sites. Information of one type or from one site is not sufficient to distinguish potentially hazardous situations requiring detailed processing; this can only be determined from the spatial-temporal correlations in the overall pattern of events. Suppose that one class of information consists of wave forms extending in time measured at each of the 10 sites, while the other three classes are number of discrete target reports or hits, temporal patterning between adjacent hits, and frequency spectral characteristics.

The 10 wave forms could be displayed so as to give rise to a convoluted surface as shown in Figure 5. Frequency spectral characteristics might then be encoded in color, ranging from blue through to red, painted on each band or ribbon of the convoluted surface representing the wave form received at a particular site. Hits or threshold returns would be shown as bright dots within each band, painted in the color of that band. The temporal patterning between hits might then be encoded by varying the writing time on the scope for adjacent dots so as to give rise to apparent movement ( $\phi$  phenomenon) between dots.

Under these conditions it would be simple for the operator to pick out dotted green hills or ridges showing some movement between dots; or other patterns of relationship between attributes. A stimulus pattern of this type is ideally suited for discrimination of contours, form characteristics, and other coherences in a complex array of events. It can, moreover, assist in finding new patterns and relationships and developing finer discriminations within classes of patterns by increasing the facility and extent to which learning can improve operator performance in the course of system operation.

It seems a very reasonable expectation that there will be a requirement for complex data-processing displays of the type described above for use in military systems involving complex pattern recognition within the foreseeable future. This appears to be true regardless of the trend toward greater emphasis upon automatic data processing and decision-making procedures. Even in completely automatic systems capable of developing new and more efficient recognition and decision-making techniques in the course of system operation, it will still be necessary and expeditious to include facilities for human operator monitoring and data processing functions operating in parallel with the automatic system. Given adequate displays for scanning inputs to the system and examining the adequacy of system performance, human operators can be expected to provide new insights and hypotheses to guide the search for optimal automatic procedures. There is, therefore, the need to devise new display techniques adequate to these needs, and the danger that such efforts will not keep pace with system requirements and the increasing complexity of data processing techniques.

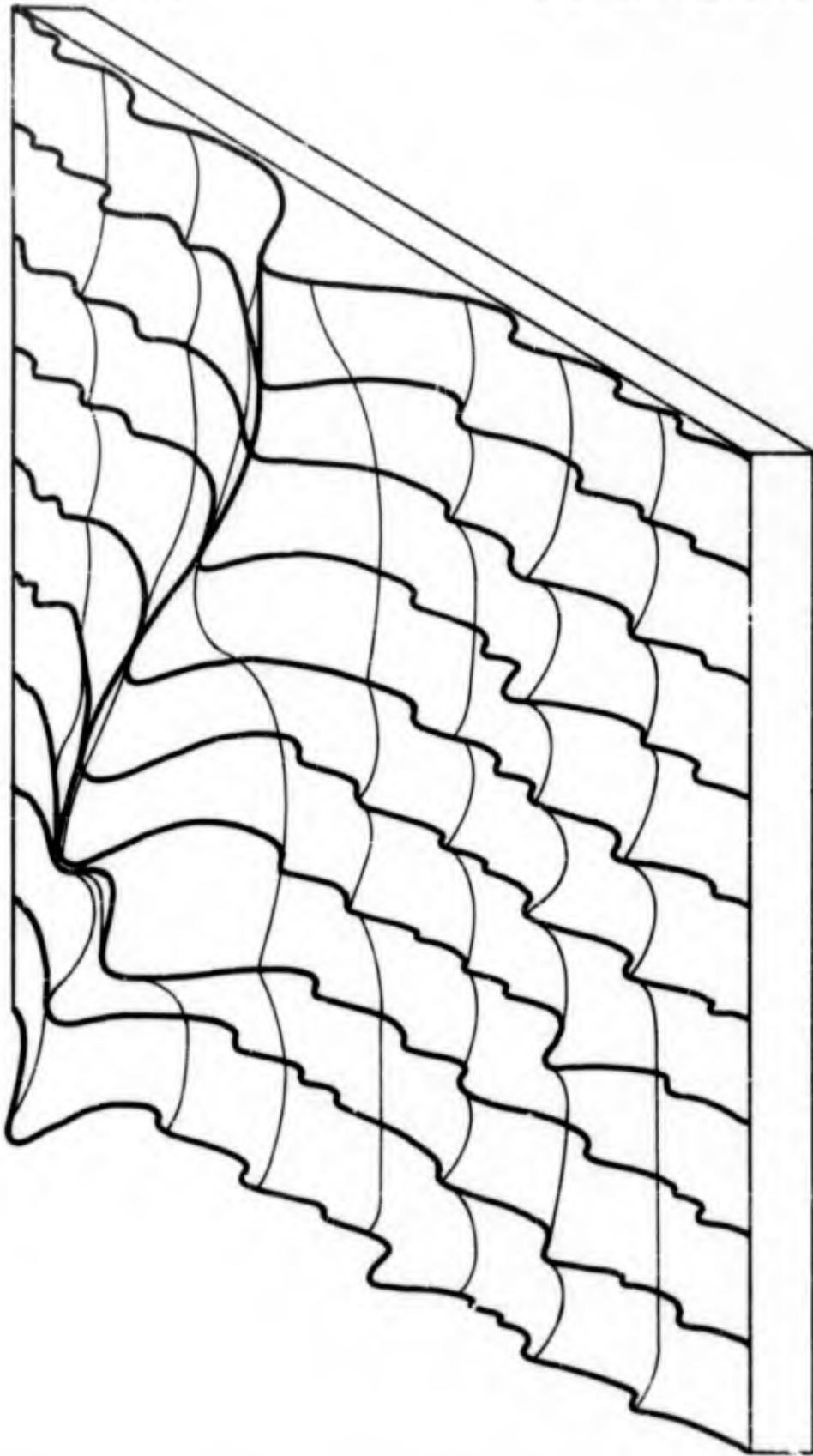


FIG. 4

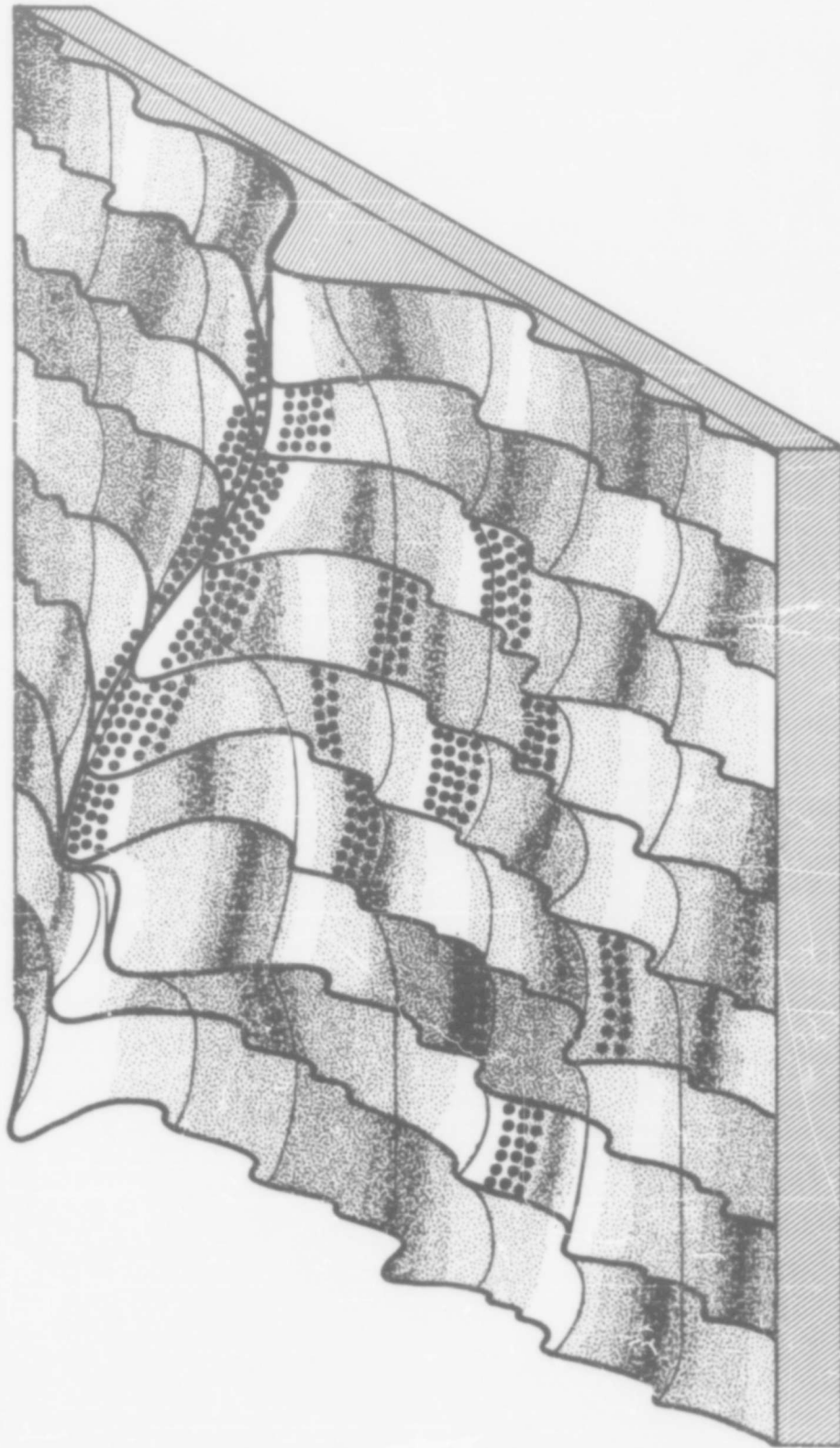


FIG. 5

There are a number of general ways in which human operator capabilities can be used to advantage in such systems in addition to the monitoring function already described. Human perceivers have unique capabilities to serve as first-level "data demons" in pattern recognition systems constructed on general lines of the "Pandemonium" model of Selfridge (57). In Selfridge's model, it will be recalled, data demons are units designed to detect certain attributes or patterns and transmit a measure of the degree of confidence of the presence of that quality in the incoming signal on to higher levels where "cognitive demons" combine and weight the received data. Some of the functions required at this lowest level of the decision process - identification of contours, patterns, and sensory qualities - are unique capabilities of biological systems. A group of human operators, each responsible for evaluating a different aspect of the incoming data, would, by means of light pen, push button, or other devices, pass their inputs to a computer better equipped than they to deal with conditional probabilities in arriving at a final decision.

This appears to be a very reasonable arrangement, minimizing the data processing load on individual operators while utilizing the computer as a means of assembling and manipulating a large amount of data.

Following along this line of reasoning, it becomes apparent that human operators can be used with great effectiveness as middle-level "cognitive demons." In Selfridge's model, the function of each middle-level unit is to collect and weight the lower-level inputs in support of a particular hypothesis or

identification and to then pass the data up to the final decision-making unit. Our impression is that human capabilities, in combination with adequate displays, can be used to evaluate the pattern of correlation or consistency between several attributes or properties of the incoming data. The results of these comparisons would be entered into the automatic portion of the system and there combined and evaluated.

At this point we can describe an important way in which our man-computer pattern recognition system might differ from the Pandemonium model. It would be far more efficient to have operators serving as middle-level demons process data to evaluate only those hypotheses which appear on the basis of preliminary analysis of individual attributes to be the more likely alternatives. One way of accomplishing this is to subject the results of the lowest-level single-attribute analysis to preliminary computer processing in order to remove the least likely hypotheses from further consideration. The computer would then select the specific multi-attribute comparisons required to make a decision between the remaining alternatives, and assign them to the appropriate consoles for analysis. At each such console the operator would compare the multi-attribute pattern against a model display for the hypothesis under test and send back a discrepancy measure between the data pattern and model. It should be noted that there is great similarity between this arrangement and the schema for human pattern recognition presented earlier in this report.

Let us recapitulate some points made in this section. We have argued that humans are capable of analyzing complex relationships in data encoded in forms consistent with characteristics of the nervous system and well-practiced perceptual skills. Some approaches to display design have been suggested which appear to be better suited to the requirements of military systems involving object recognition than techniques currently in use. In this regard, it appears that what is needed are general display techniques which can be used very flexibly to encode a variety of data types, rather than displays specifically designed to specific individual system requirements on a piece-meal, ad hoc basis. Finally, some approaches have been suggested for integrating human perceptual abilities and automatic data handling techniques in efficient, flexible systems capable of learning and growth to meet changing operational requirements.

#### A Problem-Solving Approach to Pattern Recognition

The paradigms for automatic pattern recognition discussed in Section III have implied more or less pre-determined procedures. If the statistical theory of signal detectability is taken literally as a normative model for pattern recognition, it sets forth clearly a definite procedure, a sequence of steps that should be taken to insure optimal recognition of patterns of a specified class. The Pandemonium-like paradigms, the paradigms involving lists of descriptors, are somewhat less definite in their prescription of procedure, but they imply fairly clear guidelines. We should therefore turn attention to another, as yet less-well-developed approach, in which the recognition of a pattern is considered to be the solution of a

problem, in which a variety of sub-procedures are available for application, in which the overall procedure is governed by a set of heuristics, but in which it is not clear, in advance, even what general form the course of solution (or recognition) will take.

There are two broad sub-categories under this general rubric of problem-solving pattern recognition. In the first, the human operator is recognized as the source of heuristics, and also as the applier of heuristics. The overall-pattern-recognizing system is therefore a man-machine system (a "man-computer symbiosis") consisting essentially of (a) sensory sub-systems, (b) processing and display equipment under the direct and immediate control of the operator, and (c) a ready supply of preformed sub-procedures (e.g., computer subroutines) that may be strung together to form an overall procedure under the direction of the operator. In the second sub-category, the heuristics have come, in the main, from human sources, but they are incorporated into a problem-solving program (51). There is little possibility of making a significant development in this second sub-category until much research and development has been carried out in the first. For military applications in which very fast response is required, therefore, it appears that problem-solving pattern recognition is at least several years off. However, the approach has several very attractive features, and it seems well worth while to conduct research along the line of the first sub-category with the aim of shifting emphasis, eventually, to the second.

second.

The initial phases of pattern recognition through problem solving are likely to be concerned with definition of the problem. The first step may be acquisition of enough data to characterize the present situation sufficiently to support the formulation of initial hypotheses. In a continuing pattern-recognition task, of course, there will always be a more or less well-defined situation. One often used sub-procedure will be to determine what other situations, within the experience of the system, are similar to the present one. Given those, it will be possible to employ sub-procedures found effective in the similar situations. If that approach is not rewarding, it may be possible to formulate rough hypotheses concerning the nature of the pattern, or its source. With these hypotheses will be associated certain tests, and these tests will dictate sub-procedures to follow. If they are rewarding, or appear to be promising, they should be continued. If they are made to appear improbable by the data acquired in the process of testing, then they should be rejected, and the next-most-appealing hypotheses should be formulated and subjected to test.

The hypotheses may be tested through synthesis as well as through analysis. That is to say, instead of determining from the overall hypothesis what local features should appear, then testing for the presence or absence of those local features, it may be as effective, or even more effective, to construct, from the overall hypothesis, a hypothetical set of sensory data, and then to measure the degree of correlation between those hypothetical data and the sensory data actually received. This formula leaves a wide range of choice, of course, among levels of processing at which to make the comparison. The comparison might be made between hypothetical and actual raw sensory data,

or between the two sets of data after preliminary processing. In general, it seems desirable to filter or smooth or abstract far enough to eliminate most of the characteristics of the signals that can be expected to vary greatly from one observation to another despite constancy of a pattern source.

To the best of our knowledge, there is no fully developed example of the problem-solving approach to pattern recognition. A character recognizer developed by Selfridge at the Lincoln Laboratory had some of the properties we are here discussing, but only a few. It worked with a small set of procedures, which it applied one after another in sequence. At first, the sequence was random, but the system organized itself, to some extent, on the basis of its previous experience.

The approach is exemplified best, we think, by the system of pattern-recognition subroutines and control programs that T. Marill is currently developing in our laboratory. In Marill's system, the operator will be able to apply, to a configuration displayed before him on an oscilloscope, any one or any sequence of a set of "useful" subroutines, and then to examine the outcome, and then to decide upon the next step. If the outcome is unsatisfactory, he will be able to back up to an earlier point and try something different. At the present time Marill's system includes only the basic control program and a few subroutines for finding straight and curved lines in a field where it is presented initially as a collection of dots. His aim is to develop further the set of subroutines, and then to use the system as a facility for studying pattern-recognition procedures.

Inasmuch as each subprocedure or subroutine can be regarded as an arrangement for determining a measurement, the problem-solving approach has much in common with the Pandemonium approach. In spirit, however, we regard the two as fairly separate and distinct. In particular, in the problem-solving approach, when synthesis from hypothesis is employed, the measures are applied, not to the sensory data or to the outputs of lower-level measuring devices, but to the hypothesis or to the pattern at some stage as it is built up from the hypothesis. It is not until the final comparison is made between actual and synthetic data that it can be said that measurements are made upon incoming data. Furthermore, as a practical matter, quite dissimilar ideas about system design appear to arise from the two starting points.

It is natural, perhaps, to think of the problem-solving approach as involving a succession of steps carried out by a single operator or under the guidance of a single supervisor. However, there is no intrinsic bar to parallel operation. It is certainly possible to think of a system involving several or many operators, acting in parallel upon the input data and applying to it processing subroutines of their own, individual choices. Operators at a higher level might then work with the results obtained by these parallel operators and something similar in general configuration to a Pandemonium might emerge. Such a team approach to problem solving, using sophisticated computer aids at every stage, seems quite far off, however, and it might be better to think in terms of simpler, sequential problem-solving systems for the time being. We urge this as a promising, but fairly long-term, course of research.

Human Probability Estimates for Mechanized Decision Processes

Currently, several efforts are being made to mechanize, in a rather literal way, the procedures of statistical decision theory. These efforts are destined, in our opinion, to engender embarrassment when it comes to determining the a priori and conditional probability distributions required by the decision process, for there has been very little direct experience (with space systems, for example) from which to estimate probabilities from relative frequencies of occurrence. However, human beings are capable of making probability estimates on the basis of considerations other than direct experience with events in the class to be predicted. We think, therefore, that there is, in military identification and classification systems, a rich area for the design of systems that may be fully automatic at running time but only semi-automatic in the warm-up or pre-operation stage.

"Appropriate Precoding"

The outstanding feature of the frog's visual mechanism (discussed earlier) is the appropriateness of the retinal coding, of the property abstractors, to the frog's way of life. It appears to us that there may be value in the development of ad hoc property abstractors appropriate to the various properties that we can foresee, with moderate confidence, in the objects with which our future systems will have to deal.

We might, for example, devise and perfect abstractors of "tumbling," of "exploding," of "heating rapidly," of "linear acceleration," of "scintillation in the band  $f_1$  to  $f_2$  cycles per second and not in the band  $f_3$  to  $f_4$  cycles per second," etc.

We might do so well in advance of full assurance that anyone was going to build a system to cope with objects that do all those things--justifying our action on the ground that all those properties are potentially important, that the required research and development is inexpensive but time-consuming, and that, when and if someone starts out to build a system, he will want devices to detect those properties.

In short, the idea of factoring out property abstractors offers an approach to research and development in advance of system need. There is nothing new in the idea of research and development in advance of system need, of course, but this seems to us to be a particularly suitable occasion for it. Note, incidentally, that predeveloped abstractors should have outputs compatible with standard data processing equipment.

#### "Parallel Heuristic Processing"

The technology of data processing abounds with parallel devices that do simple things and serial or sequential devices that do complex things, but there is no parallel hardware for doing complex things.\* We understand the technical and economic difficulties of replicating complex devices many fold. It appears to us, however, that the problem of achieving a feasibly replicatable complex processor is an extremely worthwhile subject for research.

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\* Most "parallel" digital computers perform all but their simplest operations sequentially. In the largest machines, a few operations go on in parallel but not a thousand or a million.

It may be a necessary step in the development of information processing hardware to create replicatable processing units capable of recognizing their own names or having goals or purposes. Although there is no definitive evidence to support a conclusion, several students of the nervous system have the feeling that a fundamental unit processor ("fundamental" on some level of discourse) must be complex enough somehow to simulate, or to represent dynamically, the thing or idea for which it stands (14, 15). Save for a computer program or a subsystem of interconnected analogue equipment, there is nothing like that in the information-processing technology at the present time. It seems possible that study of protein molecules or enzyme systems or neuronal networks might lead to improved understanding, and even the ability to construct, or grow, such units.

#### Combining the Functions of Processing and Memory

In the nervous system, insofar as one can judge from available evidence, there is no clear spatial separation of memory from processing. Both functions may take place in the same tissue, much as they do in the integrators and potentiometers of analogue computers. That arrangement is fundamentally different from the one used in most modern digital computers.

In digital computers, the separation of memory from processing is made in part for economic reasons. If the economic factor were not important, it might turn out that memory units capable of some processing--such as recognizing their names--would be extremely useful. It seems to us, therefore, that attention should be given (1) to ways to overcome the economic obstacle, and (2) to ideas for using components with both mnemonic and processing capabilities.

Since neuronal networks, of the kind simulated on digital computers by Farley and Clark (9), Rochester et al (54) embody inter-mixed memory and processing, it may be that advanced theoretical analysis of such networks would clarify the idea. As matters stand, however, it is conspicuous that our best hardware is arranged in a way so different from our best brains. For numerical calculation, that may be good. For pattern recognition, it may not be good.

#### Apperceptive Set

Human memory has the characteristic of improving the accessibility of stored information when that information is likely to be required. There is evidently either an arrangement for measuring relevance and activating or alerting the relevant material or an arrangement of connections from almost every item to almost every other item. Fano\* has described a model of memory with (literally) such interconnections. There is some approach to set control of memory in "list structures." Fredkin (10) has a set of ideas based on his "trie" memory concept that lead farther in this direction. In our view, this is an extremely interesting field, and we think it will have great practical importance in the information-processing technology.

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\* R. M. Fano, personal communication

## VII. RESEARCH FORMULATIONS

Out of our reading and theorizing have come several lines of approach to psychological research in pattern recognition that may lead to new and interesting data.

A main theme throughout this report has the selectivity of information processing during perception -- a selectivity based upon the influences of hypotheses active prior to the beginning of the process and continuing to influence its course as initial discriminations further limit the alternatives remaining to be explored. Within such a context, we are interested in knowing in detail to what extent processing is serial and how much goes on in parallel fashion. We consider it important, moreover, to discover what types of descriptor processing go on in parallel; to look for "natural" units in descriptor processing.

There is a long history of psychological experimentation along these lines in which short tachistoscopic exposures have been employed to trace the development of perceptual images and to test the amount of information available within the momentary span of apprehension. Exposure of a visual stimulus for a small fraction of a second demonstrates that the visual image does grow slowly in time, with new information and greater discrimination developing with successive exposures. The tachistoscopic technique has not, however, yielded clear-cut data of great generality, so that its present use is generally as a means of introducing ambiguity into the stimulus situation.

Sperling (62) has recently provided an explanation by demonstrating that information remains available at the retina for approximately a quarter of a second following the tachistoscopic flash, so that it is available for central processing during this period. It appears, therefore, that experimental data has been contaminated by interactions between rise time of specific stimulus dimensions and the short-term storage capabilities of the receptor.

A new perceptual phenomenon has been reported by Lindsley and Emmons (38) wherein information presented in a short tachistoscopic flash followed by a second, more intense non-informational flash is not perceived. The "blank out" of the perception of the first flash by the second is essentially absolute if the second flash follows the first by an interval of up to 25 msec; there is a gradual rise in correct recognitions with increasing temporal separation. Little or no interference is found when the interval is increased to 45 msec. Although the exact mechanism of the effect is not yet known, it provides a means of varying processing time in the central nervous system with rather precise control.

There are a number of interesting questions amenable to investigation by this technique. First, how much descriptor processing is carried on in parallel? We can instruct subjects to report on a single descriptor dimension in a psychophysical experiment with intervals between information-flash and blanking flash as a major variable. We can then repeat the process with a second dimension. If we then instruct the subject to report on two or more of these dimensions, changes in performance will

indicate directly the extent to which parallel processing is possible.

The combinations of descriptors presented together can then be varied. It is likely that certain pairings or groupings can be processed simultaneously without mutual interference, while other combinations will lead to significant performance decrements. Information of this type would be of basic theoretical interest and also have value in providing specifications for optimal encoding and design of information-processing displays.

An extension of this line of endeavor would utilize a task designed to have redundancy (conditional probabilities) among various perceptual dimensions or cues. The subject would be given extended practice to learn the task characteristics. At the beginning of training and at frequent intervals during training he would be tested with the perceptual blanking technique to discover the manner in which his information selection techniques altered to conform to task characteristics.

Finally, an experimental series would be devised to test the role of spatial frameworks in information-processing. Perspective drawings of three-dimensional figures in various non-normal orientations would be presented in the two-flash arrangement to investigate the temporal order in which spatial transformations and object identification develop. Corollary experiments would present displays of information encoded in unitary and mixed spatial frames of reference, utilizing good and poor display relationships, to test whether differences in parallel and serial processing are involved.

If the experimental technique described here should prove feasible, it appears that it would provide a potent means of studying the fine-grain structure of human processing of perceptual information.

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