TIME-ANALYSIS OF LOGICAL PROCESSES IN MAN

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Summary

Pattern recognition in man is assumed to be mediated by a hierarchical organization of specialized systems, each of which abstracts a certain property from its input. Some characteristics of the overall organization can be inferred from the times that are needed to carry out various information processes. These times can be determined independently of reaction factors by a scanning method. Preliminary results with the method demonstrate the flexibility of the processing hierarchy in man. They also suggest that parallel processing is used under some conditions, while sequential procedures are dominant in others.

It is a commonplace now that perception and judgement involve the processing of information. The world presents itself to our sense-organs in a superficially chaotic flow of data, from which perceived objects as well as concepts and ideas are abstractions. Human behavior can be regarded as consisting of a series of decisions each of which is based on very extensive stimulus analysis carried out over time. From this point of view, the psychologist who studies cognition is examining the characteristics of a processing system.

It seems clear that the adult human perceptual and cognitive apparatus must be hierarchically organized. A system so flexibly able to respond to many properties of the input can not be radically redesigned for each task. For the most part, new stimulus analyses must occur by reorganization of existing parts rather than by starting from scratch. When you learn to recognize a new word, for example, you certainly use pre-existing and established sub-systems that identify the letters of the English language. You simply use a novel combination of their outputs. The letter-systems, in turn, are probably fed by the output of simpler organizations (let us call them "recognizers") which select various kinds of curves and shapes from the visual input.

There are three fundamental methods for exploring the organization of the processing hierarchy in man. We can look inside with the techniques of physiology; we can take another kind of look by introspecting on the processes as they occur in ourselves; or we can make inferences from human behavior. Each method has both advantages and drawbacks, and this is not the place to discuss them. The procedure reported here is based on inference from behavior, as is most of modern psychology. In particular, it takes advantage of certain time-relations in human cognitive activity. However fast the information processes may be, they must occur in real time. In situations which permit reasonable inferences about the patterns of processing, we may be able to find confirmation by looking at the times involved.

A particularly interesting question stems from the distinction, in programming, between parallel and sequential processing. As Selfridge[1] has pointed out (see also Selfridge and Neisser [2]), a device for pattern recognition may use either of two fundamental modes, which have been called sequential and parallel. They may be used singly or in combination. In the sequential mode, each partial analysis of the input results in a decision which governs the type of analysis to be made next. Only one process is carried out at a time, and the particular sequence of processes determines the final result. In the parallel mode, many analyses are made simultaneously, with the outcome depending on some (perhaps linear) combination of their outputs. How do human beings operate? It is evident from introspection and gross observation that the sequential mode is common. We often think, and act, step-by-step. On the other hand, the anatomy of the nervous system rather suggests parallel operation. It is likely that people are capable of working in either mode, depending on circumstances. The sort of time-analysis to be described here is particularly well adapted for discovering these circumstances.

Method

Fundamentally, our experiments involve timed visual pattern recognition. That is, the subject must decide as quickly as possible whether the stimulus input has a certain property or not. Typically, the input might be a letter, and the question might be whether it is the letter "Z". We assume that at least two levels of processing are involved in such a task. Certain visual characteristics are abstracted from the input -- roundness, angularity, the slopes of lines, and so on -- by sub-systems we may call shape-recognizers. The recognizer for a letter, say "Z", is some weighted combination of their outputs. For example, a certain visual pattern might produce a positive response in a recognizer for horizontal lines, and in another which detected slanted lines. These two in turn would activate the recognition system for "Z", but not that for "O". (Note that the effectiveness of these particular shape-recognizers depends on context. They would not serve to distinguish between "Z" and "A", although it is easy to imagine others that would.) To be sure, we do not assume that these particular shape-recognizers exist in any person. They are meant only as illustrative examples.

Suppose now that several letters are presented at once, and the subject is asked whether any of them is "Z". If he can process them simultaneously, in parallel, his speed will be independent of the number of letters. If he must examine them one by one, his time will increase linearly with the number of letters. To be sure, there is no doubt that the processing must be sequential if the number of letters is large. We cannot examine an entire page in a flash, if only because of the limited area on which the eye can focus. But is there a more intrinsic limitation?

Another interesting case arises if the subject is not looking for "Z" alone, but for either of two letters; say "Z" or "Q". It is evident that these two letters require different shape-recognizers. That is, two different analyses of the same visual input must be made. We could easily build a computer to make them simultaneously. But can human information-processing go on in parallel under these conditions? If so, is there a limitation on the amount of parallel activity that can be carried on? A program of research is under way to answer these questions, and some preliminary results can be presented here.

Unfortunately, the actual experiments can not be as simple as the prototype described above. The time which a human subject needs in order to indicate whether a given letter is "Z" includes much more than stimulus-analysis. The total measurable reaction time includes the response itself as well. Nor can we safely consider the total time as the sum of two parts. There are many components: the subject must fixate, must begin actual search, must decide to react, must actually respond (by speaking, or pressing a button) etc. In addition, the interrelation between these times may change if the problem is altered. For example, the final decision to press the button may be longer delayed in problems where the subject feels relatively less confident. Analysis of simple reaction times is unlikely to give adequate answers to our questions. Indeed, reaction-time analysis was common in nineteenth-century psychology, and was ultimately abandoned for these reasons.

It seems possible, however, to obtain a measure of processing time that is relatively independent of reaction factors. We have tried to achieve this by using a scanning technique instead of measuring reaction times directly. The subject is not presented with a single string of letters, but with a list of fifty strings, arranged in a column. In the entire list, only a single string has the critical property. A typical list is shown in Figure 1. In this case, the subject is to look for a "Z". As soon as the list is shown, he begins to scan down from the top. When he comes upon the item with a "Z" (in this case the 15th one down), he turns a switch. The switch stops a clock, which had been started at the instant the list was presented. Thus, the time needed to find the critical item is recorded. Of course, the number at the bottom of the list, which identifies the position of the Z, is concealed from the subject's view. To insure that he has actually found the critical item, he is instructed to turn the switch to the right if the item has a dot beside it, and to the left otherwise. Both directions stop the clock, but the experimenter can check whether the decision was correct.

When this method is used, the scanning time necessarily depends on the position of the critical item in the list. The time will necessarily be greater for lists with the "Z" nearer the bottom. If the subject is given a number of lists, each with the critical item in a different position, it becomes possible to plot the time as a function of the list-position of the item. Such a plot is shown in Figure 2. Each point in the figure represents the search time on a single list. All of them were produced by one subject in a ten-minute session, working on one problem. He simply scanned down each list until he came to a "Z". Actually, our subjects always scan 20 lists in each problem, but the first six are considered practice. From the subject's point of view, the different possible positions of the critical item occur at random, so he cannot predict in advance where his scan will end. Actually, the six practice lists always have critical items in positions 5, 6, 25, 30, 45, and 46, and the 14 lists to be used in determining T/I have their critical items in positions 9, 11, 14, 16, 19, . . ., 39 and 41. The order of presentation is randomized separately for the practice lists and the experimental lists. Thus, while the subject is kept alert to the possibility of finding the item near the very top or bottom of the list, these extreme positions are not used in the analysis of the data. There is good reason to suppose that departures from linearity will occur at the extremes, especially at the beginning.

The straight line in Figure 2 has been visually fitted to the points. It is a representative example of the extent to which our data approach linearity. The fit is generally good enough so we feel justified in treating the average time per item scanned (T/I) as a meaningful quantity, which can be directly determined from the slope of the line. (We do not imply that each item is separately fixated or processed. Even if the subject treats them in groups, T/I remains a valid measure for the comparison of scanning time across different types of lists.)

The types of logical processing that can be explored with this method include any abstractions whatever that can serve to distinguish one item in such a list from all the others. The presence of a particular letter is merely an example. The experimenter may require the presence of either of two letters, or of both, or of a particular sequence. The critical feature can also be the absence of a letter or of some logical combination of letters. In every case, the T/I being measured is for the opposite of the function being sought by the subject. If he is looking for a "Z", then all the items he scans contain no "Z", and T/I reflects the time necessary to make certain that "Z" is absent. If he is looking for the absence of "Z", each of the items scanned necessarily contains one, and T/I measures the time necessary to process it.

Procedure and Results

The present paper is a report of an exploratory experiment with this method of time-analysis. Three subjects were systematically given a variety of functions, using items of two different lengths. Although the sample is small, the results seem consistent enough, and informative enough, to justify a preliminary report. Further work is in progress to check on the findings of this study.

The design of the experiment included seven different functions, or problems. Three were positive, in the sense that the subject was looking for the first occurrence of something. These functions were "Z", "Q", and "ZvQ". In the last of these, the critical item was defined by the first appearance of either "Z" or "Q" or both together. (The "or" lists were so constructed that each type of critical item actually occurred in approximately one-third of the twenty lists.) In addition to these positive functions, we studied four others that were negative or mixed. These were "-Z", "-Q", "-ZvQ", and "Zv-Q". In the first two the subject scanned down items containing the letter in question until he found one without it. In the last two, the critical item might be distinguished either by the absence of some letter (that all the others had), or by the presence of another (that no other item had), or by both.

These seven functions were realized in two sets of lists. In one set, each item was six letters long; in the other, each had only two letters. The seven functions and two lengths yielded 14 experimental conditions. The subjects went through two conditions (i.e., scanned forty lists) at a session, which took about half an hour. The first two sessions were devoted to practice with varying types of lists. Thereafter, each subject worked in each condition twice. To control for the effects of order and practice, the 14 conditions were first given in a certain order (different for each subject) and then repeated in reverse order. The results have been plotted, and slopes calculated for the best-fit lines.

The lists were prepared by an IBM 7090 computer, and printed on an ANELEX. In preparing the lists, the computer program formed random permutations of the letters J, P, Q, S, T, V, X, Z, and examined the last six (or two) places of the permutation to see if it was an example of the desired function (e.g., if it contained "Z"). The program prepared randomly ordered lists of non-examples, inserted proper examples into the chosen list-positions, and prepared an appropriately spaced printout. The printout was cut into separate lists and pasted on to 2 x 11 cards for experimental use. An apparatus was constructed in which such a card fit under a spring-loaded door. When the door was opened by the experimenter, a timer was initiated which continued to run until the turn of the subject's switch indicated that he had found the critical item. Occasionally he overlooked it, and scanned to the bottom of the list. These trials were discarded, and the same list was re-used later in the same session.*

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The results of the experiment are displayed in Table 1. The internal consistency of the data is good, for the most part. The two replications of each condition usually yield very similar values of T/I, although two of the subjects (LS and MA) show distinct improvement with practice, with the second run generally faster than the first. The important trends can be summarized as follows:

1) "-Q" is slower than "Q"; "-Z" is slower than "Z".
2) In the positive functions, "Z" is slower than "Q".
3) 2-letter items can be scanned more quickly than 6-letter items.
4) "QvZ" takes no longer than does "Z" alone.
5) With two letters, the negative and mixed functions are all equally fast.
6) With six letters, the negative and mixed functions vary in difficulty.

Conclusions

1) In scanning for "-Z", the subject must make sure that each item he passes does contain a "Z". The recognition sub-system, or recognizer, for "Z" must be fully activated each time, and the high values of T/I reflect this requirement. In the positive function, by contrast, the Z-recognizer is not fully activated until the critical item is reached. However, the subject must scan slowly enough so that this recognizer could react with the proper input. In other words, the shape-recognizers which distinguish between "Z" and other letters must have time to act. The observed time-difference between positive and negative functions may be assumed to correspond to the different levels in the processing hierarchy which they require. The positive functions need only enough time for such recognizers as (for example) "paired horizontal lines" or "angle near top". The negative functions must have time enough for, say, "Z" itself to receive its input from such features and then to react. Perhaps we are justified in saying that any artificial pattern recognizing system, if organized in parallel, would display these time differences.

2) The two-level hierarchy becomes more articulate when we consider the difference between "Z" and "Q". Why should some letters be harder to find than others? Evidently, identification of "Z" involves different features of the visual stimulus than identification of "Q", and processing the latter is easier than the former. Without direct knowledge of the critical properties, we can only speculate about the reason. Perhaps the shape-recognizers involved with "Z" are themselves hierarchically deeper than those for "Q". Perhaps it is only that more attributes of shape must be examined for "Z", but we shall see later (No. 4, below) that this might not require an increase in time.

It would be hazardous to suppose that the letter "Q" is intrinsically easier to see than "Z". The context of alternative letters must play an important part. The shape-recognizers that suffice to distinguish "Q" from J, P, S, T, V, X, and Z might not be adequate in a context that included C, D, G, and O. The processing system must be expected to change with the context, and T/I will also change. We are now conducting an experiment to explore this point.

3) At first thought, it seems entirely reasonable that six letters should take longer than two. After all, each item contains substantially more information in the 6-letter case. Yet it would be easy to build a 6-channel device that would handle both cases with equal speed. It follows that the subjects are not acting like such a device; they do not process all the letters in parallel. There is no immediately clear reason why they should not do so. The entire six letters subtend a visual angle of less than 5^{o}, and can easily be read in a single fixation. Thus, the visual information can all get to the cortex simultaneously. (Experiments now in progress confirm that the actual number of letters, and not their spatial separation, is the important variable.) We conclude that, at least under some circumstances, the shape recognizers can not be applied simultaneously in different regions of the visual field. On the other hand, their application is probably not simply successive; T/I does not triple as we go from two letters to six. Pending further research, we can only state that fully parallel operation, at least, is not the rule for spatially separate inputs.

4) On the other hand, the clear-cut results with "QvZ" show that fully parallel operation can be achieved among various shape-recognizers acting on the same input. There can be no doubt that the system examines different features of the stimulus pattern in looking for "Q" than for "Z", but the examination uses no extra time. It follows that different elementary figural properties can be processed simultaneously.

In a projected experiment, we will examine "or" functions of more than two variables, such as "QvPvXvZ". One wonders whether there is an effective upper limit to the number of parallel searches which can be carried on. It seems at least possible that there is no such limit. The question can be referred to a common experience: anyone can scan a crowd to see if it contains a familiar face. Does scanning time increase with the number of recognizable acquaintances we have made in the past?

5) The equivalence of the T/I values for all the negative and mixed functions in the two-letter case seems paradoxical at first. We would have at least expected "-Q" to differ from "-Z". A look at the list themselves explains the paradox, however, and emphasizes the great flexibility of organization which characterizes human pattern recognition. In "-Z", as in "-ZvQ", each item except the critical one contains a "Z".* Since the items are but two letters long, the "Z" in any item has a 50-50 chance of lying exactly underneath the "Z" in the preceding item. The visual effect is the formation of short and long <u>columns</u> of "Zs", shifting haphazardly between the <u>left and</u> the right sides of the list. The subjects commented spontaneously that they handled these lists differently from the others, following these columns with their eyes without heeding the horizontal structure of the items at all. Essentially, they were using different shape-recognizers. The features that distinguish "Z" from other letters in a row are not the same as those which mark the continuity of a column of "Zs". The column-continuity features of "Z" seem to be no different, or at least no more complex, than those for "Q".

This result, more than any other, emphasizes the extraordinary adaptiveness of human information processing. It is unlikely that any artificial device we will know how to make in the near future will be as efficient in taking advantage of the vagaries of its environment.

6) The remaining results are not easy to interpret. The T/I for "-QvZ" is much longer than the model we have been using would predict. We would have expected it to be near the value for "-Q".

In summary, we have presented a rough model of human information processes, a method for studying these processes in detail, and some preliminary data obtained by the method. The model is simply a hierarchical organization of specialized subsystems, called "recognizers"**, which effectively abstract certain features from their input. The method consists of measuring the average time needed to process successive items of a list that is being scanned for some particular characteristic. The data suggest that different elementary recognizers have different operating times; that different recognizers can operate simultaneously on the same input; that spatially distinct parts of the input cannot be handled entirely simultaneously; and that the processing hierarchy can be flexibly adjusted to meet the demands and opportunities of the task.

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*In the case of the function "-ZvQ" the critical item itself may also contain a "Z" (if it contains a "Q"). However, this does not substantially change the present argument, though it suggests that the subjects can check for the presence of a "Q" simultaneously with tracking the columns of "Zs".

** The model is a version of Selfridge's "Pandemonium", in which the subsystems were called demons.

Z

XVSJTQ
TXSVQP.
XPTQJV
PTQSXV.
PJSXQT
QJVXSP.
PVQTSJ
SVQPXJ.
TXQSJV
XSTPQV.
JSXQPT
QVXPTS.
PSQVTX
JTXSQV.
ZVJPXQ
XQVJSP.
QJVXTP
QJTSXP.
XQPJST
VJSPTQ.
XJVQSP
PXJTQS.
PXJSTQ
QSTJVP.
PJVSTQ
TJQSPV.
VQXJST
XQVSPT.
JQVSTX
VSJPXQ.
XPJVQS
PTJSXV.
PSQVTJ
VPTJQX.
PTSVJX
SQXTJP.
SJVPTX
QTVPJX.
PVXSTQ
PVQJSX.
JVQPSX
PJVXTS.
TQPXJV
XPVJSQ.
SXVTQP
TSQXVJ.
VXPSJQ
PXJTSV.
JXTVPQ
XVPQTJ.

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C54-44

FIG. 1

A-13211 2-27-61 McKeon Slide NEISSER A-13211

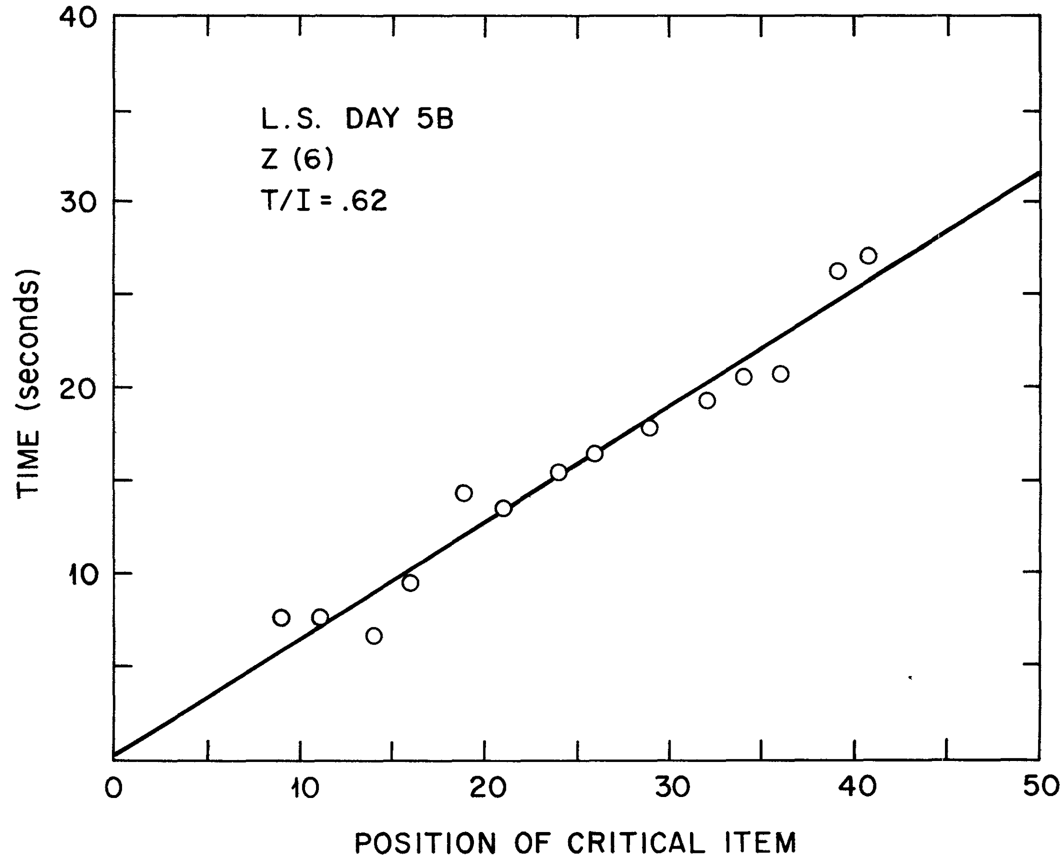

FIG. 2

C54-45

Length:	two letters				six letters			
Subjects:	SS	LS	MA	mean	SS	LS	MA	mean
Function								
Q	15	13	07		20	16	11	
	14	06	06	(10)	14	13	08	(14)
Z	23	31	19		38	62	60	
	26	22	17	(23)	70	49	51	(55)
QvZ	24	22	20		52	86	59	
	25	20	16	(21)	47	44	51	(57)
-Q	34	35	33		36	68	46	
	32	28	28	(32)	30	60	36	(46)
-Z	34	36	40		56	96	73	
	30	34	26	(33)	60	88	52	(71)
-ZvQ	30	39	28		60	96	90	
	32	37	33	(33)	68	98	58	(78)
-QvZ	34	32	28		132	104	75	
	36	47	28	(34)	95	82	66	(92)

Table 1. T/I as a function of experimental conditions and subjects. Replications appear with the second beneath the first. Times are in hundredths of a second. Each mean is based on the six figures to the left of it.