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ПЕРЕРАБОТКА ЗРИТЕЛЬНОЙ ИНФОРМАЦИИ И РЕГУЛЯЦИЯ ДВИГАТЕЛЬНОЙ ДЕЯТЕЛЬНОСТИ
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PARALLEL TESTING OF STIMULI IN VISUAL SEARCH

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This paper is concerned with how people process information during visual search. Suppose that a person is searching through a list of letters or digits, looking for one or more target characters. For each stimulus in the list, the person must decide whether it is a target. If he decides that it is one of the targets, he makes a response and stops searching; if he decides that it is not a target he makes no response and continues the search. The aim of our work was to discover how his decisions are arranged in time.

One reason this problem is of interest is that visual search is remarkably fast. The rate at which the total search time to find a target increases with the number of stimuli searched gives the search time per stimulus. This can be 100 ms or less. On the other hand, if we present a single stimulus we find that the reaction-time for determining whether or not it is a target might be about 500 ms. Some of this 500 ms, of course, is the interval between the internal decision and the overt motor reaction itself. But that interval cannot be large enough to account for a difference between 500 and 100 ms. Our problem is how to reconcile these two values. Our answer is that the high speed of visual search may be possible because decisions about several different displayed stimuli can be made at the same time.

Let us begin by considering the process of making a decision when there is only a single stimulus. When he is shown a single stimulus-character, how does a person decide whether it is one of a set of target characters? The procedure in some earlier experiments (Sternberg, 1966, 1969) is shown in Fig. 1*A*. First, the subject memorized a set containing *s*

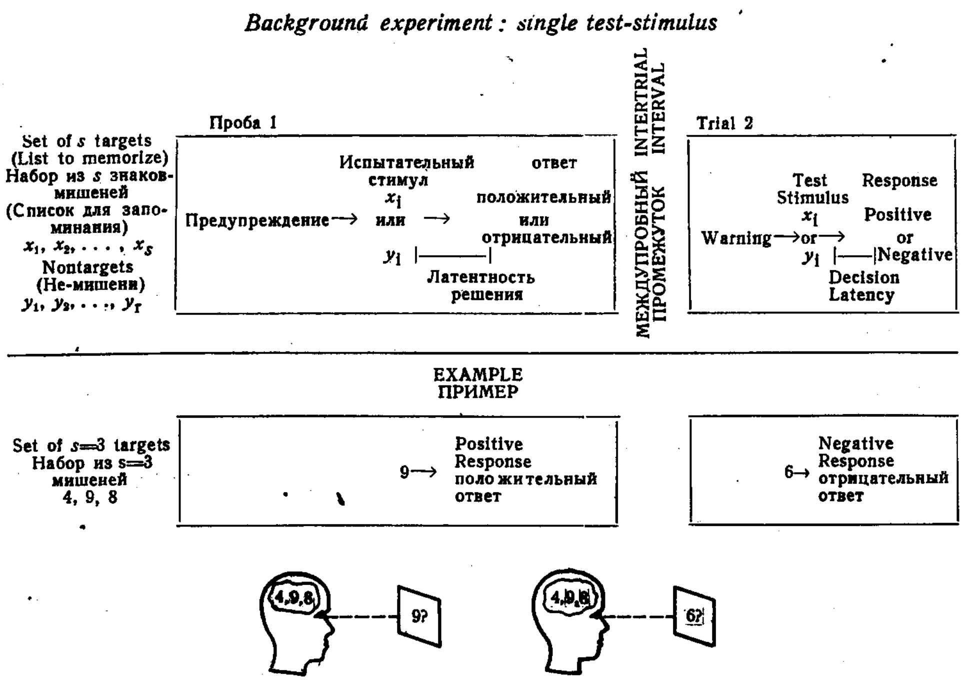


Fig. 1 *A*

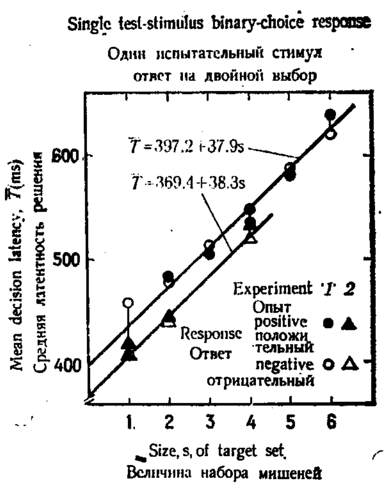


Fig. 1 *B*

target numerals. After memorizing the targets, the subject had a series of test trials, two of which are shown. On each trial, after a warning signal, he saw a stimulus numeral that was either a target or a non-target. If it was a target, he had to make a positive response by pulling a lever with one hand; otherwise he had to pull a second lever with his other hand, to make a negative response. Subjects were instructed to respond as quickly as they could, and to make few errors.

We measured the time between the presentation of the stimulus and the manual response. This includes the time to make the decision, as well as the time for the motor response. For simplicity we shall call it the *decision time* or decision latency.

In the example shown, the subject memorizes a set of three targets, consisting of the numerals 4, 9 and 8. If the test-stimulus is a 9, the subject is required to make a positive response by pulling one lever. If the test-stimulus is a 6, he is required to make a negative response by pulling the other lever.

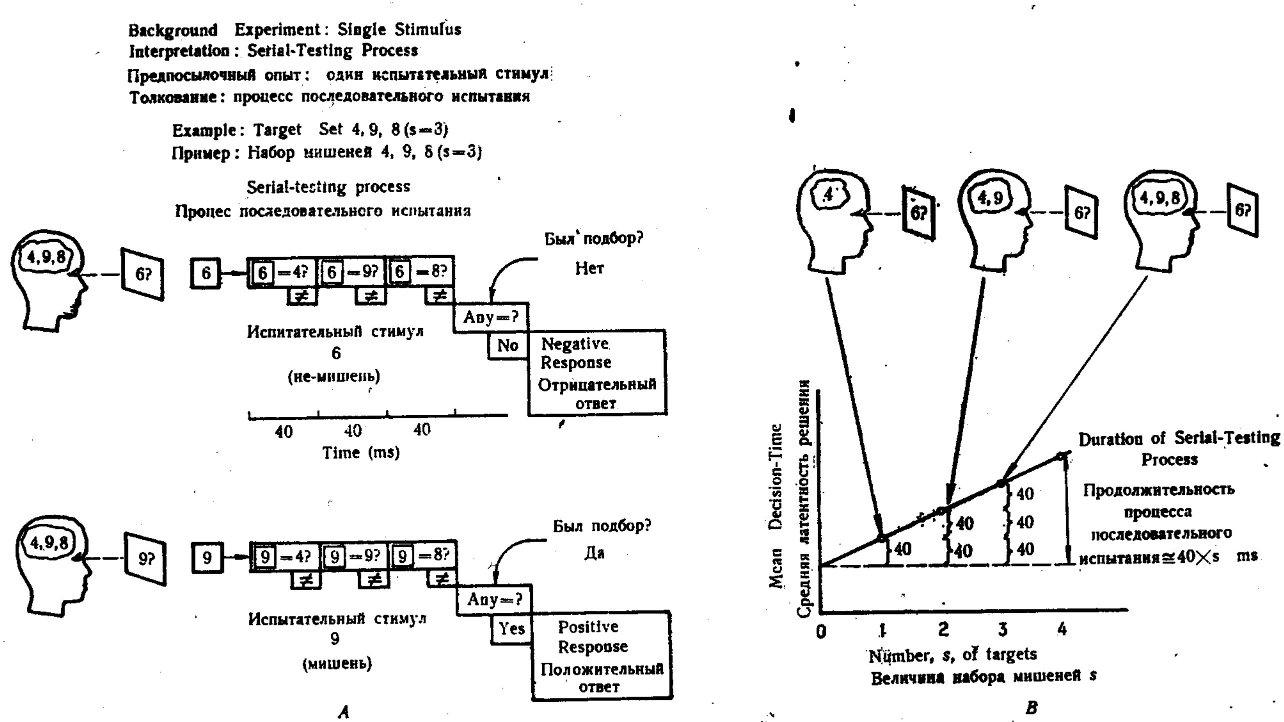
Results from two experiments of this kind are shown in Fig. 1*B*. Mean decision-time in ms is plotted as a function of the number of items in the target set. In the experiment, shown by circles, the target set contained from one to six items. In the experiment shown by triangles, the target set contained one, two or four items. Times for positive decisions are shown by *filled* circles and triangles; times for negative decisions are shown by *open* circles and triangles. A line was fitted by least squares to the mean times in each experiment.

The data have three important features. First, the decision-time increases linearly with the number of items in the target set. Second, the times for positive and negative decisions increase at the same rate. And finally, the rate of increase is about 40 ms for each added target.

The interpretation of these findings is shown in Fig. 2. In the course of both positive and negative decisions, the stimulus is tested against each of the memorized targets, one at a time. We call this a *serial-testing process*. When serial-testing has been completed, a further internal process ascertains whether there was a match between the stimulus and any of the targets. If there was a match, a positive response is made. Otherwise, a negative response is made. In the example in Fig. 2*A*, the target set contains 4, 9 and 8. If the stimulus is a 6, the 6 is tested against 4, 9 and 8, one after the other. Then it is found that no match occurred, and a *negative* response is made. If the stimulus is a 9, it is tested against 4, 9 and 8 in the same way. But then it is found that a match *did* occur, and a *positive* response is made. Since the mean duration of each test in the serial-testing process is about 40 ms, the process takes 40×3, or 120 ms.

The way decision-time varies with the number of targets is shown in Fig. 2*B*. The duration of the serial-testing process for a specified number of targets is given by the distance on the ordinate between the zero-intercept of the decision-time function, and the point on that function for the specified number of targets. It is important to note that in this kind of decision, the testing process appears to be as thorough for stimuli that are non-targets as for those that are targets, since the times for positive and negative decisions increase at the same rate. That is, the decision that a stimulus is a target does not depend on more processing than the decision that a stimulus is *not* a target.

Now let us return to visual-search, in which there are many stimuli. Consider a subject searching through a list of numerals for any one of a set of five target numerals. The subject must make a negative decision



Background Experiment: Single Stimulus
Interpretation: Serial-Testing Process
Предпосылочный опыт: один испытательный стимул
Толкование: процесс последовательного испытания
Example: Target Set 4, 9, 8 (s=3)
Пример: Набор мишеней 4, 9, 8 (s=3)
Serial-testing process
Процес последовательного испытания
4,9,8
6?
6
6 =4? 6 =9? 6 =8?
≠
Any=?
No
Был подбор?
Нет
Negative Response
Отрицательный ответ
Испытательный стимул 6 (не-мишень)
40 40 40
Time (ms)
4,9,8
9?
9
9 =4? 9 =9? 9 =8?
≠
Any=?
Yes
Был подбор?
Да
Positive Response
Положительный ответ
Испытательный стимул 9 (мишень)
A
4
4,9
4,9,8
6?
Mean Decision-Time
Средняя латентность решения
40
Duration of Serial-Testing Process
Продолжительность процесса последовательного испытания ≅ 40×s ms
0 1 2 3 4
Number, s, of targets
Величина набора мишеней s
B

Fig. 2

about each stimulus he sees, until he finds a target. We have seen that for a single stimulus such a decision includes a serial-testing process; for 5 targets this process takes about 200 ms. Yet Neisser et al. (1963) have shown that after a little practice, subjects can search for five targets at average rates closer to 100 ms per stimulus. With more practice, search becomes even faster. The question we asked, then, was how can visual search be so fast that the search-time per stimulus is shorter than the duration of the serial-testing process for a single stimulus. Neisser has suggested that a serial-testing process is not used in visual search (1963, 1967). Instead, each stimulus is tested against all targets at the same time. (This is illustrated at the top of Fig. 4*A*.) In other words, he proposes that the testing process in visual search is different from the testing process in the single-stimulus experiment. Another possibility, however, is that each stimulus is tested serially, just as in the single-stimulus situation, but that the serial-testing process for one stimulus can occur in parallel with the serial-testing process for another. (This is shown at the bottom of Fig. 4*A*.)

Since the time of Cattell (1885) it has been known that some of the processing of one stimulus can occur at the same time as the processing of another. Cattell allowed a subject who was naming a series of letters to see a new stimulus before he completed his response to the preceding stimulus. He found that with this kind of preview, the rate of responding increased. Preview permits the subject to begin processing one stimulus before he has completed the processing of another. Chase (1969) has recently shown that visual search is speeded by increasing the amount of preview. These findings lead to the general question of which steps in the processing of different stimuli can occur at the same time. The purpose of our research was to find out whether the testing process for one stimulus can occur at the same time as the testing process for another, during visual search.

To answer this question it is important to measure not only the search time per stimulus, but also the decision time, that is the time from when the subject first sees a stimulus to his response or to his decision about that stimulus. But typical methods for the study of visual search make it difficult to measure the decision time, because the time of input of a stimulus, which is determined in part by the subject's eye movements, is hard to measure. To solve this problem and control the timing of stimuli, we devised a procedure called simulated-search, in which a subject sees stimuli presented one after another (at regular intervals) in one location. The interval between successive stimuli in the simulated-search procedure corresponds to the search time per stimulus in the usual search task.

The paradigm is as follows: The subject first memorized 1, 3 or 5 target numerals. Then, on each trial he saw 20 stimulus numerals, one after another, in the same location, at a rate of 14 stimuli per second. On one third of the trials, the sequence contained no target numeral. On two thirds of the trials there was one target numeral at a random position in the sequence. The subject's task was to respond by pulling a lever as quickly as possible if a target appeared, and to make no response otherwise. On trials on which the sequence contained one of the targets, we measured the time from the appearance of the target stimulus to the subject's response, which gave us the time for a positive decision.

Fig. 3*A*, which shows a single trial on which a target numeral was presented, will make the procedure a little clearer. Time proceeds from left to right. Each rectangle represents one of the twenty successive stimuli. Each stimulus was a numeral, presented for 15 ms. The time between

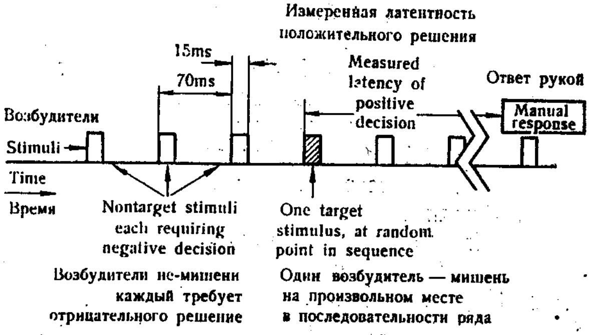


Fig. 3*A*

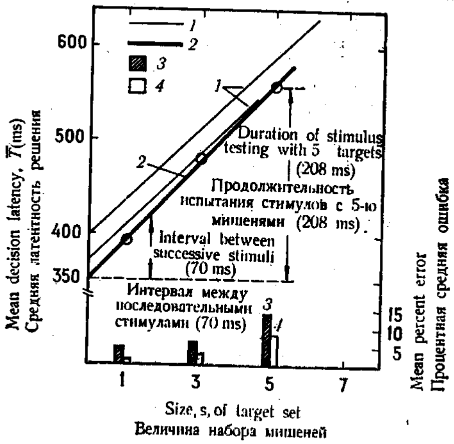


Fig. 3*B*

1 — Single test—stimulus, один испытательный стимул ; *2* — simulated search I=351 1+41,5 s, условный поиск ; *3* — Wrong positives, неправильные утверждения ; *4* — wrong negatives, неправильные отрицания

successive stimuli was 70 ms. Each of the non-target stimuli required a negative decision, but not an overt motor response. However, the target stimulus did require an overt response, and this gave us a measure of the time for a positive decision.

There were four subjects in our experiment on simulated search. Each had about 30 practice trials and 60 test trials with sets of 1, 3 and 5 targets. Results are shown in Fig. 3*B*. The top of the figure shows the mean time for positive decisions as a function of the number of targets. The light lines come from the previous experiments with a single test-stimulus. The circles and the heavy line come from the simulated-search experiment. The time for a positive decision grows linearly with the number of targets, at a rate of about 40 ms. per target. The agreement between experiments is excellent, showing that the same serial-testing process underlies the positive decisions in both experiments. Because negative decisions are not converted into responses in the simulated-search task, we did not measure their times. For negative decisions, therefore, we cannot make a direct comparison with the single-stimulus experiment. But that is not necessary. All stimuli are tested by the same serial-testing process, since it is not until this process is completed that a stimulus can be classified as either positive or negative. What we have discovered, then, is that the same serial-testing process is used for stimuli in both the single-stimulus experiment and the simulated-search task.

Let us examine some other aspects of the results. One vertical arrow in Fig. 3*B* shows the interval between successive stimuli, namely 70 ms. Another vertical arrow shows the duration of the stimulus-testing process for five targets, namely 208 ms, which is three times as great. Note that for conditions with three targets, and those with five, stimulus-testing takes longer than the interval between stimuli. At the bottom of the figure is shown the mean per cent of errors. The important thing to remember here is that even in the most difficult condition, the average rate of error did not exceed about 10 %.

Fig. 4*B* will help in summarizing the implications of this work. It shows a classification of models for visual search. First, the testing process used for each stimulus in the search task might be different from that used in the single-stimulus experiment, or it might be the same. We have already concluded that it is the same. Second, the testing of successive stimuli might occur sequentially or in parallel. We noted that the testing process takes longer than the time between successive stimuli. This suggests that the testing of different stimuli might occur in parallel. Suppose that testing does not occur in parallel. One possibility is that the subject would fall further and further behind the stimulus sequence in his testing of stimuli. The decision latency would increase with the serial-position of the target numeral in the sequence. With five targets in our experiment this would produce an average time lag of about 2 seconds. But decision latencies were much shorter than this, and they did not increase systematically with the serial position of the target numeral in the stimulus sequence. A second possibility is that the subject would keep up with the stimulus sequence, but would simply fail to test any stimulus that appeared while he was testing another. This would produce a high rate of error — about 40 % with 5 targets. But the rate we observed was only about 10 %. We are left with the conclusion illustrated at the bottom of Fig. 4*B*: In the simulated-search task each stimulus is tested serially against the items in the target set. But this testing process occurs in parallel for different stimuli.

This conclusion has some methodological implications. If we are interested in understanding the decisions made about individual stimuli in the course of visual search, then the rate of search, or the search time per stimulus, may not be very useful. For example, if the rate of visual search in an experiment is limited by input factors such as eye movements, it

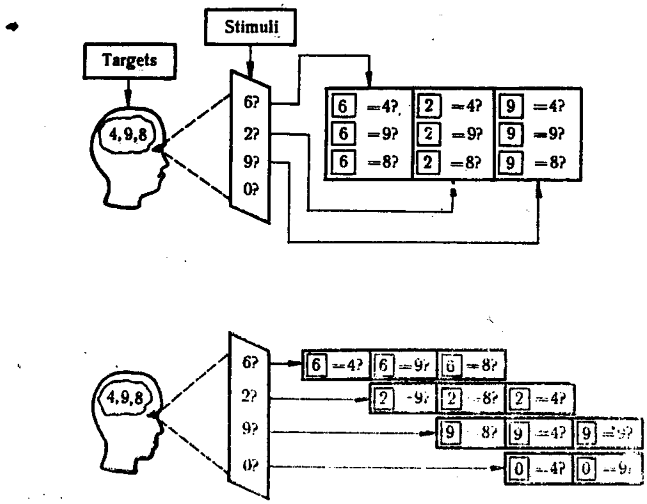


Fig. 4 *A*

Some possible models for visual search

Некоторые возможные модели зрительного поиска

Testing process different from single-stimulus experiment

Испытательный процесс, иной чем в опыте с одним возбудителем

Serial testing process for each stimulus as in single-stimulus experiment

Процесс последовательного испытания для каждого стимула как в опыте с одним возбудителем

Testing of different stimuli does not occur in parallel

Испытание различных возбудителей не происходит параллельно

Testing of different stimuli does occur in parallel

Испытание различных возбудителей происходит параллельно

Cumulative lag (average 2 s when 5 targets)

Общая задержка (в среднем 2 s при 5-ти мишенях)

High error-rate (about 40% when 5 target)

Большая частота ошибок (приблиз. 40 процентов при 5-ти мишенях)

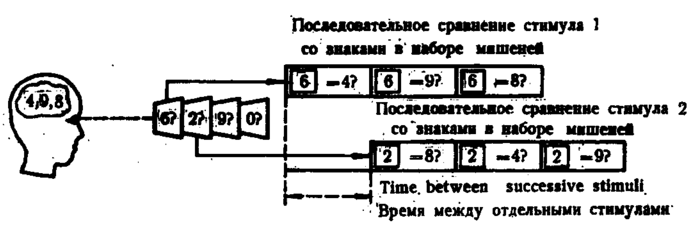


Fig. 4 *B*

might not respond at all to factors influencing the decision-time. In this case the search rate might reveal nothing about the decision process.

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ПАРАЛЛЕЛЬНОЕ ИСПЫТАНИЕ СТИМУЛОВ ПРИ ЗРИТЕЛЬНОМ ПОИСКЕ

С. СТЕРНБЕРГ, Д. Л. СКАРБОРО

(Резюме)

Зрительный поиск можно понимать, как принятие положительного или отрицательного решения для каждого из ряда стимулов, представляемых зрению движением глаз по набору объектов. Обыкновенно измерению подвергается влияние изменений задачи на скорость поиска, или (что представляет больший интерес) на обратную ей величину — интервал между стимулами (Neisser, 1963). Чтобы лучше понять природу положительных и отрицательных решений, а также их временных соотношений, полезно знать, каким образом изменения задачи влияют на латентность решения — время от момента стимула до заключения решения. Однако при широко употребляемых приемах для изучения зрительного поиска латентность решения измерить трудно, так как момент стимула определить непросто.

В настоящей работе мы пытались устранить это затруднение путем построения задачи условного поиска. При каждой попытке, двадцать знаков представлялись последовательно с большой скоростью на определенном месте. Испытуемые просматривали эти ряды, чтобы обнаружить присутствие в них распознавательных знаков из набора от одного до пяти таких знаков-примет. Не более одного распознавательного знака содержалось в показном ряду. Отрицательные решения были скрыты, а при появлении распознавательного знака испытуемый должен был как можно скорее проявить открытый ответ, соответствующий положительному решению. Правильность и латентность решения измерялись как функция величины приметного набора.

Увеличение набора от одного до пяти приводило к увеличению латентности положительного решения на 150 ms, т. е. к изменению, значительно превышающему промежуток между стимулами (прибл. 70 ms). Но ошибок было мало.

Подобные результаты были получены и раньше, когда при каждой попытке показывался один знак (Стернберг, 1966), и было найдено, что латентность отрицательных решений относительно единственного стимула увеличивается с увеличением численности набора так же, как и положительных, и что возрастание латентности решений отражает продолжительность стадии, в которой распознавательные приметы памяти последовательно сравниваются со стимулом.

Таким образом следует, что если в условной распознавательной задаче численность приметных знаков велика, то стадия испытания каждого стимула, в продолжение которой данный стимул сравнивается с приметным набором, длится не менее 150 ms. Поскольку такая длительность стадии сравнения значительно превышает промежуток между стимулами и в то же время правильность решений указывает на отсутствие частых пропусков, то стадии сравнения отдельных стимулов должны перекрываться во времени. Простейший образ этого явления состоит в параллельном сравнении двух или нескольких стимулов с каждой приметой.

PARALLEL TESTING OF STIMULI IN VISUAL SEARCH

S. Sternberg & D. L. Scarborough

English Translation of Russian Summary

Visual search may be thought of as the making of a positive or negative decision for each of a series of stimuli which the subject presents to himself by moving his eyes over an array. It is usual to measure how task variations influence the search rate or, more interestingly, its reciprocal, the interstimulus interval (Neisser, 1963). In understanding the nature of the positive and negative decisions, and their temporal relations, it is also helpful to know how task variations influence the decision latency--the interval between the input of a stimulus and the occurrence of the decision. But typical methods for studying visual search make decision-latency measurements difficult, since the time of input of a stimulus is hard to determine.

In this study we tried to overcome this difficulty by constructing a simulated-search task. On each trial, 20 characters were displayed serially, in a fixed location, and at high speed. Subjects monitored such displays for the presence of any member of a set of from one to five target characters. At most one target was contained in the serial display. Negative decisions were covert, but if a subject saw a target he was to make an overt response, corresponding to a positive decision, as quickly as he could. Accuracy and decision latency were measured as a function of the size of the target set.

Increasing the size of the target set from one to five caused an increase of about 150 msec. in the positive-decision latency, a change substantially greater than the interstimulus interval (of about 70 msec.). Yet there were few errors.

Data with these features have been obtained in previous research in which a single character was displayed on each trial (Sternberg, 1966). That research also showed that the latency of negative decisions concerning a single stimulus grows as fast with set size as the latency of positive decisions, and that the increase in decision latency reflects the duration of a stage of processing in which the targets in memory are compared serially to the stimulus.

It follows that when the target set is large in the simulated search task, the stimulus-testing stage associated with each stimulus, during which it is tested against the set of targets, has a duration of at least 150 msec. Since the duration of the testing stage is therefore much greater than the interstimulus interval, and since the high accuracy implies that few stimuli are missed, the testing stages of different stimuli must overlap in time. The simplest arrangement that accomplishes this is one in which more than one stimulus is tested in parallel against each target.

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