SIMULTANEOUS vs. SUCCESSIVE RESPONSE SELECTION:
A STUDY OF ATTENTION AS THE LIMITING MECHANISM

by

Marilyn Chapnik Smith
B.A., University of Toronto
(1963)

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF DOCTOR OF
PHILOSOPHY

at the
MASSACHUSETTS INSTITUTE OF
TECHNOLOGY
June, 1966

Signature of Author

Department of Psychology, May 6, 1966

Certified by

Thesis Supervisor

Accepted by

Chairman, Departmental Committee
on Graduate Students
Simultaneous vs. Successive Response Selection:
a study of attention as the limiting mechanism

Marilyn Chapnik Smith

Submitted to the Department of Psychology on May 6 in partial fulfillment
of the requirement for the degree of Ph.D.

This study was concerned with the conditions under which response
selections occur sequentially or in parallel. The problem was explored
by studying the reaction time (RT) to two visual stimuli which were
presented simultaneously or in rapid succession. Using such a procedure
it has typically been found that the RT to the second stimulus (RT₂)
is prolonged. This delay suggests the presence of a limiting mechanism in
the system, and various theories have been put forward to explain the nature
of this mechanism. These theories are reviewed in Chapter I.

One possible explanation for the delay in RT₂ is the presence of a
limited capacity attention mechanism which is required to initiate response
selection, and which can initiate only one such selection at a time. Two
models which could describe the nature of such an attention mechanism are
considered. According to a fixed interval model, attention switches to the
second response selection at a fixed interval following the initiation of the
first selection. Thus, while the initiation of the second response selection
is delayed, the selection of both responses can proceed simultaneously.
A successive response selection model, on the other hand, holds that the
attention switch cannot occur until the first response has been selected, so
that all selections must occur sequentially. These models were examined in
Chapter II, and it was found that a successive response selection model best
described the operation of the attention mechanism. Attention appears to
switch after the performance of the first response. It was estimated that
the attention switching process occupies about 100 ms.

If attention is the limiting mechanism, then response selections which
are highly practiced and proceed without selective attention should be able
to occur in parallel. In Chapter III it was found that parallel processing
appeared to occur in a situation with high stimulus-response compatibility.
It was suggested that if the choice RT to a stimulus is not influenced by
the number of response alternatives, then selective attention is not operative
during the response selection.

The experiments provided support for the hypothesis of a limited
capacity attention mechanism as a limiting factor in information processing.

Thesis Supervisor: Wayne A. Wickelgren
Title: Assistant Professor of Psychology
Table of Contents

| Acknowledgements                             | 4 |
| Biographical note                            | 5 |
| Chapter I A review of the psychological refractory period phenomenon | 6 |
| Chapter II Two models of attention as a limiting mechanism in response selection | 29 |
| Experiment I                                 | 34 |
| Experiment II                                | 49 |
| Chapter III Stimulus-response compatibility and parallel response selection | 55 |
| Experiment I                                 | 56 |
| Experiment II                                | 61 |
| Bibliography                                 | 68 |
| Tables                                       | 71 |
| Figure captions                              | 82 |
| Figures                                      | 83 |
Acknowledgements

I am indebted to the members of my thesis committee, Wayne A. Wickelgren, Hans-Lukas Teuber and Peter H. Schiller whose guidance, encouragement and constructive criticism have been of great value to me in this undertaking. I am especially grateful to Professor Wickelgren, my thesis advisor, who gave unstintingly of his time and effort.

These persons, however, are not responsible for any errors in the dissertation, nor do they necessarily concur with the methods or accept the conclusions of this study.

Research funds were provided by a fellowship granted by the Massachusetts Institute of Technology, and by a National Institute of Mental Health grant, number MH 08890-02.

Finally, I thank my parents for their encouragement throughout the years, and my husband whose patience, interest and understanding have been invaluable to me.

Marilyn C. Smith

Cambridge, Mass.

May, 1966.
Biographical Note

The author was born in Toronto, Ontario on March 15, 1942. She attended the University of Toronto from 1960 to 1963, where she received her B.A. degree. From 1963 to 1966 she studied in the psychology department at the Massachusetts Institute of Technology. Three articles were published with Peter H. Schiller during this period. These articles are: Detection in metacontrast, in the Journal of Experimental Psychology; Forward and backward masking: a comparison, in the Canadian Journal of Psychology and A comparison of forward and backward masking, in Psychonomic Science.
Chapter I

A review of the Psychological Refractory Period phenomenon

When two stimuli are presented simultaneously or in rapid succession, the reaction time (RT) to the second stimulus is typically prolonged compared with the RT to that stimulus when it is presented alone. This increase is maximal at the shortest inter-stimulus interval (ISI), and declines as the ISI is increased until at some value of ISI no further delay is encountered. This phenomenon has been studied using both continuous and discrete responses. Continuous responses usually are required in a tracking task, where \( S \) must keep his pencil on a moving target, and measurement of the delay in responding to changes in the direction of movement of the target is possible. Discrete responses are those most typically used, where \( S \) has two keys before him, and is told to press one key when the first stimulus comes on, the second key when the next stimulus comes on. In both cases, it is possible to vary the interval between the stimuli, hence varying the interval between the required movements.

The delayed second RT (RT\(_2\)) suggests the presence of a limiting mechanism in the processing system, and various theories have been put forward to explain the nature of this mechanism. In this review, we shall attempt to state the various theories which have been proposed, and then examine their validity on the basis both of experimental findings and of logical consistencies. Because they are ad hoc theories, based on the finding that RT\(_2\) declines as the ISI increases, they all "predict" this particular finding. Consequently, the various hypotheses must be judged on the basis of their other predictions.

General Method

The method typically employed by experimenters examining this phenomenon is quite similar in all the studies. Subjects face a visual array
which consists of two light sources, one on the left and one on the right. Their left forefinger rests on one telegraph key, their right forefinger on another, and they are instructed to press the left key when the left light comes on, and the right key when the right light comes on. The ISI between onset of the two lights, and hence between the required responses is systematically varied. Occasionally, auditory stimuli are used rather than visual stimuli. Ss are instructed to respond to each stimulus as rapidly as possible. Unless otherwise stated, this is the method employed in the experiments described below.

Proposed Theories

The explanations employed may be placed into three general categories. First, there is the theory that there is some physiological inhibitory effect of the first stimulus \(s_1\) upon the second \(s_2\) -- the Psychological Refractory Period theory.

The second group of theories attribute the delay in \(RT_2\) not to the influence of the first stimulus, which is considered to play the role of a warning signal initiating the foreperiod before presentation of the second stimulus, but to S's preparatory state, which is influenced by the values of ISI employed. These are referred to as Preparatory State theories.

The final theoretical position is that somewhere in the arc of perception - response selection - response performance, there is a "single channel" which cannot process both stimuli simultaneously, with the result that the second stimulus must be "held in store" until after the processing of the first. These are the "Single Channel" theories.

We shall now turn to a closer examination of these hypotheses.
I Psychological Refractory Period Theory

The earliest explanation of the observed delay in the second response was put forward by Telford (1931), who appears also to have been the first to report this phenomenon. Telford postulated that following some event in the chain of processes leading from the reception of the signal to the responding action there is a refractory state, analogous to that found in nerve fibres, but of much longer duration -- up to about one second. Telford named this period the "Psychological Refractory Period", a name now commonly applied to this phenomenon.

The idea of a true refractoriness has also been suggested by Davis (1957) in order to explain the not uncommon finding that delays in RT₂ often occur after ISI's exceeding the total duration of RT₁. Since in these cases the first stimulus must obviously have been completely processed before the second stimulus was presented, Davis suggests that "there may exist a truly refractory period following central activity". He therefore predicts the latency of the second RT by the formula:

\[ \text{RT}_2 = \text{RT}_1 + \text{central refractory time} - \text{ISI} \]

Davis estimates the duration of this refractory time to be about 100 ms.

Let us examine some predictions of this theory:

1. The interval over which a delay in RT₂ should occur would be a fixed amount, equal to the value of the refractory period. Therefore, as the ISI is increased between the two stimuli, the delay in RT₂ should decrease, until at an ISI equal to or greater than the refractory period, there is no further delay.

While the delay in RT₂ does decline as the ISI is increased, the interval over which a delay occurs does not appear to be a constant, such as one
could predict for excitation of nerve or muscle. The ISI's over which delays occur vary greatly depending upon the particular experimental conditions.

2. The delay in RT\textsubscript{2} should be unaffected by the uncertainty (i.e., amount of information) associated with the first stimulus, since speed of conduction and resulting refractoriness should not be influenced by the number of alternatives from which the stimulus was selected.

Careful study of the delay in RT\textsubscript{2} as a function of the informational content of the first stimulus has not been done. The most relevant findings are those of Kay and Weiss (1961), who found that as the time uncertainty of the first stimulus was increased, by varying the range of foreperiods prior to the first stimulus, the delay in RT\textsubscript{2} also increased. This study will be presented in some detail under the discussion of Preparatory Set theories.

Thus, of the predictions made by the Psychological Refractory Period theory, only the prediction that there will be a delay in RT\textsubscript{2} which declines with increasing ISI has been substantiated by experimental data. Further, as there is no physiological evidence of a refractoriness in any part of the nervous system for durations as long as those required, this theory does not seem to provide an adequate explanation.

II Preparatory Set Theory

Many experimenters have argued that the prolonged second RT is in no way due to the influence of the first stimulus. Rather, they believe, delays in responding to the second stimulus can be explained along lines identical with those for explaining delays in responding to a single stimulus, namely, the range, frequency, or duration of the foreperiod
preceding the stimulus. Preparatory set theories fall into two general categories:

a) Expectancy theories

In a simple RT study Mowrer (1940) found that signals occurring before or after a modal or mean interval were reacted to relatively more slowly and explained this as being due to decreased expectancy at values other than the mean. Based on this finding, expectancy theorists explain the observed delay in RT$_2$ by stating that when the ISI between the two stimuli is randomly varied, as is usually done, Ss develop a high expectancy for the second stimulus ($s_2$) at the mean value of ISI. Consequently when very short ISI's are presented, Ss expectancy of $s_2$ is minimal, with the result that RT$_2$ is very high. As the ISI increases, the expectancy that $s_2$ will arrive momentarily increases, with a corresponding decline in RT$_2$.

This theory was first proposed by Elithorn and Lawrence (1955). In probability terms they explain the delay as follows: "At time 0 at the end of the foreperiod one of two responses will almost certainly be required and the probability of each stimulus response situation occurring then is approximately 0.5. The arrival of a single stimulus raises the probability of its own response to the region of 1.0, but at the same time it causes the probability of the alternative situation to fall abruptly. Since the latter situation will arise sometime the probability that it will occur at the next time interval if it has not already occurred will increase with the passage of time until towards the end of the cycle this probability approaches unity. If, therefore, the observed RT to the second stimulus is inversely proportional to the hypothetical state of preparation, expectancy or probability of the appropriate response mechanisms, then it may be expected
to be longer when this stimulus occurs shortly after the disjunctive situation. Similarly, it may be expected to approach that of a simple RT as ISI increases."

**Predictions**

1. This theory would predict that it is not the absolute but rather the relative value of the ISI which determines the delay in RT$_2$. If the majority of ISI's are small, so that S develops an expectancy for s$_2$ very soon after s$_1$, then delays should not be maximal at the shortest ISI.

Some support for this prediction of the expectancy theory is provided by Adams (1962), who varied the frequency of presentation of the shortest ISI (100 ms.). He argued that if expectancy is an important variable, S should be more expectant for s$_2$ at short ISI's when a greater frequency of small intervals is used, and therefore there should be less delay in RT$_2$. His results supported the expectancy view, in that over-all RT$_2$ did decline in the group with greatest frequency of the smallest ISI. One could argue that since this was the most expected ISI, RT$_2$ should be fastest here. However, although the over-all RT$_2$ latency declined, the RT to the signal at the shortest ISI (100 ms.) was still greater than at any other ISI.

2. If the second stimulus were always given at some fixed period after the first (i.e., constant ISI), S should come to develop maximum expectancy at that value, and no further delays would be observed.

This prediction has not been supported. Since an expectancy theory states that the delay in RT$_2$ is due exclusively to subjective uncertainty about arrival times of the second signal, then if the ISI between signals is fixed, thus eliminating any uncertainty, no delay is predicted. In
order to test this Borger (1963) presented Ss with two stimuli, either auditory or visual. His procedure was as follows:

<table>
<thead>
<tr>
<th>Ready foreperiod (500 ms.)</th>
<th>Signal</th>
<th>ISI - fixed for any run of 30 one presentation and varied two between runs from 50-800 ms.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Click</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In addition to the "double runs", where S had to respond to two stimuli, there were also "single runs", in which S responded only to the second signal, the first being the same on every occasion and different from either of those normally given. During a "single run" S removed his hand from the key corresponding to the first stimulus. Borger's results clearly do not support an expectancy theory, for even with ISI constant, there is a significant delay in RT₂ in the "double runs". For "single runs", however, RT₂ for short ISI's is no longer than for long ISI's. Thus, when S is required to respond to two stimuli, there is a delay in RT₂ at short ISI's, even if the interval between the two stimuli is fixed.

3. Finally, Davis (1965) has performed an experiment which suggests that the delayed second RT cannot be attributed solely to the statistical nature of the ISI series (i.e., range, duration and frequency of the particular ISI's). He wished to demonstrate that the effects are due mainly to the influence of the first signal, rather than the distribution of ISI's. Consequently, in one condition he eliminated the first signal altogether and substituted for it a "spontaneous" emitted response by S. In the experiment, S pressed a key with his left hand whenever he chose, and at some interval following this, at the same ISI's used in the usual situation where two signals are presented -- i.e., 50 to 500 ms., a visual signal appeared to which S pressed a key with his right hand. The results are very clear. No delays were found in the RT, even with an ISI of 50 ms.
This is in marked contrast to the large delay found in the second RT in experiments where $S$ must respond to both stimuli. This would seem to support the theory that the delay is in some way influenced by the first signal.

Based on the experimental findings reported here, an explanation of the delay in $RT_2$ solely in terms of $S$'s expectancy of when the second stimulus will appear is not sufficient. Delays are observed even when $S$'s expectancy is very high (Borger, 1963), and no delays are observed when $S$ does not have to select a response to a first stimulus, even though the set of ISI's employed is identical (Davis, 1965).

b) Readiness theory

A more satisfactory explanation of the delay in terms of preparatory set is given by the Readiness theory (Poulton, 1950). This hypothesis states that $S$s require a fixed period of time to prepare a response to a stimulus. If $s_1$ is considered to be the warning signal for $RT_2$, then the ISI between $s_1$ and $s_2$ is analogous to the foreperiod -- i.e., period between the warning signal and the stimulus in a single RT study. If it could be shown that delays occur in the single reaction situation analogous to those found in the two response situation, this would be strong support for the theory that delays in $RT_2$ are due to lack of readiness.

Such support is provided by Nickerson (1965). He performed a simple RT study employing a range of foreperiods similar to that used in the double stimulation studies -- i.e., 100 to 900 ms. It was found that as the foreperiod between the stimulus and the warning signal (a visual signal similar to the first) was increased, simple RT was maximum at the
shortest foreperiod and declined in a manner analogous to that found in situations where two reactions are required. Further, both the absolute and the relative duration of the foreperiod was found to be important. By varying the range of the foreperiods employed, he found that RT at a particular ISI was greater if that was the shortest ISI used than if the ISI fell in the middle of the series. This suggests that both expectancy and readiness may affect RT, since RT was found to decline both as the absolute and the relative duration of foreperiod increased. Thus, if $S$ is completely ready (as in the Davis, 1965 experiment, where $S$ pressed a key to initiate the ISI), expectancy has no influence on RT. However, if $S$ is not completely ready, then while readiness plays the predominant role, delay is also influenced to some extent by expectancy.

Finally an experiment performed by Kay and Weiss (1961) suggests that the interval between the first and second stimuli is not the only determinant of the delay in $RT_2$. They wished to show that the delays in $RT_2$ are similar to delays occurring when only a single reaction is required, and carried out an investigation specifically to compare simple and serial RT. The design of their experiment was as follows:

<table>
<thead>
<tr>
<th>S pressed a</th>
<th>foreperiod of 1, 2, 3 or 4 secs.</th>
<th>click one</th>
<th>ISI of 25 - 1000 ms.</th>
<th>click two</th>
</tr>
</thead>
<tbody>
<tr>
<td>ready key</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Seven conditions were employed. In conditions one and two, only the first click was given, and simple RT's were examined after regular and irregular foreperiods. However, we are more interested in the remaining five conditions of the experiment, where both clicks were given, with the foreperiod and ISI being varied either randomly or regularly. $S$ responded in some cases to both signals, in other cases only to one. The following chart outlines the various conditions:
<table>
<thead>
<tr>
<th>Condition</th>
<th>Foreperiod</th>
<th>ISI</th>
<th>Signal responded to</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Regular</td>
<td>Regular</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Regular</td>
<td>Irregular</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Irregular</td>
<td>Regular</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>Irregular</td>
<td>Irregular</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>Irregular</td>
<td>Regular</td>
<td>1 &amp; 2</td>
</tr>
<tr>
<td>8</td>
<td>Irregular</td>
<td>Irregular</td>
<td>1 &amp; 2</td>
</tr>
</tbody>
</table>

It was found that in all cases $RT_2$ was maximal at the shortest ISI and declined as the interval was increased. The mean RT to the second signal for conditions three through eight were 155, 175, 189, 192, 244 and 265 ms. respectively. These results indicate that RT increases at the minimum foreperiod with the increasing uncertainty of the experimental conditions. Since RT increased in both the single and double response situations with increasing time uncertainty, the authors conclude that "one possible explanation for the delay in responding to the second signal is along lines identical with those for explaining variability in the speed of responding to the first". However, although increasing uncertainty does lead to increased RT, there is a very important quantitative difference observed when S is required to make a response to the first stimulus, compared to the situation where no response to it is required, all other conditions being equal. Comparing RT's in conditions five and seven and in conditions six and eight, RT is increased by 55 ms. in the former when a response is required, and by 73 ms. in the latter. Both these increases were significant.

On the basis of this study by Kay and Weiss we might note that

1) the delay in $RT_2$ is significantly increased when Ss are required to make a response to $s_1$; and

2) the amount of delay is a function of the time uncertainty associated with $s_1$. In fact, $RT_2$ is greater if the first signal is irregular
(procedure five) than if the second signal is irregular (procedure four). If increasing the time uncertainty of $s_1$ may be assumed to increase the time required to process the information associated with $s_1$, then this suggests that the delay in $RT_2$ is a function not only of the ISI, but of the processing time of the first stimulus. Such a view would support a "single channel" theory, to which we shall now turn.

III Successive Processing -- "Single Channel" Theories

The final type of explanation proposed to account for this phenomenon is that somewhere in the central mechanisms there is a "channel" of limited capacity, which cannot attend to both response requirements simultaneously. Views differ as to where in the arc of sensory input - response selection - response performance this limited capacity mechanism is to be found. Some hypotheses place it on the sensory side and others on the response side, but most believe that the limitation occurs at the response selection stage. A brief summary of these theories follows.

a) Perceptual delay

Broadbent (1958) has suggested that there may be a quantizing of perception into samples of about $1/3$ seconds. He has arrived at this figure on the basis of findings by Cherry and Taylor (1954), who showed that there was impairment in the understanding of speech when it was switched on and off at the rate of 3 c.p.s. If this is taken as evidence that perception is quantized in units of about $1/3$ seconds, then the delay in $RT_2$ is explained in the following way: when the first signal is given, $S$ immediately closes him sample, and relays the information on for the selection of a response. However, the next quantum will not be relayed
for another 1/3 seconds. If the second signal arrives immediately after the first, it will have to wait until the 1/3 seconds has elapsed before it is relayed. It therefore follows that the longer the arrival of $s_2$ is delayed after the relaying of $s_1$, the less time it will have to be held in store before being sent on. If it arrives after an interval greater than 1/3 seconds, there should be no delay at all.

**Predictions**

1. If two stimuli arrive exactly simultaneously they should be packaged in the same quantum, and no delay in responding to the second stimulus should occur.

   This prediction is not supported by the data. Although some Es report less delay at 0 ms. than at slightly larger ISI's (Elithorn and Lawrence, 1955; Marrill, 1957), there are no reports of no delay at all, and most experimenters have found maximum delay with ISI's of 0 ms. (Davis, 1956; Adams, 1962; Creamer, 1963; Reynolds, 1966).

2. Delays in RT$_2$ should be a function solely of the ISI between the two stimuli. The time required to select a response to $s_1$ should in no way influence the amount of time $s_2$ must be held in store.

   This prediction appears to be contradicted by the findings of Kay and Weiss (1961), who found that the delay in RT$_2$ tended to increase with time uncertainty of the first stimulus. However, this problem has not been carefully studied.

3. Since the delay is caused by a perceptual process occupying a fixed time interval (the duration of the quantum), some constant value over which the delay exists should be found.

   Though many experiments have been done on this question, no such fixed value has been found, and the delay appears to vary with the conditions of
the particular experiment.

4. If the delay were due to a quantizing of perceptions, it would seem highly unlikely that perceptions from all modalities would be placed in the same unit. Thus, if the first stimulus were given in one modality, and the second in another modality, no delays in the transmission of the second response would be expected.

Davis (1957) tested this by presenting S with two successive stimuli, the first consisting of an auditory click, the second of a visual flash, 50 to 500 ms. after the first, the interval between the two stimuli being randomly varied. Once again, delays of the usual magnitude were found. This experiment tends to indicate that the delay is probably not on the sensory side of the arc.

Although this theory has the advantage of trying to explain the delay as the result of normal perceptual processes which can be demonstrated in other perceptual situations, such as Cherry and Taylor's auditory interference experiments, it does not appear to be supported by the present data.

b) Response Delay

Other theorists believe that the delay occurs in the operation of the response mechanisms, rather than in the perceptual mechanisms. The theory that the delay in responding to the second stimulus was the result of interference on the response side of the arc was first proposed by
Elithorn and Lawrence (1955). They argue that during the foreperiod preceding the first signal, S's expectancy that the stimulus may require a response by either hand causes increased excitability in both limbs. As soon as the first signal appears, the hand in which a response is not required is inhibited, to prevent the occurrence of the wrong response. This inhibition dissipates during the ISI, resulting in declining RT's with the second hand as the interval increases.

A slightly different hypothesis is expressed by Reynolds (1964). Reynolds believes that in the double stimulation situation competing responses, of the type described by Berlyne (1960), are elicited by the two stimuli. He describes this as follows: "when events are uncertain, responses to both must be held in readiness to insure maximum efficiency of response to both. When either stimulus occurs, there well may be competing response tendencies which are associated with the other stimulus". The response more closely associated with a particular stimulus will overcome this competing response tendency. In order to explain the fact that it is the second reaction which is delayed, Reynolds must postulate that "if one of the two responses available to S is not stronger than the other, then the response elicited by the first stimulus may become the 'pre-potent' or dominant response". Reynolds emphasizes that his theory has the advantage of being able, by training responses to specific stimuli previously unassociated with them, to operationally define a pre-potent response -- i.e., that response which has most often been associated with a particular stimulus -- and hence to determine in advance which RT will be longer.

Predictions

1. According to this theory, delays occur not in the selection of the response,
but rather in its execution. Hence, if $S$ never had to make an overt response to $s_1$, no such competing responses should arise, and consequently there should be no delay in the reaction to the second stimulus.

Unfortunately, this problem has not been carefully investigated. Some indication that this is not so, however, is provided by the experiments of Nickerson (1965) and of Kay and Weiss (1961). In both these experiments there was a delay in the simple RT to a stimulus even if no response was ever required to the first stimulus. In other words, when $S$s had only one response to prepare, the response was delayed at short ISI's, even though no response was required to the first stimulus, and therefore no competing responses should have arisen. However, the magnitude of this delay was much smaller than the delay found when a response is required to the first stimulus. Therefore, while competing response tendencies cannot account for the entire delay, it may play some role in the double response situation.

2. A response competition theory would predict that the greater the similarity between the two responses required, the greater should be the tendency for response competition. For example, greater delays in $RT_2$ would be expected when both responses were manual than if one were verbal and the other manual.

Again, this problem has not been investigated.

c) **Response selection delay**

A final "single channel" theory is that of response selection delay, which states that selection of two responses cannot proceed simultaneously. Hence, when $S$s are presented with two response tasks which must be performed in rapid succession, first one response is selected and then the other. During the selection of the first response the second stimulus must be
"held in store". The response selector or "decision mechanism", as it is
referred to by proponents of this theory, is thus conceptualized as a
"single channel" as opposed to a multi-channel system which could simul-
taneously select many responses.

This theory has received considerable support (Hick, 1948; Vince,
1948; Craik, 1947; 1948; Welford, 1952, 1959; Davis, 1956, 1957, 1959,
assumptions have been listed by Welford (1959):
1. That there are a number of sensory input mechanisms each capable of
receiving data and storing it for a limited period of time, so that, for
example, a short series of signals can be received as a unit.
2. That there are a number of effector mechanisms containing both
central and peripheral elements and capable of carrying out a series of
actions such as the pressing and release of a key or a series of taps
as a single unit.
3. That between these two there is a single channel decision mechanism
which is of limited capacity in the sense that it takes a finite time to
process information and can thus only deal with a limited amount of infor-
mation in a given time.
4. That sensory input data can be accumulated while the decision channel
is occupied by dealing with previous data, and can be passed (together)
to the decision channel as soon as it is free.
5. That the decision channel can "issue orders" to the effector side for
a series of responses, the execution of which can overlap with the
decision channel's dealing with fresh input.

A possible mode of operation of this limited capacity mechanism can be
conceptualized from some recent experiments on attention by Kristofferson (1965). He describes attention as a limited capacity switching mechanism which is responsible for gating the flow of information. The information carried by each stimulus is considered to be transmitted in separate "channels", with the assumption that attention must be aligned with a channel before "read out" of the information can occur. If we assume that attention can be aligned with only one channel at a time, then the read out of the second channel will be delayed until attention is shifted to it.

Just when this attention shift can occur is not clear. Kristofferson believes that the attention mechanism has a fixed periodicity of M ms., which is controlled by an internal generator whose physiological manifestation may be the alpha rhythm. Thus once attention is lined up with the first channel, it switches to the second channel M ms. later, or at some multiple of M.

Such an attention switching model may operate in one of two ways. One possibility is that attention is switched after some fixed interval following the initiation of the first response selection. Consequently, while the initiation of the second response selection is delayed, both can proceed simultaneously. Thus, provided the value of the fixed interval is not too long, some "multi-channel" processing is possible.

On the other hand, attention may not switch until the first response selection is complete. If this is the case, response selections must occur sequentially. Since Kay and Weiss's findings suggest that the delay in RT₂ increases as the time required to process the first response is increased, it appears that the switch does not occur until after the first response has been selected -- hence supporting the successive response selection model.
Given this assumed schema of operation, several authors have suggested formulae from which the magnitude of the delay in RT\(_2\) could be calculated. Davis (1956) suggests the following formulation:

If CT\(_1\) = actual first choice time

CT\(_2\) = predicted second choice time

CT\(_N\) = mean normal choice time

X = amount of delay

ISI = interval between the two stimuli

Then X = CT\(_1\) - ISI for CT\(_1\) > ISI

= 0 for CT\(_1\) < ISI

CT\(_2\) = CT\(_N\) + X

Therefore, CT\(_2\) = CT\(_N\) + CT\(_1\) - ISI

A similar formula was suggested by Welford (1952). However, according to this model no delay should occur at values of the ISI which are greater than the choice time for the first response. This, however, has not always been the case, and delays have been found at values of ISI as large as and larger than RT\(_1\) (Vince, 1948; Telford, 1931; Davis, 1957). To account for this, Welford has added an additional assumption: (1952,p.4)

"If the stimuli fed back from a response are dealt with by the subject's central mechanisms in a similar way to stimuli given by the experimenter, we should expect that those fed back at the beginning of the response would 'capture' the central mechanisms for a brief period, and that only when this period was over could any further stimuli from the response or any new stimulus given by the experimenter be attended to."

In other words, the second reaction is delayed not only while the first response is being selected, but also while the proprioceptive feedback
from the first response is being attended to.

Rather than introduce this feedback requirement, Davis (1957) has postulated that following the selection of a response the central "single channel" may be refractory for a fixed period of time. He postulates that the refractory time may be about 100 ms. Unlike Telford, he does not believe the delay in RT₂ is totally the result of refractoriness after the passage of the first stimulus. Instead, he argues, that while the delay is due to a single channel response selector, following the selection of a response there is a period of "refractoriness", adding an additional 100 ms. to the delay in RT₂.

Delays at values of ISI greater than the first RT are relatively easy to explain if an attention switching model is accepted. According to such a model, some time may be required for the attention shift. Thus, the second response selection will be delayed not only by the time required for the first response selection, but by the interval required for attention shifting.

Let us now examine the predictions of a "single channel" response selection model:

1. The delay in RT₂ should be a direct function of the time required to select the first response.

This question, as pointed out earlier, though an essential one for discriminating between so many of the theories, has not been systematically investigated. The only experiment we can refer to is that of Kay and Weiss, which would support this prediction, for as the time uncertainty of s₁, and thus perhaps the time required to select a response to it, was increased, the delay in RT₂ increased as well.
2. Since the delay in RT\textsubscript{2} is due to the necessity of first selecting a response to s\textsubscript{1}, if no response selection is required to s\textsubscript{1}, there should be no delay.

The data collected by Kay and Weiss (1961) and by Nickerson (1965) suggest that this is not so. Delays are still found in the response to s\textsubscript{2} after the presentation of s\textsubscript{1} even if no response is required to s\textsubscript{1}. However, the delay is much greater when a response selection to the first stimulus is required.

3. If we assume that the "single channel" is limited only to the response selection process, then the selection of the second response should be able to occur during the performance of the first response.

This question has not been carefully studied. Davis (1962) conducted an experiment to determine whether the actual performance of the first response was important in determining the delay in RT\textsubscript{2}. In this experiment two sets of lights were displayed, each consisting of a left and a right neon bulb. For display one, either bulb in the first set came on. For display two, coming on 50 to 250 ms. after display one, again either the left or right bulb came on. Ss were to respond only to display two, and were to ignore display one (sessions two and three), or to report, after responding to display two, which light had been flashed in display one (sessions four and five). Three Ss performed under a regular interval situation (intervals presented in blocks of 20) and three under a random interval situation.

In the regular interval group, no delay was encountered in the response. In the random interval situation, even when Ss were told to ignore the first display, there was some delay in reacting to the second display. However,
this delay was much less than when S made a response to the first signal, and the delay was significant only at the shortest ISI. This led Davis to the belief that "the blockage caused by attention to a situation may not be as long as when an overt response to it has to be organized". Since the first signal could be identified without causing a delay in the response to the second, Davis suggests that the first stimulus was held in store and analyzed only after the response to the second display had been made. To explain the difference between the regular and random intervals, Davis postulates that if the S doesn't know when the second signal will come, he starts analyzing the first signal at once, so that the second signal will find the mechanism blocked.

Although Davis' results would seem to indicate that the prime delay in RT₂ is the result not of response selection to s₁, but of the performance of the first response, an important point should be noted. Under the no response condition, Ss could completely ignore the first stimulus, or, as Davis suggests, delay analyzing it until the second response has been selected. Therefore this experiment has not really differentiated at all between relative delays in RT₂ as a function of whether a response was performed, but rather between relative delays when response selection is or is not carried out. To adequately test the effect of the performance of a response, response selection times must be kept constant, even under conditions where no overt response is required.

The fact that delays in RT₂ are found with ISI's as long or longer than RT₁ suggests that under some circumstances the "single channel" concept may apply to response performance as well as to response selection. For example, in some situations attention may be required for the performance of a response, and cannot shift to the second response selection until the first response has been performed.
Summary

Many experiments have been conducted to explain the delay occurring in the second of two successive reactions since this phenomenon was first described by Telford in 1931.

The explanation that the delay is due to S's subjective uncertainty as to when the second stimulus will arrive, with expectancy increasing as the ISI is increased, does not seem adequate, based on the finding of Borger (1963) that even when the ISI is kept constant over a run of 30 trials the same delay curve is generated.

Similarly, the "readiness" hypothesis, which states that the delay is due to S requiring a fixed period of time to prepare himself for a response cannot entirely explain the delay. Some portion of the delay may be due to readiness, for Nickerson, studying simple reaction over a range of foreperiods similar to the ISI's typically employed in the double response situation, found that RT varied inversely with the duration of the foreperiod. Since S did not have to select a response to the first warning signal, the delay in the RT to the second stimulus was clearly not due to the delay of response selection. However, the magnitude of the increase at the shortest ISI was very small when compared with delays when a response had to be selected to the first stimulus. Thus, while readiness appears to play some role, it is, in itself, not an adequate explanation. Rather, the majority of the experiments strongly suggest the presence of some limited capacity "single channel" in the system. However, further experiments are required to determine the nature of this mechanism. Questions of importance are: 1) does the delay in RT₂ vary with the time required to select the first response? 2) Is the delay in RT₂ increased when S must, in addition
to selecting a response to $s_1$, actually perform this response? 3) is the delay in RT$_2$ a function of the difference between the two responses? 4) are there any situations in which the delay in the second RT can be overcome with practice?

These questions are examined in the experiments which follow.
Chapter II

Two models of attention as a limiting mechanism in response selection

This study is concerned with the conditions under which response selections occur sequentially or in parallel, and with the consequences of sequential vs. parallel processing. One way in which this problem can be explored is to study the reaction time (RT) to two stimuli presented simultaneously or in rapid succession. By examining the changes in the RT to the stimuli under the double presentation situation as compared with RT in a control situation when only one of the stimuli is presented, it is possible to make some inferences as to whether parallel or sequential response selection has occurred.

This method appears to have been first employed by Telford (1931). He found that when Ss were required to make two responses in rapid succession, the response to the second stimulus was unusually long when compared with RT to that stimulus in a control situation. The increase was maximal when the inter-stimulus interval (ISI) was very short, and declined as the interval was lengthened. This phenomenon has since been confirmed by many experimenters (Davis, 1956; Poulton, 1950; Craik, 1948; Fraisse, 1957; Welford, 1952).

This prolonged second RT suggests the presence of a limiting mechanism in the processing system, and various parameters have been systematically investigated in attempts to understand the nature of this limiting mechanism. The delay in the second RT (RT₂) occurs both when the two stimuli are presented in the same modality or in different modalities, suggesting that it is not the result of peripheral sensory interference (Davis, 1957). Similarly, the delay occurs when different limbs are used for the two responses, so that it cannot be attributed to a physical inability to make the two responses simultaneously (Davis, 1956). One requirement for the
occurrence of the delayed second RT appears to be that the first response represent a choice RT. If it is a simple RT (event certainty), there is no delay in the second RT (Adams and Chambers, 1962; Reynolds, 1966). On the other hand, the delay in RT₂ has been found to increase with increasing uncertainty associated with the first stimulus. Kay and Weiss (1961) report that when the variability of the foreperiod preceding the first stimulus was increased, there was a corresponding increase in the delay in the RT to the second stimulus. The above findings suggest that the delay occurs quite centrally, possibly at the response selection or "decision" stage. However, the nature of the limiting mechanism has not been clarified.

Telford (1931) believed that the delay in RT₂ was the result of a refractoriness in the central mechanisms similar to that found in nerves or muscles after the transmission of an impulse, and therefore called the phenomenon the "psychological refractory period", a name which is now applied to this finding even though the notion of central refractoriness is not generally accepted.

One possible cause of the delay may be the presence of a selective attention mechanism which is necessary for a response selection and which is of limited capacity, so that two response selections cannot be initiated simultaneously. Kristofferson (1965), using several different procedures, has suggested that attention may act as a selective control or gating mechanism, and has provided evidence that in some situations selective attention operates as a switching mechanism with a fixed periodicity.

Two models which could describe the operation of this attention mechanism are presented below. The models share the following assumptions:
1. That the time involved in making a reaction may be divided into at least three components: afferent travelling time (AT), response selection time (RST), and response performance time (PT), i.e., $RT = AT + RST + PT$.

2. That AT can occur in parallel with PT, and also that AT can occur in parallel with RST.

3. That in order for response selection to occur, selective attention is required, at least initially. After extensive practice, response selections may become "automatic", so that attention is no longer required.

4. That attention operates as a switching mechanism, such that it is aligned first with one response selection, and then switches to the other.

5. That since it is the second response which is delayed, with the delay decreasing as the ISI is increased, attention must initially be directed to the selection of the first response and, after some interval, is switched to the selection of the second response.

Let us now consider two different models of how the attention mechanism may operate.

I The Fixed Interval Model

According to this model, once attention has been aligned with the first response selection, it cannot be switched to the second until a fixed interval has elapsed. Consequently, if a second signal is presented within this interval, the second response selection will not begin immediately, and there will be a delay before a response can occur. The greater the ISI between the two signals, the less time the second response selection must wait until the attention shift occurs, and consequently the less the delay in the second response. If the ISI is greater than the value of the fixed interval, no delay at all will occur.
The essential characteristic of a fixed interval model is that the occurrence of the attention switch is independent of the time required for the first response selection. The only important variable in determining the delay in the response to the second stimulus is the ISI between the two stimuli. Attention thus acts as a switch which is necessary to start response selection, but once this switch has been thrown, response selection can proceed without attention. Consequently, simultaneous selection of two responses or "parallel processing" is possible. Many theories based upon a fixed interval model have been proposed.

Broadbent (1958) has hypothesized that humans sample the environment in time units of a fixed duration -- say x ms. As soon as a first stimulus is given, Ss can close their sample, but the second stimulus is not acted upon until the second sample is examined x ms. later. Thus, the longer the interval between the two stimuli, the less time the second stimulus must wait before it is relayed, and consequently the less the delay in RT\textsubscript{2}.

While Broadbent places the emphasis on the sensory side, other theories have presented fixed interval models with the emphasis on the response side (Poulton, 1950; Elithorn and Lawrence, 1955). According to such theories, a fixed period of time is required following a warning signal in order to optimally prepare a response to a signal. If the signal is presented earlier, RT will be prolonged. This view as a possible explanation of the delay in RT\textsubscript{2} is supported by a recent experiment of Nickerson (1965). He conducted a simple RT study using a range of foreperiods comparable to the range of ISI's employed in double stimulation studies (100 to 900 ms.) and showed that RT was greatest at the shortest foreperiod and declined as the duration of the foreperiod was increased. To apply this explanation in
the double stimulation situation, the first stimulus must be considered analogous to a warning signal, initiating the period of preparation for the second response. Hence, following the occurrence of the first signal, a fixed preparation period is required.

II Successive Response Selection Model

In contrast to the fixed interval model, the successive response selection model postulates that the shift in attention does not occur until after a response has been selected to the first stimulus. Consequently, the longer it takes to select a response to the first stimulus (s₁), the longer will be the time before attention can be switched, and hence the longer will be the delay in RT₂.

A successive response selection model is appropriate for the numerous "single channel" hypotheses which have been proposed (Davis, 1956, 1957, 1959, 1962, 1964, 1965; Borger, 1963; Welford, 1952; Hick, 1948; Hick and Bates, 1950; Fraisse, 1957). This theory emphasizes that two responses cannot be selected simultaneously, so that with regard to response selection there is only a "single channel" available. Some support for this hypothesis is provided by Kay and Weiss (1961), who have found that as the variability of the foreperiod prior to s₁ was increased, the delay in RT to the second stimulus increased as well. If we assume that increasing the variability of the foreperiod prior to s₁ resulted in an increase in the time required for processing, then the delay of the attention switch would appear to be a function of the information processing time.

The purpose of these experiments was to determine which model best describes attention switching in a double response situation, and hence to determine whether simultaneous selection of two responses occurs under these conditions.
Experiment I

The aim of this experiment was to examine the influence of varying the time required to select the first response on the delay in the second reaction. Response selection time was manipulated by varying the number of possible alternative members of the group from which a particular stimulus was selected. Under conditions of low stimulus-response compatibility, RT has been shown to increase linearly with the number of bits of information, i.e., \( RT = k \log_2 n \), where \( k \) is a constant, and \( n \) is the number of alternatives (Hick, 1952; Hyman, 1953; Crossman, 1953). A verbal response was employed for the variable-information response selection. A two-choice manual key-press response was employed for the constant-information response selection.

The two stimuli were always presented simultaneously. The order of attention alignment was manipulated by varying the order in which Ss were instructed to emit their responses. Three orders of responding were employed:

Condition 1: the verbal, variable-information response first; the manual constant-information response second.

Condition 2: the constant-information manual response first; the variable-information verbal response second.

Condition 3: Both responses simultaneously.

The predictions of the two models under these conditions are presented below:

**Condition 1**

**Successive Response Selection Model**

The longer it takes to select the first response, the longer will be the time until attention can be shifted, and hence the longer the delay in RT\(_2\). The two response curves would be parallel, as shown in Figure 1. The
time difference, \( d \), between \( RT_1 \) and \( RT_2 \) approximates the time required to shift attention, select the key-press response and perform this response -- a value which would be close to the manual choice RT. Over-all RT (i.e., the total time required to make both responses) should approximate the sum of the two choice reaction times independently.

Fixed Interval Model

Attention shifts at a fixed interval after alignment with the first response selection, so that the delay in \( RT_2 \) is independent of the time required to select the verbal response. Consequently, the manual response selection curve is horizontal; the height of this curve is determined solely by the amount of time needed to select this response, as shown in Figure 2. The response selection curves which are assumed to underlie the RT curves are referred to as the "covert" curves. The manifested RT's are referred to as the "overt" curves.

The appearance of the overt RT curves is determined by the relative times required for the two response selections:

i) If the time required to select the manual response is greater than that required for the verbal response, the manual response selection curve will always lie above that of the verbal curve, as shown in Figure 2A. Since Ss are instructed to emit the responses in the order verbal-manual, they will make each response as soon as it is selected, and the overt RT curves will bear the same relationship to one another as the covert response selection curves.

ii) If the manual response selection time is only greater than the two- and four-choice verbal response selection times, the covert response selection curves would intersect, as shown in Figure 2B. Since Ss must
always emit the verbal response first, the overt manual reaction must be withheld and performed following the verbal reactions in those instances when the verbal response takes longer to select.

iii) If the manual response selection time is always smaller than the verbal, S can begin the verbal response selection, switch attention to begin the manual response selection, and be able to complete the latter task first. This is shown in figure 2C. The covert manual response selection curve always lies below that of the verbal. To comply with the order-of-responding instructions, the overt manual response must be withheld until the verbal response has been made. Consequently, the two overt RT curves will appear parallel. Unlike the curves predicted by the successive response selection model, however, the difference $d$ between $RT_1$ and $RT_2$ should be very small -- approximately equal to the time required to perform the key-press response. Similarly over-all RT (the total time required for the two responses), should approximate the verbal RT alone.

In our experiment, manual RT is always less than the verbal RT, so this is the prediction of the fixed interval model with which we shall be concerned.

**Condition 2**

**Successive Response Selection Model**

Over-all RT should be the same regardless of the response selection with which attention is first aligned. Thus, over-all RT should be the same as in condition 1.

**Fixed Interval Model**

In this condition attention is aligned first with the response selection which takes the least time. Hence attention is not switched to the longer
verbal response selection for the period of the fixed interval. Therefore, the more time-consuming response selection is not begun for a period equal to the fixed interval plus switching time. Consequently, over-all RT should be increased over RT in condition 1 by approximately the value of the fixed interval.

Condition 3

Successive Response Selection Model

Since the response selections must occur sequentially, over-all RT will once again be the same.

Fixed Interval Model

By aligning attention first with the verbal response selection, both response selections could proceed in a period no longer than that required for the verbal RT alone. Since there is no need to withhold the manual response, as in condition 1, over-all RT should equal verbal RT.

Method

Subjects:

Three male M.I.T. undergraduate volunteers participated in this experiment. They were paid for their services.

Apparatus:

1) Visual array

The light sources were cold-cathode mercury argon lamps coated with magnesium tungstate phosphor, housed in light boxes having a diffusing surface of \( \frac{1}{4} \)" milk plexiglass. The visual array consisted of two non-overlapping stimuli, as shown in Figure 3.
a) Variable-information stimulus -- bar

The variable-information stimulus was a luminous bar (hereafter referred to as the bar stimulus), prepared by cutting a slit, 1" long and 1/8" wide (visual angle = 1.36 degrees by 0.17 degrees), in a disk of P.V.C. plastic, which was placed in front of the light source. This disk was mounted on a metal disk and rod assembly, which, by means of a knob outside the viewing box, could be rotated through 360 degrees. Eight equally spaced stimulus positions were employed. By turning the knob, E could place the bar in any one of these positions. A click-in device assured the accuracy of the settings. The bottom of the slit was 3½ cm. from the focussing light. The amount of information transmitted by the bar stimulus was varied by having either two, four or eight possible alternatives from which the position of the bar could be selected.

A luminous ring, 1/8" wide with an outer diameter of 5 1/8" (visual angle = 6.97 degrees) appeared around the array, as shown in Figure 3B. This ring helped S in localization of the stimulus positions.

b) Constant-information stimulus -- disk

The constant-information stimulus consisted of a small disk of light (hereafter referred to as the disk stimulus) which could appear either to the left or right of the focussing light. This disk was 2 cm. from the focussing light. To change this stimulus E moved a sheet of P.V.C. plastic, in which a circular hole with diameter of ½" (visual angle = 0.68 degrees) had been punched, into one of two positions in front of the second light source. Since this stimulus could take only two different positions, the information transmitted was constant.

The luminance of the stimuli was 2.5 ft. candles. They were both presented for 100 ms.
2) Reaction time apparatus

The RT apparatus consisted of the following:

a) a Sky Instrument Company type tachistoscopic programmer, which was used to adjust the duration of the stimuli;

b) two Hunter model 120A Klock-Kounters, which measured RT and which were read to the nearest .01 seconds;

c) a Hunter decade interval timer, model 111C, which determined the interval between the sound of a buzzer and the simultaneous onset of the two stimulus lights and the two counters;

d) a voice key which, on activation by S's first vocalization, stopped one of the counters, to which the voice key was connected;

e) two microswitches, which were employed for measuring the manual key press response. Pressing either switch stopped the second Hunter counter. E was made aware of a wrong response by the off-set of a red neon light when the wrong key was pressed. This light was controlled by a switch which E set for each trial.

f) a chin rest, which was used by Ss to help maintain constant direction of gaze.

Procedure:

The experiments were conducted in a dark room, to which Ss had become dark adapted. Ss were first taught to associate a nonsense syllable with each of the eight positions of the bar stimulus. These eight nonsense words were the same as those used by Hyman (1953), i.e., bun, bee, bore, by, boo, bev, bate and bix. In addition to making the verbal response to the bar stimulus, Ss were required to press the left microswitch when the disk stimulus appeared to the left of the focussing light, and the right
microswitch when it appeared to the right. For each trial, E said "ready" and pressed a buzzer. 1.4 seconds after the onset of the buzzer sound both stimuli came on simultaneously. Ss were required to make the appropriate verbal response to the bar position and press the appropriate key depending on the position of the disk. The order of making the responses was varied, as indicated above.

**Design:**

Three orders of responding were employed:

1) first the verbal response and then the manual response;
2) first the manual response and then the verbal response;
3) both responses simultaneously.

For each session only one order was employed. The presentation of orders was randomized in blocks of three. Each order was given six times, making a total of 18 sessions, of which only the last 15 were included in the data analysis. In addition, Ss were given two other practice sessions to learn the eight nonsense syllables and to familiarize themselves with the responses required to the stimuli.

Within a given session, the three different choice conditions described above for the verbal response were employed. The order of presentation of conditions was likewise randomized in blocks of three, and counter-balanced so that each condition appeared first, second or third in a session an equal number of times. During each session 32 measures were taken at each information level. S was informed before each condition of the number of alternatives, and each new information-level condition was begun with 16 practice trials on the verbal response alone, to familiarize S with the number of choices in the condition. To clearly delineate conditions, there
was a short break of about three minutes after each condition.

To assess the effect of the presence of another stimulus on RT to a given stimulus, several trials were included during the session in which only one of the stimuli was presented although S was expecting both. Under each information condition, each of the two stimuli, the bar and the disk, was presented alone four times. These eight trials were randomly dispersed among the regular trials. Thus, a total of 40 measures was taken at each information level, giving a total of 120 measures per session. In addition, 24 choice RT measures to the disk presented alone were taken at the beginning and end of each session, 12 measures with S pressing the left or right key (manual response) and 12 with S calling out whether the disk was left or right (verbal response), giving a total of 48 choice RT (CRT) measures. This provided a measure of CRT when the bar stimulus was not present, and allowed a comparison of the verbal- and manual RT's when the response selection decisions were the same.

Results

The mean choice RT to the bar at each of the three information levels as well as the choice RT to the disk are shown in Table 1. It can be seen that the verbal RT is considerably greater than the manual RT. Thus, we will use the predictions of the fixed interval model presented in Figure 2C for determining which model best describes the data.

The mean first and second RT's under each of the three conditions is shown in Figure 4. The mean over-all RT's under the three conditions are presented in Table 2.
Condition 1

For all three Ss, the verbal RT increased linearly as the number of bits of information was increased from one to three. As can be seen in Figure 4, the first and second RT curves are parallel. Since the manual response selection time is so much less than the verbal, both models predict parallel curves. To distinguish between them, we must first examine the magnitude of the RT$_2$ - RT$_1$ difference, to see if this approximates choice RT to the disk, and then look at the over-all RT, to see how this differs from the verbal RT alone.

The mean difference between the verbal and manual RT's was 300 ms. For observer DE, this value was not significantly different from his choice RT to the disk, and for TL and YK, it was about 100 ms. smaller. Hence, the 300 ms. appears to be a reasonable approximation to the choice RT to the disk.

In order to determine more closely the time required for the various components of the reaction, the formula suggested by Vaughan, Gilden, and Costa (1964) that simple RT = latency of visual evoked response (VER) + 100 ms. was used. One hundred simple RT measures were taken for each S, using a constant foreperiod of 1.4 seconds. Then, the latency of the VER was calculated by the formula VER = simple RT - 100 ms. This was taken as an approximate measure of the time required for the impulses generated by the stimulus to travel to the cortex. This VER estimate was then subtracted from the mean choice RT to the disk presented alone, to provide an estimate of response selection plus performance time to the disk. This last measure was compared with the difference between RT$_1$ and RT$_2$, which, according to the successive response selection model, should also
represent this value plus the additional component, attention switching time. The results are given in Table 3.

It can be seen that in all cases the difference between $RT_1$ and $RT_2$ is greater than the response selection plus performance time measure calculated from the above formula by from 50 to 100 ms. This increase may represent the time Ss require in shifting from one response to the other. It appears, based on the close correspondence between the choice RT to the disk and the $RT_2 - RT_1$ difference that the second response selection does not occur until after the first response has been selected, thus supporting a successive response selection model.

Similarly, the mean over-all RT far exceeds verbal RT alone. This suggests that the two response selections occurred sequentially.

**Condition 2**

Comparing over-all RT's in conditions 1 and 2 (Figure 4 and Table 2) it can be observed that for TL and YK reaction time is not significantly different under the two conditions. This is in agreement with the predictions of the successive response selection model. A fixed interval model would have predicted larger RT's in condition 2. Although it is possible that the time these Ss arbitrarily chose to separate the two responses exactly equals the value of the fixed interval plus switching time, this would seem unlikely, especially since Ss were instructed to emit all responses as rapidly as possible, and it is doubtful that they would have withheld the second response for so long.

For DE, it can be seen that over-all RT is significantly less in this situation than in condition 1 ($p < .001, F_{1,958} = 71.3$). This decrease may mean that for this S switching time is not a constant, and more time is required
to switch after a verbal response than after a key-press response. Another possibility is that after making the verbal response this S waited for a short period to make sure the response had been correct, and then switched, whereas he did not wait as long after the key-press response.

It should also be observed that manual RT to the disk increases as the information level of the bar stimulus is increased. Although this increase is slight, it is significant for all three Ss (p<.001, F2,477 = 11.54 (TL); 18.8 (DE); 9.01 (YK)). It thus appears that the information load of the second response selection has some influence on the rate of the first selection.

Finally, an estimate of attention switching time based on the data of condition 2 is presented in Table 4. It can be seen that the range of calculated values (75-150 ms.) agrees fairly well with that calculated from condition 1. The variation may be due to the method of calculation, which provides only a very approximate measure of the latency of the VER, or to individual differences -- some Ss may switch more rapidly in one direction than the other. At any rate, the attention switching time appears to center around 100 ms.

**Condition 3**

When Ss were instructed to emit their responses simultaneously, over-all RT was in all cases greater than verbal RT alone, as a fixed interval model would have predicted, and instead was quite close to the over-all RT observed in the sequential responding conditions. This again supports a successive response selection model.

An interesting finding, however, was that while the over-all RT was quite close to that of conditions 1 and 2, it was slightly smaller for all
three Ss. For DE and TL, this reduction was significant ($p < .001$, $F_{1,958} = 27.7$ (DE); 39.5 (TL)). To support a fixed interval model, this reduction should have resulted in over-all RT's which were equal to verbal RT to the bar alone, but in no case was the reduction sufficiently large to meet this prediction.

One possible explanation for this reduction is the time at which the attention switch can occur. Under sequential responding conditions, attention may not switch until the first response has been performed, while under the simultaneous responding conditions it may shift as soon as the response has been selected. This is shown below:

Sequential Select ----- Perform ------switch ----- select ---- perform
Responding $R_1$ $R_1$ $R_2$ $R_2$

Simultaneous Select ----- switch ---- select ----- perform $R_1$ and $R_2$
Responding $R_1$ $R_2$ simultaneously

This hypothesis is tested in Experiment II.

Finally, to assess the effect of the presence of a second stimulus on the RT to a given stimulus, the mean RT to each of the stimuli when they were presented alone (control measures), when the second stimulus was also presented, and when the second stimulus was expected but not presented, are shown in Table 5 (bar stimulus) and Table 6 (disk stimulus).

It can be seen that there is an increase in the RT to the bar of about 175 ms. when it is the first of two reactions. However, this increase is not significantly different when the disk is not presented if $S$ is expecting it. This indicates that the increase is a function of set, rather than the actual presence of the first stimulus, as has been suggested by Gottsdanker, Broadbent and Van Sant (1963).
For the disk, while there is an increase in RT both when the bar is presented and when the bar is expected, the increase is greater in the former case. Also, while the amount of the increase appears to be related to the information load of the bar stimulus when it is presented, the number of alternatives of the bar does not appear to have any effect if the bar is expected but not presented. Thus, in this case the actual presence of the bar appears to have some effect other than that of change of set alone.

Discussion

The results of this experiment support a successive response selection model of attention switching. This support is based on the findings that a) when the variable response was selected first (condition 1), the magnitude of the difference between RT₁ and RT₂ suggested that the second response was not selected until after the selection of the first response had been completed; b) over-all RT's were approximately the same regardless of the order in which the responses were selected; and c) Under instructions to emit both responses simultaneously, over-all RT was significantly greater than the verbal RT to the bar alone -- i.e., greater than the longer of the two response selections (condition 3), and approached that of the sequential response condition.

Calculation of the components of the RT revealed that the difference between RT₁ and RT₂ exceeded the calculated response selection and performance time for the second response by about 100 ms. This increase may represent attention switching time. However, other possibilities exist as well. It may indicate a period of "refractoriness" following a response, as suggested by Telford (1931) and by Davis (1957), or the time which S
may use to check on the correctness of the first response, as suggested by Fitts (1951).

Kristofferson (1965) has suggested that attention may be controlled by an internal mechanism with a periodic frequency of $M$ ms., such that attention can be shifted only at the end of this period. Since our result of 100 ms. agrees closely with his calculated value of $M$, it may be that while the attention switch does not occur until the first response has been selected, after that time it can switch only at the next period termination.

An unexpected finding in condition 2 was the increase in the manual RT to the disk as the information level of the bar stimulus increased. Although this increase was slight, it was significant for all three Ss. It thus appears that the information load of the second response selection has some influence on the first response selection. The first explanation to come to mind is one based on change in set. Gottsdanker et al. (1963) have shown that RT to a stimulus is increased when S knows he will have to make a second reaction shortly after the first. This finding was confirmed for condition 1. The results of condition 2 might then indicate that the set S adopts is a function of the difficulty of the second task he will have to make, such that the more difficult the expected second task, the longer he delays the first response. However, an explanation in terms of change of set alone cannot account for these results, because if the bar was not actually presented, even though S was expecting it, in two of the three Ss we do not get a corresponding increase in manual RT with information level of the bar, although set was identical in the two cases.

One possibility is that some division of attention can occur. While
most of the attention is aligned with the first response selection, some small amount of attention may be required to maintain the memory trace of the second stimulus. The amount of attention required for this latter task may vary with the number of possible alternatives from which the stimulus was selected. If we assume that speed of response selection varies inversely with the amount of attention aligned with it, then the more attention which is diverted to maintaining the memory trace of the second stimulus, the longer will be the first response selection. This would account for the slight increase in RT₁ which is observed with increasing information load associated with the second stimulus. However, this division of attention does not seem to result in decreased or increased efficiency, for over-all RT was not significantly smaller than in condition 1 for two of the three Ss.

It should also be noted that in condition 3, although the Ss were instructed to emit both responses simultaneously, this was not in fact done. All three Ss emitted the key-press response earlier than the verbal response. When E asked the Ss if they felt they were making the responses exactly simultaneously, two of the Ss said yes, and the third, YK, said that he felt the key-press response was lagging slightly. This difference in verbal and manual RT's for the same task was also found in the control measures, where Ss called out left or right (verbal RT) or made a manual key-press response to the disk. Mean verbal RT's were 580 (TL), 670 (YK) and 390 (DE) ms. -- i.e., approximately 200 ms. larger than the manual RT for the same task.
Experiment II

The results of Experiment I indicate that when two responses are required in rapid succession, attention is not switched to the second response selection until the first response has been selected. However, it is not clear whether this switch occurs as soon as the first response is selected, or whether it is delayed until the first response has been performed. This experiment was done to examine this problem more carefully.

Experiments which have examined the delay in RT\textsubscript{2} as a function of whether or not the first response was performed have not provided a clear-cut answer. Davis (1959; 1962) found that the delay in responding to the second of two stimuli was greater if a response was required to the first stimulus than if no response was required. In fact, he found (1962) that if no response was required to the first stimulus, and if the ISI was regular (i.e., the same ISI was employed during a block of 20 trials), then there was no delay at all in RT\textsubscript{2}. Even with a random ISI, Davis found a delay in RT\textsubscript{2} only at the shortest ISI if no response was required to the first stimulus. Kay and Weiss (1961) have similarly found that RT\textsubscript{2} is not delayed as much when no response was required to the first stimulus.

However, in both these experiments no measures were taken to ensure that attention was ever aligned with the first response selection, or that response selection times for the first stimulus were the same regardless of whether the performance of a response was required to the first stimulus. When no overt response was required, Ss might simply have ignored it.

In order to avoid this problem, and to vary only whether or not a
response had to be performed to the first stimulus, in this experiment a go no-go choice paradigm was employed, and delays were examined as a function of whether a response had been made to the first stimulus.

Method

Subjects:

Four M.I.T. undergraduates served as Ss in this experiment. Two of these Ss (YK and DE) had participated in the first experiment.

Apparatus:

The apparatus was the same as that described in Experiment I. Only two positions of the bar were employed. The stimuli were re-wired so that instead of coming on simultaneously, the disk always came on first. The ISI between the two stimuli was controlled by the tachistoscopic programmer.

Procedure:

The duration of the light stimuli was reduced to 20 ms. The disk was always presented first, followed after an interval by the bar. The ISI's from onset of the disk to onset of the bar were 25, 50, 100, 200 and 600 ms. For DE and CH the ISI's were randomly presented. For YK and IE, the ISI's were constant over blocks of 20 (regular presentation).

Ss always emitted the second response (to the bar), giving the appropriate name for the stimulus presented. However, the first response was made on only half of the trials. Ss attended a total of eleven one-hour sessions, of which the first constituted a practice session. For the first five experimental sessions, the first stimulus (disk) was responded to only if it appeared to the left of the focussing light for two of the Ss and if it appeared to the right of the focussing light for
the other Ss. In the last five sessions this was reversed. A total of 100 measures were taken at each ISI with S responding to the first stimulus, and 100 measures at each ISI with the first response omitted. To reduce competing responses, S removed the non-responding hand from the key and rested it in his lap. The data from the first session of each condition were not included in the analysis.

In the random condition (DE and CH), all the ISI and stimulus conditions were randomized and counter-balanced. In the regular condition (YK and IE) the five ISI's were randomized in blocks of 20, and counter-balanced for practice effects during a session. The left-right position of the disk stimulus was randomized within each block.

In addition to the above trials in which both stimuli were presented, two blocks of 12 trials each were given at the beginning and end of each session, one in which only the bar appeared (two-choice verbal RT) and a second block in which only the disk appeared (two-choice manual RT). Ss were instructed to respond as quickly as possible. When the disk was presented, S responded only to the side to which he would respond under the double stimulation condition.

Results

The mean second RT for each of the Ss under the two conditions of responding or not responding to the first stimulus is shown in Figure 5. The mean two-choice verbal RT is also shown to indicate the amount of increment when the disk was presented.

It is clear that under both the regular and random presentations of ISI's the second RT is greatly increased when S has to select a response to a first stimulus before he can attend to the second response, even if the
performance of an overt response is not required. This delay averaged 195 ms. at the shortest ISI.

A comparison of RT's under the conditions of responding or withholding the first response, as shown in Figure 5, indicates that $RT_2$ was increased to a greater extent if Ss were required to perform a response to the first stimulus. A two-way analysis of variance, comparing response vs. no response conditions and decline in RT's over the range of ISI's employed, showed that both these variables were significant beyond the .005 level. For DE the mean increase was 66 ms. and for YK it was 80 ms. It should be noted that these values are very similar to the decrease in over-all RT under the simultaneous condition which was observed in Experiment I (70 ms. for DE and 40 ms. for YK).

Since three of the Ss showed a reverse trend when the ISI was large -- i.e., RT was greater when Ss did not respond, an analysis of variance was done for each S comparing the two conditions only at these ISI's. The observed differences were found to be insignificant.

An examination of mean first reaction times, as seen in Table 7, indicates an increase in first RT over the mean two-choice RT. This agrees with the results of Experiment I. There are no significant changes in the first reaction time at different ISI's.

If we examine the delay in $RT_2$ across ISI's (Figure 5), it is clear that, with the exception of CH, the second response is still delayed when the ISI is 600 ms., even though the first response is completely over by then. Delays occurring at ISI's greater than the first RT have been observed previously (Davis, 1957; Welford, 1952). This would seem to suggest that over and above the delay in $RT_2$ as the result of not attending
to the second stimulus until the first response has been made, there is an extra delay involved, perhaps due to the time required to switch from one mode of responding to another.

Discussion

Our finding that there is a significant delay in RT₂ even when no response is required to s₁, provided Ss are forced to align attention with s₁, supports the hypothesis of an attention switching mechanism. Our results do not agree with those of Davis (1962), who found that if the ISI was regular, no delay occurred in the second RT if no first response was required. However, in his experiment, precautions were not taken to assure that attention was aligned with the first stimulus as soon as it was presented, and Ss may have ignored it completely, or not attended to it until the second response had been made, as Davis himself suggests. In our experiment, Ss were required to selectively attend to the first stimulus in order to determine whether a response was needed, before they could switch attention to the second response selection. The results show that if selective attention is given to the first stimulus, then the second RT is delayed, even if no overt response is made to s₁.

The main problem with which this experiment was concerned was whether the attention switch occurred as soon as the first response was selected, or whether the switch did not occur until the first response had been performed. Because in Experiment I we found that RT was significantly faster when both responses were made simultaneously, we hypothesized that under conditions of sequential responding, attention does not switch until the first response has been performed. Our results indicate that for all Ss RT₂ was delayed significantly longer when a response to s₁ was required.
Since first response selection times were the same, this increase must be related to the performance of the first response. Except for IE, where delays are still found with an ISI of 600 ms., the ISI over which increased delays are observed corresponds approximately to the duration of the first reaction. If the first response has been performed prior to the presentation of the second stimulus, there are no longer any significant differences between the response and no-response conditions.

It is of interest that the amount of the increment observed for DE and YK, who had participated in Experiment I, corresponded very closely with the decrease in the over-all RT observed for these Ss when they made both responses simultaneously. This suggests that the decrease in over-all RT under the simultaneous responding condition of Experiment I was the result of being able to switch attention as soon as the first response was selected, rather than after the first response was performed.

To sum up, in situations where two responses are performed sequentially, selective attention appears to be required for the performance of a response, as well as for the selection of it. Although two responses can be performed simultaneously, it does not appear that response selection and response performance can occur in parallel. If the two stimuli are presented simultaneously and Ss are instructed to make both responses simultaneously (as in Experiment 1, condition 3), attention may switch after the first response selection, and the performance of both responses is made after the selection of the second response. However, when the two responses are made sequentially, attention does not seem to switch until after the performance of the first response.
Chapter III

Stimulus-response compatibility and parallel response selection

When a response must be made to each of two rapidly succeeding stimuli, the reaction time (RT) to the second stimulus is typically prolonged (Telford, 1931; Davis, 1956; Marrill, 1957; Hick, 1958; Kay and Weiss, 1961). This phenomenon is commonly referred to as the "psychological refractory period", and suggests the presence of a limiting mechanism in the processing system. This limiting mechanism appears to be quite central, and not the result of peripheral sensory or response interference.

It has been suggested (Smith, 1966) that selective attention may operate as the limiting mechanism in this situation. Selective attention is considered necessary for the facilitation or "boosting" of the S-R connection, and is thus required for the occurrence of the response selection. A model presented by Smith (1966)* describes the operation of selective attention as a switching mechanism which can be directed to only one response selection at a time. Hence, if two response selections must be made, each of which requires the presence of the attention mechanism, attention must be aligned first with one response selection, and then, when this is completed, switch to the second response selection. Because of this limiting mechanism, response selections which require selective attention must proceed sequentially -- i.e., parallel processing is not possible.

According to such a model, if the S-R bond becomes so well established that any facilitation or "boosting" by the attention mechanism is no longer required, then the limitations of this mechanism would not be operative.

* Chapter two in this thesis.
and parallel processing should occur. The possibility of such an occurrence is suggested by our first experiment. This experiment was conducted in order to determine whether the delay in switching attention from one response selection to another was influenced by the motor similarity of the two responses. An interesting finding of the experiment was that in this situation a delay in the second response did not always occur. The second experiment was therefore conducted to examine this possibility more carefully, and to attempt to provide a second criterion for whether selective attention is needed for response selection — namely, the increase in RT to a single stimulus as the number of alternatives from which it is selected is increased. It is suggested that a limited capacity selective attention mechanism may underlie both the psychological refractory period and the observed relationship between RT and the number of response alternatives.

Experiment I

The aim of this experiment was to determine whether the delay in the response to the second of two rapidly succeeding stimuli is influenced by the motor similarity of the two responses. If we assume that a given set is adopted for a particular movement, then when two responses require the same movements, the same set can be adopted for both, and this may have a facilitatory effect on attention switching. Our experiment was conducted to examine this possibility.

In order to keep constant both the time required to select a response and the time required to execute this response, a task was employed in which only the direction — i.e., forward or backward — of the two responses was varied. We were interested in determining whether the latency of the second
response differed significantly depending on whether it was in the same or opposite direction to the first response. This was studied under two conditions -- one in which S did not know in advance what relationship the two responses would bear to each other, and one in which S knew that the second response would always bear some definite relationship to the first response. This latter condition allowed us to determine whether Ss could "pre-arrange" one order of switching more easily than another.

Method

Subjects:

Three male M.I.T. undergraduates and one 17-year-old female from a local school participated in this experiment.

Apparatus:

A diagram of the apparatus is shown in Figure 6. The apparatus consisted of four red neon lights mounted at the corners of a square with side length of 2" (visual angle = 8.7 degrees). A dim orange bulb placed at the center of the square served as a focussing light. These lights were mounted on a table in front of S, so that two lights were on his left side and two on his right side. The interval between the warning click and the onset of the first light and the ISI between onset of the first light and onset of the second light were controlled by two Hunter decade interval timers. These timers also started two Hunter counters: the first counter started as soon as the first light was presented, the second started as soon as the second was presented. The lights were wired so that they could come on in any order -- i.e., left-right or right-left. For a given side (left or right) either the upper or lower light could be selected. Hence, any arrangement of the four lights
was possible, with the restriction that the two stimuli presented were always on different sides. It was also possible to present only one light at a time. Each light stayed on until S had reacted to it by throwing a switch, as described below.

Two RT switches were mounted as in Figure 6. Each switch could be pushed either up (away from S, in the direction of the upper light) or down (toward S, in the direction of the lower light). Throwing a switch toward a given light caused the off-set of the light. It also stopped a Hunter counter, which measured RT in ms. If S responded in the wrong direction, the light stayed on and the timer continued to count.

Procedure:

For each trial, E said "ready" and pressed a switch which made a loud click. 1.4 seconds after the click the first light came on. The ISI between the two lights was fixed at 100 ms. Three response conditions were employed:

1) **Both responses independent**

   No restrictions were placed on the possible combinations of onset of the two lights. All presentations were randomized and counter-balanced with regard to order (L-R or R-L) and direction (up or down).

2) **Both responses in the same direction**

   S did not know the direction of the first response, but was told that both responses would always be in the same direction.

3) **Both responses in the opposite direction**

   S was told that the two responses would always be in opposite directions -- one up, the other down, or vice versa. He did not know in which order the responses would be required.
The three conditions were presented in blocks, with 32 measures taken in each block. In addition, eight "catch trials" -- i.e., trials in which S was expecting two stimuli but only one was presented -- were included, to prevent S responding to the second stimulus before it was presented. The order of presentation of blocks was randomized. Since there are six possible combinations of the three blocks, Ss were run for six days, receiving one of these orders in the morning of each day, and the reverse order in the afternoon, making a total of twelve one-hour sessions. Only the data of the last ten sessions were included in the analysis.

To provide a measure of RT when only one light was presented, 24 four-choice RT, 24 two-choice RT and 24 simple RT measures were taken each day, one-half at the beginning and one-half at the end of each session.

Results

The mean second RT's are shown in Table 8 as a function of their similarity to the first response. When the two responses are independent, \( RT_2 \) represents a two-choice response, and for comparison the mean two-choice RT to a stimulus presented alone is given in the third column. When the direction of the second response was known as soon as the first stimulus was given, this second RT represents a simple RT, and the mean simple RT for each S is given in the third column also.

The results do not point to any clear relationship between the similarity of the two motor responses and the delay in \( RT_2 \). For JW, \( RT_2 \) was significantly faster when the two responses were in the same direction. For CH and MB, on the other hand, there was no difference when
the two responses were independent. However, RT₂ was significantly faster when the two responses were in opposite directions in the condition where the prior relationship was known. Finally, for LF the direction of responding did not appear to have any effect at all. Thus, similarity of motor responses does not seem to have any consistent effect on ease of attention switching.

It should be noted that in the condition where the second response should have represented a simple RT (relation between the responses known), the over-all mean second RT (257 ms.) was not significantly different from the two-choice RT (258 ms.). This suggests that during the short, 100 ms. ISI Ss are not able to sufficiently organize the information given by the first stimulus to make the second response a simple RT. Rather, it appears that the second response more closely represents a two-choice RT.

Mean first RT's are presented in Table 9, together with the four-choice RT measures and the RT's on the "catch trials" where only one stimulus was presented, though two were expected. It may be seen that first RT's are about 25 ms. greater than four-choice RT. Since a similar increase is found on the catch trial RT's, this increase seems to be a function of change in set in the double response situation, rather than the presence of the second stimulus.

A very interesting finding in this experiment was that when the two responses were independent, RT₂ for LF was no longer than the two-choice RT to a stimulus presented alone. Similarly, for JW it is not significantly greater when the two responses are in the same direction.

This may mean that the time required to select the first response was less than 100 ms. (the value of the ISI), so that the attention switch could have been completed prior to the presentation of the second stimulus. However, since the mean first RT was about 300 ms., this would seem unlikely.

A more plausible explanation is that under conditions of high stimulus-response compatibility, selective attention may not always be required for
response selection. The importance of S-R compatibility for response selection is suggested by its influence on RT in situations where the number of response alternatives is varied. With low S-R compatibility, RT increases linearly as the log of the number of response alternatives (Hick, 1952; Hyman, 1953; Crossman, 1953), whereas with high S-R compatibility, RT is not at all influenced by the number of alternatives (Mowbray and Rhoades, 1959; Davis, Moray and Treisman, 1961). In this experiment it was found that while there was an increase in RT as the number of alternatives was increased, this increase was very slight, and appeared to be declining with practice. It is therefore possible that the same factor, namely selective attention, may underlie both the psychological refractory period and the change in RT with the number of response alternatives. This possibility is examined in more detail in Experiment II.

Experiment II

The results of Experiment I suggest that a limited capacity attention mechanism may underlie both the psychological refractory period and the relationship between RT and the number of response alternatives. To consider the way in which attention may underlie the latter, let us assume that attention is required in order to prepare all the possible response alternatives. This preparation may occur in the form of "boosting" the level of activity of the S-R bonds, in order that response selection may be speeded up when the stimulus is presented. If the attention mechanism is of limited capacity, then the greater the number of responses which it must keep in readiness, the lower will be the level of "boosting" of each response. If RT is a function of the level of this prior preparation, then it follows that the greater the number of response alternatives, the longer will be the RT. This would explain the increase in RT as the number of
alternatives is increased. To account for the independence between RT and the number of alternatives for well-practiced tasks, we can assume that after extensive practice all S-R connections are so well established that any further facilitation by the attention mechanism is unnecessary. Hence, the limitations imposed by the attention mechanism are removed.

Turning to the psychological refractory period, we have suggested that RT₂ is prolonged because of the necessity of waiting for attention to be switched from the first response selection. It therefore follows that if attention is not required for the first response selection, parallel processing should be possible. If response selections can occur in parallel, then when two stimuli are presented simultaneously, it should take very little more time, if any, to select both responses than to select one alone. Similarly, when the stimuli are presented sequentially, there should not be any delay in the second response. This experiment was conducted to examine these possibilities.

Method

Subjects:

The four students employed in Experiment I continued as subjects in this experiment.

Apparatus:

The apparatus was the same as that described in the previous experiment.

Procedure:

The procedure employed was similar to that of Experiment I, but all stimuli were randomly presented (as in the independent condition of Experiment I). After a warning period of 1.4 seconds, one of the four lights appeared, followed after an ISI by a second light. Since all responses represented
choice RT's, no catch trials were employed. The order of onset of lights was completely randomized and counter-balanced. Six ISI's were employed: 0 (both lights came on simultaneously), 30, 60, 100, 300 and 500 ms. Ss were instructed to respond to each stimulus as quickly as possible. When the two stimuli came on simultaneously, they were instructed to try to make the two responses simultaneously. There were two ISI conditions:

a) Regular ISI

For two Ss (JW and MB) the ISI was varied in blocks of 16. The order of presentation of blocks was randomized. Prior to each block, Ss were shown the ISI and were then given two practice trials.

b) Random ISI

For the other two Ss (CH and LF) the ISI was varied randomly. Sixteen measures were taken at each ISI.

Subjects attended five one-hour sessions, of which only the last four were included in the data analysis, giving a total of 64 measures per ISI.

In addition to the above trials, choice RT's to a single light were also taken. Twenty-four four-choice RT and 24 two-choice RT measures were taken at each session -- half at the beginning and half at the end. A constant foreperiod of 1.4 seconds was also employed for these trials.

Results

Since we have defined situations in which attention may not be required for response selection as those in which there is no increase in choice-RT with an increasing number of response alternatives, let us first examine the choice-RT's to see how they vary with the number of alternatives. This is given in Table 10.
It can be seen that while the four-choice RT is significantly larger than the two-choice RT for LF and MB, this difference is very small (9 ms. and 14 ms. respectively). For the other two Ss there is no significant difference between two- and four-choice RT. Therefore, according to our definition, this is a situation in which coding has become relatively "automatic" -- i.e., attention may no longer be required for the response selection, or may be required only to initiate the process. It should be noted, however, that the choice RT is still larger than the simple RT observed in Experiment I (Table 8). This suggests that a different type of preparation is required in the two cases. For simple RT S must be set merely to move when a stimulus is presented, whereas in a choice situation he does not know which of two or more responses he will be required to make. Given this difference between simple and choice RT, however, the number of alternatives required for the choice reaction no longer appears to have any influence.

Let us now turn to RT's in the double response situation, to see how they are affected in such a situation.

a) Over-all RT for the simultaneous condition

If parallel processing is possible, it should take Ss no longer to select two responses than to select one alone. Therefore, the over-all RT when the two stimuli are presented simultaneously should resemble that of the four-choice RT (which is the same as two-choice RT for CH and JW). On the other hand, if the two response selections are occurring sequentially, over-all RT should represent the sum of two choice reactions, a value which is approximately double the four-choice RT.

The data are presented in Table 11. It can be seen that over-all RT
is very close to the four-choice RT. This suggests that the response selections occurred in parallel. However, while the correspondence is very close, the RT in the double response situation is in all cases larger by about 40 ms. in the random condition and 25 ms. in the regular condition. This increase is much smaller than would be expected if sequential response selection were occurring. Rather, it appears to be a function of change in set when two responses are required. This is supported by the finding that increases of about the same magnitude are found in the reaction to the first stimulus when the stimuli are presented successively, as shown in Table 11.

An analysis of variance, comparing mean first RT's at each ISI with over-all RT in the simultaneous condition showed no significant differences for all Ss but MB. For this S, omission of the RT₁ value at the 500 ms. ISI again yielded no significant differences. This significant decline in RT₁ at the 500 ms. ISI for MB, for whom the ISI's were varied in blocks (i.e., regular ISI), indicates that when S knows that the ISI will be quite long, he can prepare for a first response almost as well as for a single response.

Thus, based on the first criterion of over-all RT in the simultaneous presentation condition, it appears that in this situation response selections occurred in parallel.

b) Second RT with sequential presentation

The second aspect of the question is to determine whether the second response is delayed when the stimuli are presented sequentially (i.e., ISI of 30 to 500 ms.). In situations where attention is required for the first response selection, RT₂ is maximally delayed at the shortest ISI, with the delay declining as the ISI is increased. The magnitude of this
increase at the shortest ISI is usually at least 100 ms. The mean second RT's in our situation are shown in Figure 7. The two-choice RT measure is also shown to allow some assessment of the magnitude of the delay.

The first thing to observe is that the second RT is very little, if at all, influenced by the ISI between the two stimuli. Unlike situations described as the psychological refractory period, where the difference in RT\(_2\) over the range of ISI's from 50 to 500 ms. is well over 100 ms., the maximum decline observed in our situation is about 35 ms. -- a very important quantitative difference.

When the ISI was varied regularly, analysis of variance did not indicate any significant differences across ISI's for MB. For JW, no significant differences were found in second RT's across the ISI's from 30 to 300 ms. Inclusion of the 500 ms. ISI gave an F value which was significant at the .05 level (F\(_{4,315} = 3.00\)), indicating that RT was slightly faster at this ISI.

When the ISI was varied randomly, although analysis of variance indicated significant differences for both Ss, the magnitude of this delay, as shown in Figure 7, is extremely small. For LF, in fact, the significance was not due to a decline with increasing ISI, as is usually reported for the psychological refractory period. RT is shorter when the ISI is 60 ms. than 500 ms., and just as large at 300 ms. as at 30 ms. For CH, the observed difference was only 35 ms. If he was not selecting the second response until after the first response had been selected, the increase would be much greater, the delay in RT\(_2\) approximating the choice RT to the first stimulus. That the increase is so small suggests that when the stimuli are presented randomly, S does not know when to expect the second stimulus, and preparation may be inadequate at the shortest ISI's. Such an explanation
is feasible because the increase in RT2 is no greater than that observed for single RT's at very short ISI's, when the foreperiod is varied randomly (Nickerson, 1965).

The second question is whether the mean RT2 value is greater than the two-choice RT alone. For MB and LF, the mean RT2's (270 and 255 ms. respectively) did not differ significantly from the two-choice RT alone. Similarly, for JW the mean RT2 value of 256 ms. (RT2 at 500 ms. excluded) was again not significantly different from the two-choice RT.

It is interesting to observe that for JW, RT2 with a regular ISI of 500 ms. was significantly faster than two-choice RT with a fixed foreperiod of 1.4 seconds. If the first light is considered to have the role of a warning signal, and the ISI is thus the period of preparation, such a difference would be expected, for Klemmer (1956) has shown that RT is faster at relatively short foreperiod durations than at longer ones.

Thus, in three of the four Ss mean RT2 is not significantly longer than two-choice RT alone, while for the fourth the magnitude of the increase is much smaller than expected if the two responses were being selected sequentially.

Discussion

The results of this experiment suggest that the same mechanism may underlie both the psychological refractory period phenomenon and the relationship between RT and the number of response alternatives. It is suggested that if RT does not increase with the number of alternatives, then selective attention may not be required for the response selection. Assuming that selective attention is a limiting mechanism in information processing, reactions whose selection times are independent of the number of alternatives should be able to occur in parallel. An examination of the over-all RT required to make the two responses when the two stimuli were presented simultaneously, as well as the latency of the second response when the two responses were made sequentially, suggests that parallel response selection did occur in this situation.
Bibliography


Davis, R. The limits of the "psychological refractory period". Quart. J. exp. Psychol., 1956, 8, 24-38.

Davis, R. The human operator as a single channel information system. Quart. J. exp. Psychol., 1957, 9, 119-129.


Davis, R. Expectancy and intermittency. *Quart. J. exp. Psychol.*, 1965, 17, 75-78.


Nickerson, R. S. Response time to the second of two successive signals as a function of absolute and relative duration of intersignal interval. *Perceptual and Motor Skills*, 1965, 21, 3-10.


Table 1

Verbal and Manual Choice RT's in ms.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Verbal Choice RT</th>
<th>Manual Choice RT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Information in Bits</td>
<td></td>
</tr>
<tr>
<td></td>
<td>One</td>
<td>Two</td>
</tr>
<tr>
<td>TL</td>
<td>800</td>
<td>1190</td>
</tr>
<tr>
<td>YK</td>
<td>690</td>
<td>950</td>
</tr>
<tr>
<td>DE</td>
<td>480</td>
<td>610</td>
</tr>
</tbody>
</table>
Table 2

Comparison of over-all RT in ms. under the three order-of-responding conditions, averaging across information levels

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Condition 1 (verbal-manual)</th>
<th>Condition 2 (manual-verbal)</th>
<th>Condition 3 (simultaneous)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TL</td>
<td>1690</td>
<td>1693</td>
<td>1493</td>
</tr>
<tr>
<td>YK</td>
<td>1453</td>
<td>1477</td>
<td>1440</td>
</tr>
<tr>
<td>DE</td>
<td>977</td>
<td>839</td>
<td>767</td>
</tr>
</tbody>
</table>
Table 3

Analysis of the Components of the RT (in ms.)
Based on data of Condition 1

<table>
<thead>
<tr>
<th>Subjects</th>
<th>TL</th>
<th>YK</th>
<th>DE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Simple RT (SRT)</td>
<td>228</td>
<td>276</td>
<td>197</td>
</tr>
<tr>
<td>2) Visual Evoked Response (SRT - 100)</td>
<td>128</td>
<td>176</td>
<td>97</td>
</tr>
<tr>
<td>3) Choice RT to disk</td>
<td>410</td>
<td>400</td>
<td>250</td>
</tr>
<tr>
<td>4) Measure of response selection time + performance time (3) - (2)</td>
<td>282</td>
<td>224</td>
<td>153</td>
</tr>
<tr>
<td>5) $RT_2 - RT_1$</td>
<td>333</td>
<td>287</td>
<td>257</td>
</tr>
<tr>
<td>Measure of response selection time + performance time + attention switching time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6) Attention switching time</td>
<td>51</td>
<td>63</td>
<td>104</td>
</tr>
<tr>
<td>(5) - (4)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4

Analysis of the Components of the RT (in ms.)
Based on data of Condition 2

<table>
<thead>
<tr>
<th>Subjects</th>
<th>TL</th>
<th>YK</th>
<th>DE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Simple RT (SRT)</td>
<td>228</td>
<td>276</td>
<td>197</td>
</tr>
<tr>
<td>2) Visual Evoked Response</td>
<td>128</td>
<td>176</td>
<td>97</td>
</tr>
<tr>
<td>3) Two-choice verbal RT</td>
<td>800</td>
<td>690</td>
<td>480</td>
</tr>
<tr>
<td>4) Measure of response selection time + performance time (3) - (2)</td>
<td>672</td>
<td>514</td>
<td>383</td>
</tr>
<tr>
<td>5) ( \text{RT}_2 - \text{RT}_1 ) Measure of response selection time + performance time + attention switching time</td>
<td>830</td>
<td>610</td>
<td>460</td>
</tr>
<tr>
<td>6) Attention switching time ( (5) - (4) )</td>
<td>158</td>
<td>96</td>
<td>77</td>
</tr>
</tbody>
</table>
Table 5

Mean first RT to the bar as a function of the presence or expectancy of the disk

<table>
<thead>
<tr>
<th>No. of response alternatives</th>
<th>Ss</th>
<th>Bar alone</th>
<th>Bar and Disk</th>
<th>Bar alone, Disk expected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TL</td>
<td>800</td>
<td>1070</td>
<td>1060</td>
</tr>
<tr>
<td></td>
<td>YK</td>
<td>690</td>
<td>1010</td>
<td>960</td>
</tr>
<tr>
<td></td>
<td>DE</td>
<td>480</td>
<td>580</td>
<td>560</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td>657</td>
<td>887</td>
<td>860</td>
</tr>
<tr>
<td></td>
<td>TL</td>
<td>1190</td>
<td>1370</td>
<td>1310</td>
</tr>
<tr>
<td></td>
<td>YK</td>
<td>950</td>
<td>1190</td>
<td>1180</td>
</tr>
<tr>
<td></td>
<td>DE</td>
<td>610</td>
<td>680</td>
<td>710</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td>917</td>
<td>1080</td>
<td>1067</td>
</tr>
<tr>
<td></td>
<td>TL</td>
<td>1360</td>
<td>1630</td>
<td>1520</td>
</tr>
<tr>
<td></td>
<td>YK</td>
<td>1110</td>
<td>1300</td>
<td>1330</td>
</tr>
<tr>
<td></td>
<td>DE</td>
<td>820</td>
<td>900</td>
<td>960</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td>1097</td>
<td>1277</td>
<td>1270</td>
</tr>
</tbody>
</table>
Table 6

Mean first RT to the disk as a function of
the presence or expectancy of the bar

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Information in bits</th>
<th>Disk and bar</th>
<th>Disk alone, bar expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>TL</td>
<td>1</td>
<td>620</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>700</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>750</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>720</td>
<td>640</td>
</tr>
<tr>
<td>YK</td>
<td>2</td>
<td>810</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>850</td>
<td>560</td>
</tr>
<tr>
<td>DE</td>
<td>1</td>
<td>280</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>330</td>
<td>310</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>380</td>
<td>350</td>
</tr>
</tbody>
</table>
Table 7

Mean first reaction time at each ISI

<table>
<thead>
<tr>
<th>Ss</th>
<th>ISI in ms.</th>
<th>Average</th>
<th>Two-choice manual RT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>DE</td>
<td>293</td>
<td>301</td>
<td>270</td>
</tr>
<tr>
<td>CH</td>
<td>290</td>
<td>307</td>
<td>304</td>
</tr>
<tr>
<td>YK</td>
<td>533</td>
<td>527</td>
<td>559</td>
</tr>
<tr>
<td>IE</td>
<td>304</td>
<td>299</td>
<td>303</td>
</tr>
</tbody>
</table>
Table 8

Comparison of $RT_2$ in ms. as a function of its motor similarity with the first response

<table>
<thead>
<tr>
<th></th>
<th>Same direction</th>
<th>Different direction</th>
<th>Two-choice RT</th>
<th>Simple RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Both responses independent</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH</td>
<td>280</td>
<td>281</td>
<td>248</td>
<td></td>
</tr>
<tr>
<td>LF</td>
<td>262</td>
<td>264</td>
<td>262</td>
<td></td>
</tr>
<tr>
<td>MB</td>
<td>307</td>
<td>299</td>
<td>263</td>
<td></td>
</tr>
<tr>
<td>JW</td>
<td>257</td>
<td>281</td>
<td>257</td>
<td></td>
</tr>
<tr>
<td>b) Relation between the responses known</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH</td>
<td>276</td>
<td>250</td>
<td>232</td>
<td></td>
</tr>
<tr>
<td>LF</td>
<td>240</td>
<td>245</td>
<td>228</td>
<td></td>
</tr>
<tr>
<td>MB</td>
<td>295</td>
<td>278</td>
<td>231</td>
<td></td>
</tr>
<tr>
<td>JW</td>
<td>230</td>
<td>245</td>
<td>207</td>
<td></td>
</tr>
</tbody>
</table>
Table 9

A comparison of four-choice RT, mean first RT, and mean RT on "catch trials" (in ms.)

<table>
<thead>
<tr>
<th>Subjects</th>
<th>four-choice reaction time</th>
<th>mean first reaction time</th>
<th>reaction time on &quot;catch trials&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH</td>
<td>254</td>
<td>280</td>
<td>281</td>
</tr>
<tr>
<td>LF</td>
<td>273</td>
<td>300</td>
<td>305</td>
</tr>
<tr>
<td>MB</td>
<td>276</td>
<td>287</td>
<td>290</td>
</tr>
<tr>
<td>JW</td>
<td>269</td>
<td>288</td>
<td>295</td>
</tr>
</tbody>
</table>
Table 10

A comparison of two-choice and four-choice RT

Reaction time in ms.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Two-choice RT</th>
<th>Four-choice RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH</td>
<td>238</td>
<td>240</td>
</tr>
<tr>
<td>LF</td>
<td>243</td>
<td>252</td>
</tr>
<tr>
<td>JW</td>
<td>264</td>
<td>262</td>
</tr>
<tr>
<td>MB</td>
<td>256</td>
<td>270</td>
</tr>
</tbody>
</table>
Table II

A comparison of four-choice RT, mean first RT and
over-all RT in the simultaneous condition

<table>
<thead>
<tr>
<th>Ss</th>
<th>4-choice RT</th>
<th>Over-all RT in Simultaneous cond.</th>
<th>Mean first RT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Random ISI</td>
<td></td>
<td></td>
<td>269</td>
</tr>
<tr>
<td>CH</td>
<td>240</td>
<td>286</td>
<td>299</td>
</tr>
<tr>
<td>LF</td>
<td>252</td>
<td>294</td>
<td>282</td>
</tr>
<tr>
<td>Regular ISI</td>
<td></td>
<td></td>
<td>293</td>
</tr>
<tr>
<td>JW</td>
<td>262</td>
<td>293</td>
<td>293</td>
</tr>
<tr>
<td>MB</td>
<td>270</td>
<td>302</td>
<td>293</td>
</tr>
</tbody>
</table>
Figure Captions

Figure 1  Predictions of a successive response selection model
Figure 2  Predictions of a fixed interval model
Figure 3  Apparatus of visual array
           A. Top view  B. Front view as seen by subject

S_b - light source for bar stimulus;  S_c - light source for
circular disk stimulus;  B - sheet of P.V.C. plastic in which
a bar-shaped slit had been cut;  C - sheet of P.V.C. plastic
in which a circular disk had been cut;  f - red focussing light;
M - half-silvered mirror with 50% transmittance and 50%
reflectance;  b - bar stimulus;  c - circular disk stimulus;
LR - luminous ring;  k - knob for changing bar stimulus position

Figure 4  Mean reaction time to each stimulus under the three order-of-
responding conditions

Figure 5  Latency of the response to the second stimulus as a function
of the prior performance of a response to the first stimulus

Figure 6  Diagram of apparatus
           S - two-way switch;  B - red neon bulb;  f - focussing light

Figure 7  Mean second reaction time across ISI's
Fig. 1

- MANUAL RT
- VERBAL RT

REACTION TIME

NUMBER OF ALTERNATIVES
Figure 2

**COVERT RESPONSE SELECTION CURVES**

A) MANUAL RT GREATER THAN VERBAL RT

B) MANUAL RT LESS THAN 8-CHOICE VERBAL RT

C) MANUAL RT LESS THAN VERBAL RT

**OVERT RT CURVES**

NUMBER OF VERBAL RESPONSE ALTERNATIVES
Figure 4

VERBAL REACTION TO BAR
MANUAL REACTION TO DISK

CONDITION 1  CONDITION 2  CONDITION 3

NO. OF ALTERNATIVE VERBAL RESPONSES  TO  BAR STIMULUS
Figure 5

REGULAR ISI

DE

CH

S. RESPONDED TO
S. NOT RESPONDED TO

2-CHOICE VERBAL REACTION TIME

RANDOM ISI

YK

EI

ISI in milliseconds

RT2 in milliseconds
Figure 6
Figure 7

REGULAR ISI

RANDOM ISI

RT$_2$ in milliseconds

ISI in milliseconds

JW
MB

CH
LF