# ANALYSIS OF SEQUENTIAL EFFECTS IN CHOICE REACTION TIMES

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This is to certify that the

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# ABSTRACT

## ANALYSIS OF SEQUENTIAL EFFECTS IN CHOICE REACTION TIMES

by Robert J. Remington

A review of the previous literature indicated that a more systematic and comprehensive approach to the study of sequential effects in choice reaction time (CRT) experiments was needed. A repetition effect analysis (i. e., a comparison of the mean reaction time for all stimulus events which are immediately preceded by the same stimulus event with the mean reaction time for all the stimulus events that are immediately preceded by a different stimulus) represents the extent of the sequential analysis carried out by a majority of the researchers who have reported on sequential effects in CRT experiments. Most current models of such sequential effects, being based upon the results obtained from this simplest sort of sequential analysis, imply that the time required to process a given signal is relatively independent of the signals presented more than one trial back. It appears that premature theorizing based on such analysis has been relatively ineffective in stimulating the sort of detailed data analysis which is needed to sharpen our theoretical formulations in this area. It was the major thesis

of this paper that carefully collected CRT data contain more information concerning the microstructure of underlying choice reaction processes than can be obtained through the more common data analysis procedures. In keeping with this thesis, new methods of data analysis were introduced and applied to data collected from a CRT experiment.

The CRT experiment reported in the present paper consisted of five experimental conditions (1) a two-choice condition in which the stimulus events were equiprobable, (2) a two-choice condition in which one stimulus event appeared with probability of .70, (3) a four-choice condition in which the stimulus events were equiprobable, (4) a four-choice condition in which one stimulus event appeared with probability of .40 and the other three stimulus events were equiprobable, and (5) a simple reaction time condition. Each of five subjects performed under all five experimental conditions. The discrete choice reaction task required that the subject press the key corresponding spatially to the stimulus light presented on a given trial. With the aid of a rather complex automated data acquisition system, a total of 26,400 data records were collected.

The results of a number of different data analyses are reported. These analyses include the usual sorts of data analysis as well as a new way of examining all possible sequential effects.

The results of the comprehensive analysis of sequential effects reported in the present paper clearly demonstrate that an adequate model of CRT must account for third, fourth, fifth, and possibly higher-order sequential effects as well as the second-order repetition effect. Findings are reported that shed some light on the nature of the repetition effect and the weaknesses of some of the theoretical notions associated with this popular sequential effect.

The results of the present study, in addition to demonstrating the feasibility of a more comprehensive approach to the study of sequential effects, contained a number of methodological implications. For example, the common practice of collapsing or averaging over components which make up an experimental condition was shown to lead to misinterpretations regarding the relative importance of certain sequential effects.

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By

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To my wife, Dee.

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# INTRODUCTION

The well-known choice reaction time (CRT) experiment has enjoyed what Kaplan (1964) describes as a "secondary analysis"--that is, an analysis in a new conceptual frame--which gives it a very different significance. As introduced by Donders (1868), the CRT experiment was undertaken with the general purpose of measuring times required for various psychological processes. An excellent account of these early classical experiments can be found in Woodworth and Schlosberg (1954).

In 1886 Merkel found that CRT was a negatively accelerated increasing function of the number of stimulus alternatives. Merkel's findings stood as such until Hick (1952), through analysis of both his own data and that of Merkel, showed that CRT was linearly related to the logarithm of the number of stimuli. The Shannon (1948) definition of information was the stimulus that led Hick to plot CRT as a function of the log of the number of stimulus categories. The finding that the average CRT is directly proportional to the information contained in the stimulus set was immediately seen as being a potentially valuable means of studying human information processing. Data from a CRT experiment are now used to evaluate different theoretical notions concerning the way in which human beings process information and arrive at the decisions required by choice reaction situations. Most of the present models of choice reaction behavior assume that these decisions are made up of a collection of component decisions and that the nature and organization of the component decisions can be inferred from the study of reaction-time data from a variety of simple choice situations. That this conceptualization of the CRT experiment has been an interesting and perhaps fruitful one is seen by the fact that there has been continuous research in the area since the Hick study in 1952. Excellent reviews of the experimental findings and theoretical formulations associated with the informational analysis approach to the CRT experimental situation can be found in a number of sources, including Bricker (1955), Rapoport (1959), Leonard (1961), Garner (1962), and Edwards (1964).

A classic study among the literature relating information theory to CRT data, and a forerunner of the research reported in the present paper, was conducted by Hyman (1953). In a brief departure from the informational analysis of his experimental results Hyman made what has become recognized as the first sequential analysis of CRT data. Averaging the results from his four experimental subjects he found that the mean reaction time (RT) for a repeated stimulus was significantly lower than the mean RT for a changed stimulus under both the four- and eight-choice conditions (equiprobable alternatives) of a light-naming discrete CRT task. This apparent "facilitation" resulting from a repetition of a particular stimulus has become known as the "repetition effect". In the case of only two equiprobable alternatives no repetition effect was observed. In fact, Hyman reports that the mean RT for a repeated stimulus was "slightly" longer than that obtained for a changed stimulus.

Taking this sort of sequential analysis one step further, Hyman plotted RT as a function of the number of stimuli intervening between successive occurrences of a particular stimulus in the series, separately for conditions with two, four, and eight alternatives. The general trend of the function for the four and eight alternative conditions was found to be parabolic; the bow-shaped curve reached a maximum at a displacement of one or two stimulus presentations and then came down again. Hyman suggested that this bow-shaped curve might be produced by the following factors:

> 1. One is S's verbalized introspection that a stimulus which has not appeared for some time in the series is reacted to more quickly than ordinarily because of the greater expectancy now attached to its appearance. This verbal expectancy apparently accounts for the fact that reaction times begin to get lower than the maximum for large displacements.
>
> 2. The second factor seems to consist of some sort of residual effect produced by just having seen and reacted to a particular stimulus; this effect seems to facilitate reaction to this stimulus if it reappears within a finite time interval. For eight alternatives this facilitation seems to last for at least a displacement of one stimulus presentation. For two alternatives this facilitation does not affect the function; perhaps it is at its maximum throughout the

> series and therefore does not show in the function for two alternatives. [p. 195]

The above paragraphs accurately summarize the extent of Hyman's sequential data analyses and theorizing concerning the observed sequential effects. It is surprising that this potentially informative phase of CRT research remained dormant until recently when Bertelson reported the first in a series of experiments which are primarily concerned with sequential effects in CRT behavior.

## Review of Recent Literature on Sequential Effects in CRT Performance

### The repetition effect

Bertelson (1961) using a self-paced two-choice responding task, varied the probability of an alternation (Pa) as his main independent variable. With the two signals kept equiprobable, three different levels of Pa formed the experimental conditions. The three conditions were called "ALT" (Pa = .75), "REP" (Pa = .25), and "RAND" (Pa = .50). The major findings of this experiment were summarized as follows:

> 1. A series of signals containing 3/4 repetitions permits a faster responding rate than a random series.
>
> 2. A series containing 3/4 alternations does not permit a better performance than a random series. [p. 93]

These findings were presented as evidence that response rate cannot be completely predicted on the basis of the amount of information transmitted.

A second experiment reported by Bertelson (1961) was aimed at testing the hypothesis that the timing of signals accounts for the relatively faster RTs for the REP condition. The same three conditions from the first experiment were employed, with the exception that the delay between the end of the response and the onset of the following signal was varied. Delays of both .05 sec. and .5 sec. were used. To distinguish between the .05 delay (the delay also used in the first experiment) and the .5 delay conditions they were referred to as the NTL (no time lag) condition and the TL (time lag) condition, respectively. As predicted, the discrepancy between mean latency for the REP series and the ALT series was reduced under the TL condition as compared to the NTL condition. However, it should be pointed out that the effect of lengthened time lag is not consonant with his stated hypothesis. That is to say, Bertelson anticipated that the increased time lag would decrease the facilitated responding to repeated signals (supposedly due to some sort of "inertia" phenomenon), thus increasing the mean RT for the REP condition, which would in turn reduce the difference between the means for REP and ALT conditions observed in Experiment I. Careful examination of the reported results (Table IV, p. 96; Bertelson, 1961) indicates that the reduction of this difference was due to a decrease in the mean RT for the ALT condition rather than the implied increase in the mean RT for the REP condition. It is somewhat surprising that Bertelson did not make note of this unpredicted result.

In a subsequent study Bertelson (1963) concentrated on the role of stimulus-response (S-R) relationships in determining the sequential effects observed in his 1961 study. In the first of two experiments the task used was essentially the same as that described in the 1961 study. However, the relative positions of the two lamps and their corresponding responses were varied so as to produce three different S-R conditions:

a. Direct (D): horizontal pair of lamps, the correct response being left key for left lamp and right key for right lamp.

b. Crossed (C): horizontal pair of lamps, the correct response being left key for right lamp and right key for left lamp.

c. Perpendicular (P): vertical couple of lamps, the two possible combinations (high-right/low-left and high-left/low-right) being given to alternate subjects.

An examination of the repetition effects for the three S-R conditions showed that the repetition effect for the more compatible D condition was smaller than the repetition effects for the less compatible C and P conditions. RTs to both repeated and alternation signals were significantly (.01) affected by the S-R conditions, but the results of a covariance analysis showed that the effect was significantly

(. 05) larger on RTs to alternation signals. These results were fully confirmed by a second experiment which employed a highly compatible four-choice task and less compatible four-choice task.

Bertelson (1965) investigated the repetition effect associated with signal repetition, not confounded with response repetition. This was accomplished by employing a task in which more than one signal was associated with each response. The relationship of a cycle to the preceding cycle was divided into three categories, (1) the "identity" category (same signal and same response for two successive trials), (2) the "difference" category (different response), (3) the "equivalence" category (different signal but same response). By comparing RT on cycles associated with the "identity" and "equivalence" categories, Bertelson proposed to find out if repetition of the signal _per se_ produced the repetition effect.

A repetition effect was found for all three transition categories for a two-choice serial reaction task. The median RT for the "identical" category was slightly shorter than the median RT to "equivalent" signals. (This difference was significant beyond the . 02 level for two of the four subjects tested. ) Bertelson concluded that the repetition of the signal _per se_ can "exert some effect"; but the main effect is linked to the repetition of the response.

The study by Bertelson and Renkin (1966) represents the latest reported study in this particular series of experiments devoted to the repetition effect. This experiment was designed to examine in more detail the findings reported by Bertelson (1961) that the repetition effect practically disappeared when the time-lag (TL) between the release of the response key and the appearance of the next signal was increased from 50 to 500 millisec. In addition to four different TL conditions (ranging from 50 to 1000 millisec.), an *irregular* condition was used, where the different TLs came in an unpredictable order instead of the usual procedure where the same TL is presented throughout the condition. The task was nearly the same as the previous experiments (Bertelson, 1961, 1963, 1965), with the exception that a Nixie numerical indicator was used in place of two stimulus lights.

Unlike the previous findings (Bertelson, 1961) that the repetition effect was practically eliminated when TL was increased to 500 millisec., a substantial repetition effect (60 millisec.) was observed at that TL. However, the repetition effect did decrease as the TL was increased under both conditions. Although the overall mean reaction time was slightly longer under the irregular condition than under the regular condition, the repetition effect was not differentially affected.

In a very recent study, Hale (1967) also investigated the effect of TL as well as the effect of the subject's guessing habits upon the repetition effect. Three different TL periods (100 millisec., 600 millisec., and 2 sec.) formed three of the experimental conditions.

The fourth condition consisted of a 2 sec. delay with verbal prediction of the next stimulus (i.e., preceding each stimulus presentation the subject had to predict which one of the two stimuli would be presented). Hale found a positive repetition effect for both the 100 millisec. and 600 millisec. delay conditions, the effect being greater for the 100 millisec. condition. The 2 sec. delay condition gave a slight negative repetition effect where the mean RT for repeated signals was greater than the mean RT for alternate signals. Even a greater negative repetition effect was found for the 2 sec. delay condition which required a verbal prediction of the upcoming signal.

One of a series of experiments reported by Williams (1966) also examined the relation of the repetition effect to the subject's verbalized pretrial expectancies. She reasoned that if responses associated with correctly guessed trials were faster than incorrectly guessed trials, and if the changed signal is more often expected (i.e., the "gambler's fallacy"), the observed negative recency could be accounted for by this combination of factors alone. A two-choice task with an inter-signal interval of about 12-15 sec. was used. A negative recency effect was obtained on correctly guessed trials as well as incorrectly guessed trials. Therefore, it was concluded that pretrial guessing habits could not account for the observed sequence effect. Unlike the findings reported by Hale (1967) that requiring verbal prediction produces a stronger negative recency effect, Williams reported only a general lengthening of RT as a result of requiring pretrial guesses.

The experiment reported by Williams can be criticized for the unusually small amount of data collected per subject. The entire testing session consisted of only 64-72 trials in each of the experiments conducted by Williams. Considering the general finding that CRT performance is extremely variable during the initial stage of practice, the findings reported by Williams probably reflect the transient aspects of CRT performance to a much higher degree than do the findings of other studies which have been reviewed. For example, Hale collected 265 data records per subject for a given condition, Bertelson (1963) collected 550 data records per subject for each of his three S-R conditions, Bertelson (1961) collected 2, 000 data records per subject for each of his experimental conditions, and Bertelson and Renkin (1966) collected 1, 200 data records per subject for each of their experimental conditions.

In a very recent study Kornblum (1967) made a systematic examination of CRTs for repetitions and alternations. Sequences with different numbers of alternatives (2, 4, and 8), each with probability of alternation 1/2, 3/4 and 7/8 were employed in a serial task with a TL of 137 millisec. An eight-choice sequence with Pa = 3/8 and a four-choice sequence with Pa = 1/5 were also used in this study. The major findings can be summarized as follows:

1. The mean RT for the repetitions was found to increase as a joint function of the number of alternatives (K) and Pa.

2. On the other hand the mean RT for the alternations was found to be relatively insensitive to changes in Pa and to be fairly constant for a given K, except for K = 2.

3. It was found that likelihood of an error response was, in general, inversely related to Pa, irrespective of K.

Scattered throughout the studies reviewed thus far are a number of theoretical notions concerning the reaction processes which are responsible for the observed discrepancies between latencies for changed and repeated signals. Perhaps the most comprehensive theoretical formulation among the reviewed studies is found in the article by Bertelson (1963). Although the other authors do not agree with Bertelson on all points of theory, the following passage from Bertelson (1963) typifies current theorizing regarding the repetition effect:

> A classification system which would show a repetition effect would be one which, whatever the number of alternatives, would begin by asking whether the stimulus is identical to the preceding one (this step can be called the "repeat question"). For a repeated stimulus, the decision can thus be taken in one step. For a new stimulus, in the case of choice between more than two alternatives, it is obvious that more than one step will be necessary whatever the classification strategy. In the case of two alternatives, the system will take more than one step for new signals only if some sort of Type <u>b</u> [asking redundant questions, the answer to

which can be inferred from those already asked] deviation from the optimal strategy is involved: after finding out that the stimulus is not the same as the preceding one, the system checks to see if it is the other one, or even proceeds to classify it, as though no information had been gained about it.

If poor compatibility implies asking too many questions, but for repeated signals the decision is always reached after the "repeat question", the RT to new signals only will be affected.

The fact that the RT to repeated signals is also affected, although to a much lesser degree, would mean that the "repeat question" is not always asked first. The mechanism of this question necessarily involves some memory device where the trace of the preceding stimulus is stored. If the trace undergoes a decay, the "repeat question" cannot be asked reliably. This hypothesis at the same time explains that the repetition effect is reduced when the time interval since the last response is increased (Bertelson, 1963). [p. 484]

In the same way second-order sequential effects present a problem for the information theory model, higher-order sequential effects, if found to be present in CRT performance, would cause difficulty for these theoretical formulations which have grown up around the research on the repetition effect. For example, it is apparent that Bertelson's model, which is based on a one-trial memory mechanism, would require wholesale revision to account for even third-order sequential effects. Since a majority of the research on sequential effects in CRT has been limited to the examination of the very simplest sort of sequential analysis (i. e., the second-order repetition effect analysis) there is no large body of data concerning the nature of higher-order sequential effects. However, as will be seen in the literature to be reviewed in the next section, there is some evidence that higher-order sequential effects do exist.

Beyond the repetition effect

Bertelson (1961) briefly considered higher-order interactions. He went beyond the analysis of RTs associated with adjacent signals and classified RTs according to the position of the signal in a run of repetitions in an attempt to isolate higher-order sequential effects. For the experimental situation delineated at the outset of this review, it was found that under the REP condition (i.e., a stimulus series with Pa = .25), RT continued to decrease beyond the first repetition to about the third repetition and then began to increase with each additional repetition from the fourth to the sixth repetition. (None of the 50 trial stimulus series for this condition had more than six repetitions.) These results offer good evidence that sequential effects in CRT data cannot be adequately described by a consideration of interaction between adjacent trials only. One can only wonder why Bertelson did not incorporate this potentially important piece of knowledge into his subsequent research plans or the theoretical formulation put forth in his 1963 paper.

Fortunately, the position in run analysis of repetitions procedure introduced by Bertelson did not go completely unnoticed. Leonard, Newman and Carpenter (1966) later applied this run analysis procedure to their data from a five-choice CRT experiment. Leonard *et al.* employed two different experimental conditions in which one stimulus was presented with a relatively high probability (i.e., .44 under one condition and .68 under the other) and the four remaining stimuli were equally likely. They found that successive repetitions of the high probability stimulus, under both conditions, led to additional drops in mean RT beyond the decrease associated with the first repetition. Mean RTs for successive repetitions of the high probability stimulus continued to decrease through three repetitions under the 68 per cent condition and through four repetitions under the 44 per cent condition. In addition, Leonard *et al.* reported that the relative variability decreased as the number of repetitions increased.

In a similar, but more detailed analysis of repetitions, Falmagne (1965) also found that where a signal is repeated the RT diminishes, the variance decreases, and the asymmetry increases. This trend was observed for each of the six stimulus alternatives which had different probabilities associated with their occurrence (.01, .03, .06, .10, .24, and .56). The repetition functions associated with the lower probability stimuli lacked sufficient numbers of data points; however, the curves reported for the .24 and .56 stimuli resembled the curves presented by Leonard et al. (1966). A discussion of additional data analyses associated with a stochastic model of CRT proposed by Falmagne are presented in the section which follows.

Falmagne's model

Unlike the previous mathematical models of CRT behavior which ignore the sequential effects examined in this paper, a model presented by Falmagne (1965) attempts to account for a variety of sequential effects, as well as the relation between CRT and stimulus probability. Falmagne's stochastic model of CRT is similar to the one element model outlined by Suppes and Atkinson (1960). The continuous character of the response, and the fact that the response mechanism corresponding to each stimulus is regarded as an independent process in Falmagne's model represent the major differences between the two models. The major objective of Falmagne's article was to explain, using the model presented, the apparent effect of probability on CRT in terms of the sequential effects reported by Hyman (1953) and Bertelson (1961).

According to Falmagne's model, on each trial the subject is "prepared" for a stimulus or not. If he is, his RT is sampled from a distribution $K(x)$. If he is not prepared, his RT is sampled from a distribution $\overline{K}(x)$. If the subject is prepared for a stimulus and that stimulus is presented he stays prepared; and if he is not prepared for a particular stimulus and that stimulus is not presented he remains unprepared. If he is unprepared for a given stimulus and that stimulus is presented, he becomes prepared with probability C. If the subject is prepared for the stimulus and it is not presented, he becomes unprepared with probability 1-C'. If $P_{i,n}$ denotes the probability that the subject is prepared for stimulus i on trial n, and if stimulus i is presented, then, Theorem 1 of this model says that $P_{i,n+1} = (1-C) P_{i,n}+C$. If stimulus i is not presented, then $P_{i,n+1} = (1-C') P_{i,n}$. Now, if we present r stimuli randomly with probabilities denoted $\pi_i$, we have the Markov chain of Este's one-element model with well-known expressions for $P_{i,n+1}$ in terms of $P_{i,n}$ and $P_{i,1}$, and the asymptote $P_i$.

Applying the axiom on sampling from K(x) and $\overline{K}(x)$, Falmagne obtained expressions for the distribution $J_{i,n+1}(x)$ in terms of $J_{i,n}(x)$ and the parameters of the model, when stimulus i is and is not presented on trial n. Next, he found similar expressions for the mean, variance, and skewness. He also found expressions $J_{i,n+k}(x)$ in terms of $J_{i,n}$ and c or c' for K repetitions of stimulus i presented or not presented, and studied the mean, variance, and skewness of these expressions. To simplify things, Falmagne assumes that K(x) and $\overline{K}(x)$ have the same variance and zero skewness. Finally, he examined these for interesting special cases, and found asymptotic values.

To estimate parameters for this model one can use asymptotic values and data involving K repetitions, but the data must be collected from a CRT task with three or more choices. As pointed out by Falmagne, a linear model, which essentially takes Theorem 1 as an axiom, leads to practically the same predictions as the Markov model described above.

## Evaluation of Falmagne's model

It seems appropriate to begin an evaluation of the model of CRT formulated by Falmagne in light of the results of the experiment which accompanied the model. In the article by Falmagne (1965) the predictions of the model were compared to three aspects of the experimental results (1) the RT distributions for the six stimulus probability categories (.01, .03, .06, .10, .24, and .56), (2) the successive RT distributions for the conditions 0, 1, 2 ... K repetitions of a given stimulus signal, (3) the successive RT distributions for the conditions of interval 1, 2 ... K (i.e., the number of signals between successive presentations of a particular stimulus event). The predictions and the results bearing on the means were presented first. The model predicts that the mean RT for a repetition or an interval condition is an exponential function of the number of repetitions, or of the intervals. This means that, regardless of the signal probability the mean of the distribution tends toward the same two asymptotes, and the repetition effect becomes more marked as the probability decreases. It can also be seen that the model predicts that the means for the successive repetition condition are linearly related. By taking this prediction into account, Falmagne fitted a straight line to the experimental data points from the repetition and the interval conditions to estimate the parameters of the model. The estimates obtained by means of this technique based on sequential effects did "not differ very much" from the estimates derived by a technique which was based upon probability effects.

The theoretical curve representing the predicted means of the RT distributions for the different stimulus probabilities turned out to be a hyperbola. An "acceptable fit" of the theoretical curve to the experimental points was shown in the form of an appropriate graph. Examination of the graph indicated that the mean RTs for stimuli of low probability are greater than those predicted by the model.

The fit of the theoretical curves for the means of the RT distributions for the repetition and interval condition (i. e., the sequential effects) can be summarized as follows:

> . . . The fit is better for the repetition conditions than for the interval conditions where the left-hand side [i. e., where the number of repetitions is small, or the size of the interval is small] of the theoretical curves appears to be too low. To a smaller degree, this also applies to the repetition condition. On the whole, the fit is not as good when

> the probability decreases, or when the interval increases. The fact that the theoretical curves begin too low suggests that one may improve the fit by slightly complicating the transition axiom, without in any way changing the principles behind the model . . . [p. 118]

Bertelson's (1963) suggestion that the repetition effect should be more marked with stimuli of low probability was predicted by the model and confirmed by the experimental results.

It should be pointed out that only two experimental data points were used to evaluate the theoretical curve for the mean RTs of the different repetition-conditions for the .03 and .06 stimuli. This was due to the fact that low probability stimuli do not generally yield a large number of repetitions. In addition, only data from the two high probability stimuli (.24 and .56) were used to evaluate the fit of the theoretical curve for the mean RTs for the various interval conditions. According to the author, "the results for the other probabilities showed too great a variability."

The results concerning predictions for the higher moments of the distribution were discussed separately from those concerning the means, since the former were purely qualitative. Regarding variances and sequential effects, Falmagne reported two phenomena which appeared in the experimental results.

> (i) Repetition effect. There is a significant increase in the variance for the stimulus of probability 0.24 between the conditions 0 and 1

> repetition. It may be noted that for the stimulus of probability 0.56, the increase of the experimental variance between the conditions of five and seven repetitions is not significant.
>
> (ii) Effect involving interval. When the interval increases the experimental curve rises for stimulus (0.56), and decreases for stimulus (0.24).

Falmagne attempted to correlate these phenomena with certain aspects of the model, but in general the relation between the theoretical and empirical variances is not suitably strong. He concludes that "the moments of higher order suggest lines of research for the design of better adjusted models based on the same principles."

Although Falmagne presented a relatively detailed evaluation of his model, a number of important points were not dealt with in his article. For example, the model, in essence, says that the subject draws his response from one or the other of two ideal distributions depending on whether or not he is prepared for the stimulus that is presented. For his experimental situation, Falmagne estimated the means for the $K(x)$ and $\overline{K}(x)$ distributions to be about 300 millisec. and 600 millisec., respectively. And assuming equal variance, he estimated the variances as about 2,000. The distributions, then, have means 6.7 standard deviations apart, which implies a bimodal RT distribution for each of the stimulus events within an experimental condition. However, an inspection of

Falmagne's data reveals no evidence of bimodality. Since the RT distributions for individual stimuli are not given for individual subjects it is conceivable that the process of averaging over subjects produced the observed unimodal distributions. Further evidence regarding this point was supplied by the data from a number of experiments conducted by the present researcher. The RT distributions for each of seven subjects separately for each stimulus event from a variety of 2, 4 and 6 choice conditions were examined. All of the resulting RT distributions were unimodal.

In summary, Falmagne has presented a relatively simple stochastic model that yields a number of quantitative predictions concerning detailed aspects of CRT performance, including predictions about sequential effects. This model based on the existence of two preparation states and a Markov transition gave a reasonable account of observed effects of probability and certain higher-order stimulus sequences on the mean CRT. Such a model represents a sorely needed addition to theorizing for an area in which theoretical formulations consist either of verbal models that only predict the second-order repetition effect (e.g., Bertelson, 1963; and Williams, 1966), or mathematical and information theory models that do not handle any of the sequential effects observed in CRT data (e.g., Hick, 1952; Rapoport, 1959; and Stone, 1960).

Unfortunately, judging from subsequent research reported in the very recent literature, researchers are confining themselves solely to the examination of the repetition effect while ignoring the findings of Falmagne and Leonard _et al_. regarding the importance of higher-order sequential effects. Perhaps researchers who still confine their sequential analysis of CRT data to the second-order level are not yet convinced of the general existence of higher-order sequential effects. (After all, the study of higher-order effects has been mainly confined to sequences of repetitions and it is very likely that these higher-order sequential effects based on repetition sequences represent a special case.) Or, perhaps many researchers lack the willingness or skills required to carry out the detailed data analysis of the caliber required in the study of higher-order sequential effects. For whatever the reason, information concerning higher-order sequential effects has not been forthcoming. This is an unfortunate state of affairs since such information would appear to be extremely useful in testing present models and furthering theoretical formulations in general.

## Statement of the problem

It would appear that premature theorizing based on the repetition effect has been relatively ineffective in producing predictive models as well as unfruitful in stimulating the sort of detailed data analysis which is needed to sharpen our theoretical formulations in this area of research. It is the major thesis of the present paper that carefully collected CRT data contain more information concerning the microstructure of underlying choice reaction processes than can be obtained through the more common data analysis procedures. In keeping with this thesis, new methods of data analysis will be introduced and applied to data collected from a CRT experiment. The results of these analyses will be related to the results obtained from conventional data analysis procedures. It is hypothesized that both methodological and theoretical implications will emerge from such an undertaking.

For example, it is hypothesized that the results of the proposed detailed sequential analyses will produce further evidence that the reaction processes cannot be adequately represented by a first-order Markov model of the type proposed by Bertelson (1963), Williams (1966) and others. It is also suspected that the proposed data analysis will reveal methodological shortcomings associated with the common practice of collapsing or combining certain components of CRT data without questioning the appropriateness of the resulting measure (e.g., averaging the RTs for stimulus events with different probabilities of occurrence in determining the magnitude of the repetition effect for a particular experimental condition).

## Tree diagram analysis

Previous investigations of higher-order sequential effects in CRT performance have mainly focused on the effects associated with repetition sequences. Most of the remaining types of sequences and their effect on CRT have not been explored. Clearly, a more systematic and comprehensive approach to the study of sequential effects in CRT data is needed. The data analysis procedure described in the following paragraphs represents an attempt to fill this need.

Let A represent the stimulus event which appears on trial n (i. e., a first-order stimulus pattern). By looking at the stimulus events which can occur on trial n and trial n-1, two <u>second-order</u> stimulus patterns emerge: (1) the BA pattern (i. e., the stimulus event which appears on trial n-1 is different from the stimulus event which appears on trial n), and (2) the AA pattern (i. e., the stimulus event which appears on trial n-1 is identical to the stimulus event which appears on trial n). The simplest sort of sequential analysis of CRT data consists of comparing the mean RT for all stimulus events which are immediately preceded by the same stimulus event (the AA pattern) with the mean RT for all the stimulus events that are immediately preceded by a different stimulus event (the BA pattern). This particular comparison represents the extent of the sequential analysis carried out by a majority of the researchers who have reported on sequential effects in CRT data.

In carrying the sequential analysis a step further one would first delineate the <u>third-order</u> stimulus patterns. Examination of the stimulus events associated with trials n, n-1 and n-2 reveals four possible third-order patterns; AAA, BAA, BBA, and ABA. The tree diagram in Figure 1 illustrates how the various stimulus patterns are delineated as one considers successively higher orders through the fifth-order.

It is now possible to associate a mean RT with each of the 31 stimulus patterns presented in Figure 1. The overall mean of a RT distribution resulting from an n-trial CRT experiment would be the value associated with the first-order stimulus pattern A. Let us denote this value as RT(A). Then, RT(AA) would represent the mean RT for all the stimulus events in the n-trial experiment that are immediately preceded by the same stimulus event (the mean RT for repetitions), and RT(BA) would represent the mean RT for all the stimulus events in the experiment that are immediately preceded by a different stimulus event (the mean RT for non-repetitions).

The tree diagram in Figure 1 illustrates a basic property of the overall mean of a RT distribution. Since separating the repetitions from the non-repetitions partitions the data, the overall mean is the sum of the means for repetitions and non-repetitions each weighted by their own probability of occurrence; i.e.,

$$P(A)RT(A) = P(AA)RT(AA) + P(BA)RT(BA).$$

Similarly, each of the second-order components RT(AA) and RT(BA) can be partitioned into two third-order components, etc. Thus, the tree diagram illustrates the fact that the mean RT for a given

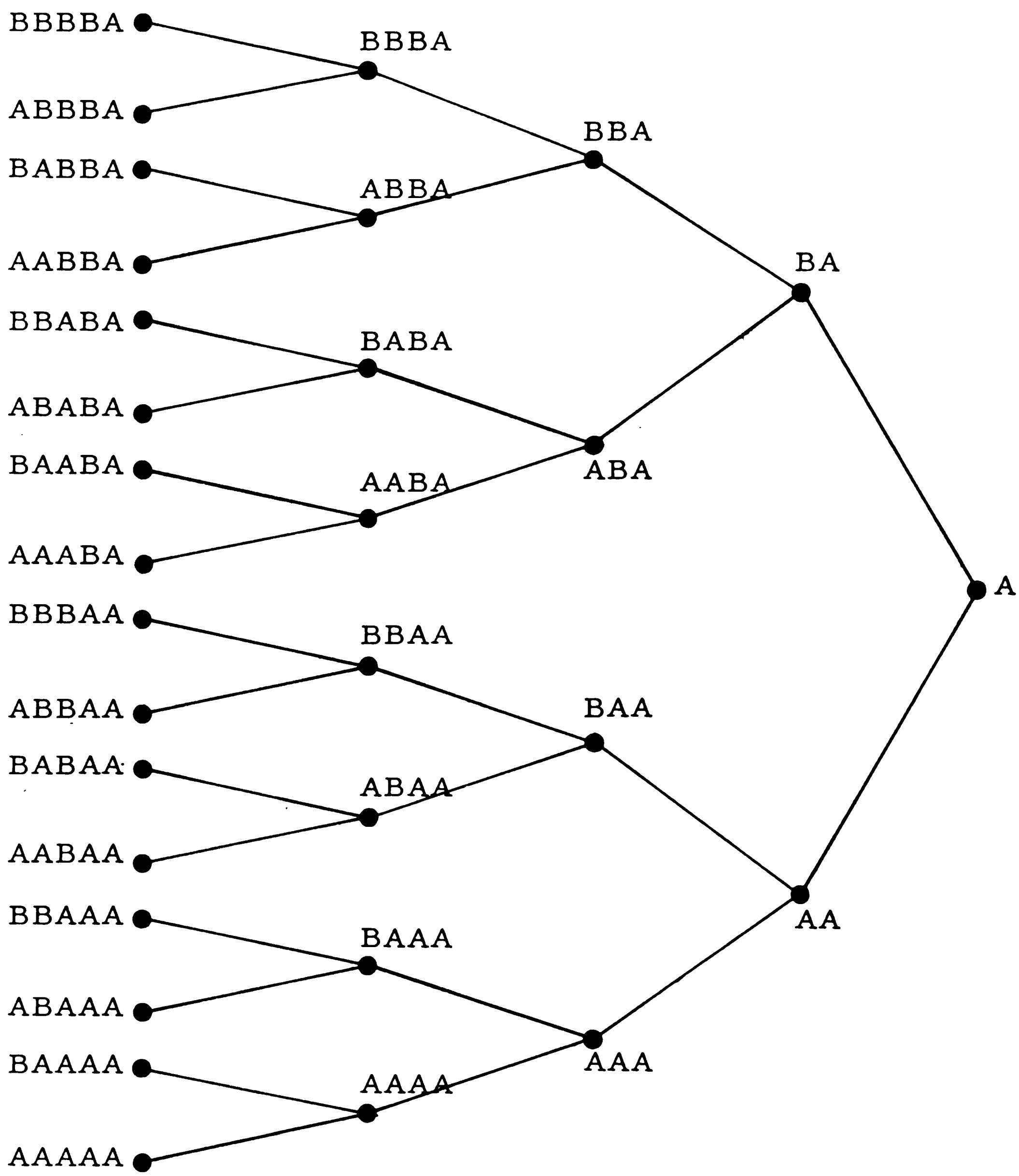


Figure 1. The stimulus patterns associated with each of the first five orders.

stimulus pattern is actually made up of the means of its higher-order patterns each weighted by their relative frequency of occurrence. Understanding of this averaging process is essential to the interpretation of observed sequential effects. In short, the proposed tree diagram analysis of CRT data consists of finding the mean RT for each of the 31 stimulus patterns shown in Figure 1.

Rationale for the tree diagram analysis

Will examination of the mean RTs associated with the tree diagram described above yield important information concerning the nature of sequential effects in CRT data over and beyond the information gained through conventional sequential analyses? Although this question can only be answered by the results of research of the sort to be described in the present paper, a tentative answer based on *a priori* considerations will be offered in this section.

First, it is apparent that a degree of redundancy would exist if the proposed tree diagram analysis were used in conjunction with the already well-established sequential analyses of CRT data. This state of affairs exists since certain tree diagram *nodes* (the mean RT associated with a particular stimulus pattern on the tree diagram represents a node) are determined as a result of the usual data analysis procedures. However, it should be pointed out that even the more detailed sequential analyses examine only a few nodes. Table 1 below indicates the extent to which each of the conventional CRT data analysis procedures incorporates information that would be made available through the tree diagram analysis.

The fragmentary nature of the approaches taken by the various investigators in their study of sequential effects in CRT performance becomes very apparent when the amount of information that they extract for the data is related to the potential information made available through the tree diagram approach. For example, Bertelson's position in run analysis of repetitions delineates only part of the lower branch of the tree diagram structure, while Falmagne's repetition analysis delineates only four scattered nodes within the tree diagram structure. In fact, only 12 of the 31 nodes of the tree diagram shown in Figure 1 would be determined if all the conventional data analysis procedures were applied to a set of CRT data. How important are each of the remaining 19 stimulus patterns in determining RT? It seems reasonable that information concerning the influence of these unexplored stimulus patterns on RT would be useful in testing present theoretical models. It would also appear that the proposed tree diagram analysis, which incorporates all the sequential information (through the fifth-order) under one experimental design, represents a relatively comprehensive approach to studying the microstructure of choice reaction processes.

Table 1. Tree diagram nodes determined by the conventional CRT data analysis procedures.

| Data Analysis Procedure | Tree Diagram Nodes Determined |
|---|---|
| Informational analysis | RT(A) |
| Repetition effect analysis | RT(AA), RT(BA) |
| Bertelson's position in run analysis of repetitions | RT(BA), RT(AA), RT(AAA), RT(AAAA), RT(AAAAA) |
| Falmagne's repetition analysis | RT(BA), RT(BAA), RT(BAAA), RT(BAAAA) |
| Falmagne's interval analysis | RT(ABA), RT(ABBA), RT(ABBBA) |

The exploratory experiments

The data from a series of exploratory experiments provided a valuable source of information that could be drawn upon in designing the present study. These preliminary experiments were exploratory in the sense that they (1) represented a wide range of experimental conditions (18 conditions differing in number of alternatives, sequential dependencies, stimulus probabilities, and inter-trial intervals), (2) represented the initial use of the data gathering system to be employed in the present research project, and (3) provided data (a total of 27, 000 CRTs from seven subjects) which were used in the development of the computer programs to be used in the present study to carry out the proposed tree diagram analyses. The results of these exploratory experiments will be referred to in the following sections as needed.

Rationale for the CRT research project that was carried out

The exploratory nature of the stated problem required many decisions concerning the details of the CRT experiment to be employed. Among the major aspects of the experimental situation that had to be determined were (1) the number of alternatives, (2) the probability of occurrence associated with the individual stimulus events, (3) the time lag (TL), (4) the number of subjects, (5) the experimental design, (6) the amount of data to be collected from each subject.

The two-choice task has been the favorite of most researchers in this area. Perhaps this is one of the reasons why Falmagne's model, which does not handle two-choice data, has been virtually ignored by subsequent researchers. Any new data analysis will probably receive the same sort of cool reception if it does not demonstrate utility for the two-choice case. The results of the exploratory experiments indicated that practice effects, which often obscure main effects, were also at a minimum in the two-choice condition. Based on these considerations, the two-choice task was included for investigation. And, since some researchers consider the two-choice condition to be a special case of choice behavior (e. g., Kornblum, 1967), the four-choice task was also adopted for investigation.

Both of the studies that have demonstrated the importance of higher-order stimulus patterns employed more than four stimulus alternatives in conditions where the individual stimulus events were not equiprobable. The role of higher-order stimulus patterns in choice reaction tasks employing two and four equiprobable stimulus events remains to be determined. Therefore, these particular tasks were chosen for investigation.

It will be recalled that Falmagne (1965) investigated the joint effect of stimulus probability and higher order stimulus sequences on CRT. To further this line of research while keeping with the stated purpose of the present study, two-choice and four-choice tasks with unequally likely stimulus events were considered for investigation. The frequency of occurrence associated with stimulus patterns of successively higher order (longer sequences) steadily decrease. In fact, potentially possible stimulus patterns involving three or four presentations of a stimulus event with a very low probability of occurrence may fail to occur in the stimulus series generated for experimental purposes. Therefore, selecting a two-choice task involved a trade-off between the case where the subject can readily distinguish between the equiprobable (50:50) condition and the biased condition, and the case where making one of the two stimulus events highly probable completely eliminates many of the stimulus patterns of primary interest. The 70:30 two-choice condition seemed to represent a reasonable compromise. Selection of the four-choice biased condition was based mainly on the desire to keep the task simple and to insure the occurrence of a large number of higher-order stimulus patterns. Since the present study is primarily concerned with the entire spectrum of higher-order stimulus patterns (through the fifth order), a four-choice biased condition in which one stimulus event occurs with probability .40 and each of the remaining stimulus events occur with probability .20 seemed appropriate for investigation (Falmagne covered a wider range of stimulus probabilities, but he did so at the expense of reducing his number of observations for repetitions of the low probability stimuli).

The S-R arrangement as well as the time lag (TL) employed in the present study were selected so as to minimize the magnitude of possible sequential effects. It will be recalled that Bertelson (1963) found that his most compatible condition (i. e., a horizontal pair of lamps, the correct response being left key for left lamp and right key for right lamp) produced the smallest repetition effect. A similar S-R arrangement was selected for use in the present study. Previous research also indicates that, at least for the two-choice case, sequential effects decrease in magnitude as the TL is increased from 100 millisec. to about 1 sec. and that they may fail to appear with TLs of 2 sec. or longer (Hyman, 1953; Bertelson and Renkin, 1966; Hale, 1967). A 4 sec. TL was adopted for the present study. One would not expect to find large sequential effects from a study that combines a compatible S-R arrangement with a 4 sec. TL. Such an experimental situation should provide a challenging test for the new approach proposed in the present paper as well as an exacting test of the quality of the CRT data collected.

After the four experimental conditions of interest had been delineated decisions regarding experimental design were required, including (1) the number of observations to be made under each condition, (2) the assignment of subjects to experimental conditions, and (3) the number of subjects to be employed. As usual, these inter-related decisions were dictated, to a large extent, by the nature of the problem and practical considerations.

First, as pointed out by Leonard (1961), a major problem in the study of reaction time lies in its variability, which tends to obscure possible effects unless the subject is allowed to go through a learning process. This becomes a particularly bothersome problem in the study of sequential effects which tend to be relatively small in magnitude. Therefore, the possibility of collecting only a few RTs for each subject was ruled out completely. In fact, the results of the exploratory study indicated that it would be advisable to collect at least 1, 000 RTs for each subject under a given condition.

The exploratory nature of the proposed study indicated that the experimental design should not unduly restrict the number of potentially meaningful comparisons which could be made. For example, the design should allow for a relatively sensitive comparison of the sequential effects observed under both two-choice conditions, as well as a comparison of the sequential effects observed for the two-choice equiprobable and four-choice equiprobable conditions. From this standpoint, a design where each subject participates under each experimental condition seemed most appropriate. Once this particular design was decided upon the decision regarding the number of subjects became a matter of practical feasibility as well as a statistical matter. Based upon information derived from the exploratory study and previous CRT research which employed this design, a total of four or five subjects was judged to be both feasible and statistically satisfactory (e. g., The classical study by Hyman employed four subjects under a similar design. ).

# METHOD

## Subjects

Five volunteer subjects participated in the experiment; three females and two males. The subjects ranged in age from 15 to 28 years. They were previously unacquainted with the task and had no knowledge of the aim of the experiment.

## Apparatus

The present experiment employed the Human Information Processing Data Acquisition System (HIPDAS) which was designed and built by a senior electronics technician. The electronic program control and data acquisition circuitry which constitutes the central feature of HIPDAS is composed of transistor logic cards such as those used in computers, and a solid state power supply. A one meg. oscillator forms the basis of an electronic clock which measures and records reaction times with millisecond accuracy.

The signals were presented by means of a visual display. The signals themselves consisted of four lights (No. 47 bulbs behind frosted lenses) approximately one inch in diameter mounted in a small metal cabinet positioned about four feet in front of the subject. The stimulus display also contained a red warning light and a small green light used to feed back to the subject knowledge of a correct response.

The response device was a small keyboard consisting of four typewriter keys. The keys were numbered, starting on the left, from 1 through 4 corresponding spatially with the numbered stimulus lights. CRT was measured from the onset of a stimulus light to the depression of one or more of the response keys. The depression of a key following a stimulus light was followed by the automatic recording of the CRT, stimulus number, and the specific key(s) depressed by the subject. A fixed one-second delay between the onset of the warning light and the onset of the stimulus light (foreperiod) was employed throughout the experiment.

HIPDAS was designed so as to maximize the quantity and quality of data which could be collected during an experimental session. The control and recording portions of the equipment, located in a room adjacent to the room containing the visual display allowed for automatic data collection without the necessity of visual inspection or intervening operations by the experimenter. Stimulus presentations were automatically controlled by means of punched paper tape programs read by a paper tape reader. The relevant information for each trial (i. e., a record of the stimulus light presented, the response made by the subject, and the reaction time in milliseconds for the trial) was automatically recorded in digital form onto paper tape by means of an eight-channel paper tape punch.

The entire inter-stimulus interval, consisting of (1) the foreperiod, (2) the stepping of the control tape, (3) the CRT, and (4) the data recording was about four seconds. Therefore, HIPDAS allowed for the collection of a maximum of 900 records per hour.

The data records, being punched onto paper tape in digital form, were read directly by the paper tape reader associated with the CDC 3600 computer system located at the Michigan State University Computer Center. Thus, in addition to eliminating stimulus presentation errors, the automated data gathering system employed in the present experiment eliminated two other common sources of human error: (1) errors made by the experimenter while reading a clock and recording the RT after each trial, (2) errors made while preparing the data records for computer-aided analyses.

Stimulus sequences

All of the stimulus sequences employed in the present experiment were 200 trials long. Randomization of the stimulus events was achieved by means of a computer program that incorporated the RANF routine available on the CDC 3600 computer system. Additional structural characteristics of these stimulus sequences are presented in the following description of the various experimental conditions.

50:50 Condition -- Four different binary sequences were constructed for this experimental condition.

Under the 50:50 condition both stimulus alternatives, consisting of light "2" and light "3", were presented equally often in each of the four 200 trial stimulus sequences.

70:30 Condition -- The second condition also employed a binary-choice reaction task. For this condition four different stimulus sequences were constructed so that the proportions of alternatives were 70:30. In two of these 200 trial series, stimulus light "2" appeared 140 times, while in the other two series, stimulus light "3" appeared 140 times. Second and third order estimates of redundancy for the combined stimulus sequences were nearly zero for both two-choice conditions.

25:25:25:25 Condition -- Five different four-choice stimulus sequences were generated for the third experimental condition. Each of these 200 trial sequences consisted of equal numbers of the four stimulus alternatives (i. e., stimulus light "1" appeared 50 times, stimulus light "2" appeared 50 times, etc.).

40:20:20:20 Condition -- Five different four-choice stimulus sequences were also generated for this four-choice condition. In all five stimulus series, light "1" appeared on 40 per cent of the trials, while each of the other three stimulus events appeared on 20 per cent of the trials.

Simple Reaction Condition -- A special sequence was constructed for each of the four stimulus events such that a given stimulus light appeared on all 200 trials. These single stimulus sequences allowed for the collection of simple reaction time data for each of the four signals.

## Procedure

Each subject performed under all four experimental conditions. At the beginning of the first experimental session each subject was familiarized with the general nature of the choice-reaction task and the apparatus. During a typical experimental session the subject was presented with four 200-trial stimulus sequences. Before each sequence the subject was told the probability associated with the appearance of each of the possible stimulus events in terms of percentages. Subjects were instructed to respond as quickly as possible to the presentation of the stimulus light without making more than five per cent error responses during a given series. During all testing the subject wore lightweight dual headphones with ear-encompassing cushions that blocked out most of the external noises. After each sequence the subject was given a brief rest period and instructions concerning the upcoming sequence.

The first three experimental sessions were devoted to the two-choice condition. During these sessions the presentation order presented below in Table 2 was followed.

Table 2. Presentation order for the two-choice conditions

| Presentation Order | Condition | Stimulus Sequence No. |
|---|---|---|
| 1 | 50:50 | 1 |
| 2 | 50:50 | 2 |
| 3 | 50:50 | 3 |
| 4 | 70:30 | 1 |
| 5 | 70:30 | 2 |
| 6 | 70:30 | 3 |
| 7 | 50:50 | 4 |
| 8 | 50:50 | 1 |
| 9 | 50:50 | 2 |
| 10 | 70:30 | 4 |
| 11 | 70:30 | 1 |
| 12 | 70:30 | 2 |

Since only four different sequences were constructed for each of the two-choice conditions, the subject experienced some sequences twice during testing. However, the presentation schedule allowed maximum separation between successive presentations of the repeated sequences (six sequences intervened between successive presentations of a repeated sequence), making memorization of particular patterns from a repeated sequence highly unlikely. Under both of the two-choice conditions the index finger on the left hand was used to respond to light "2" and the index finger on the right hand to light "3".

The four-choice stimulus sequences were presented during the final experimental sessions. Presentation of the five 25:25:25:25 condition stimulus sequences was preceded by a 40-trial practice sequence used to introduce the subject to the four-choice equiprobable situation. Likewise, a 40-trial practice sequence which reflected the characteristics of the 40:20:20:20 condition sequences preceded the presentation of the five 200 trial sequences for this condition. No sequences were repeated under the four-choice conditions. The index fingers on left and right hands were still used to respond to lights "2" and "3", respectively, while the middle finger on the left hand was used to respond to light "1" and the middle finger on the right hand was associated with stimulus light "4". During the final session each subject was presented with the four simple-reaction stimulus sequences in order to obtain a measure of simple reaction time for each of the four light-finger combinations used in the main experiment.

General data analysis

A total of 26, 400 data records were collected during the course of the present experiment. Since early trials on CRT task typically display a relatively high degree of variability which tends to obscure possible effects, a decision regarding which portion of the early data will be excluded from analysis is generally required. In the present study a separate decision was made for each experimental condition on the basis of sequential analyses made on the CRTs from each successive 200-trial sequence or block for a given condition. That is, a separate detailed sequential analysis was made on the 1, 000 CRTs collected for all subjects combined (200 CRTs per subject) on their first 200-trial block under a particular condition, a separate detailed sequential analysis was made on the 1, 000 CRTs collected for their second 200-trial block under the same condition, etc.

A relatively stable pattern of higher order sequential effects was observed for the last four blocks for the 50:50 condition. The first two blocks for this condition, being the first two blocks of practice on a CRT task for all subjects, were characterized by rather erratic higher-order sequential effects as well as a large drop in overall mean RT. Therefore, the first two blocks (i. e., the first 400 CRTs for each subject under the condition) were excluded from the final data analysis for this experimental condition.

Only the first block of trials for the 70:30 condition displayed an unstable pattern of higher-order sequential effects. With the first block excluded from analysis there remained 5, 000 CRTs from the last five blocks to be analyzed. It will be recalled that in half of the stimulus sequences associated with this condition stimulus event "2" was the biased stimulus (i. e., the stimulus event that appeared with probability .70), while stimulus event "3" was the biased stimulus in the remaining sequences. Examination of the pattern of sequential effects for each of these types of sequences indicated that there was no need to distinguish between them, and the data for these sequences were pooled.

Both four-choice conditions, coming in the latter part of the experiment, were not accompanied by strong practice trends that would tend to obscure the sequential effects under study. Only the responses to the 40-trial practice sequences specially constructed to acquaint the subject with each four-choice task were excluded from the final data analysis.

The CRTs associated with error responses (approximately 2 per cent of the total number of responses) were included in the final data analysis. Therefore, the analyzable CRT data consisted of 19, 000 data records (viz., 800 data records for each of five subjects under the 50:50 condition, and 1, 000 data records from each subject under the other three experimental conditions). In addition, the 4, 000 simple reaction times (800 data records per subject) were subjected to a separate analysis. The desired detailed sequential analysis of these data was only feasible with an electronic computer. Separate computer programs, written in Fortran programming language, were constructed to analyze the data from the two-choice conditions and the data from the four-choice conditions. The computer program for a given condition was capable of calculating and printing a number of statistics (mean RT, variance, standard deviation, number of observations, standard error of the mean, skew, and percentage of error responses) associated with every possible tree diagram node through a given order for (1) an overall tree diagram analysis and (2) a tree diagram analysis for each signal separately.

# RESULTS

The results of a number of different data analyses are reported separately for the two-choice and four-choice conditions. These analyses include the usual sorts of data analysis (i. e., the repetition effect analysis, the repetition function analysis, and the interval analysis) as well as some new and relatively detailed ways of examining sequential effects in CRT data including the tree diagram analysis.

## Two-Choice Conditions

### The repetition effect

RTs to repeated and alternate signals constituted the basic data for the conventional repetition effect analysis. The mean RT for repeated signals RT(AA) and alternate signals RT(BA) for each subject under the 50:50 condition and the 70:30 condition are presented in Table 3. The means for individual subjects were used in a paired *t* test of the difference between RT(BA) and RT(AA). The results of this test indicated a significant (. 01 level) positive repetition effect for both two-choice conditions. It appears that the 70:30 condition produced a greater repetition effect than the 50:50 condition. However, a more detailed analysis presented in the next section suggests that any straight-forward interpretation of the

Table 3. Mean RTs (in millisec.) and other statistics for repetitions and alternations for each subject and all subjects combined for the 50:50 condition and the 70:30 condition.

| Condition | | Subject 1 | 2 | 3 | 4 | 5 | Average |
|---|---|---|---|---|---|---|---|
| | Repetitions, | | | | | | |
| | RT(AA) $\bar{X}$ | 247 | 270 | 287 | 317 | 294 | 283 |
| | S. D. | 36 | 42 | 41 | 46 | 38 | 47 |
| | S. E. of $\bar{X}$ | 1.8 | 2.1 | 2.1 | 2.3 | 1.9 | 1.1 |
| 50:50 | Alternations, | | | | | | |
| | RT(BA) $\bar{X}$ | 259 | 286 | 299 | 326 | 302 | 294 |
| | S. D. | 47 | 47 | 34 | 59 | 34 | 50 |
| | S. E. of $\bar{X}$ | 2.3 | 2.3 | 1.7 | 2.9 | 1.7 | 1.1 |
| | Difference, | | | | | | |
| | RT(BA)-RT(AA) | 12 | 16 | 12 | 9 | 8 | 11 |
| | Repetitions, | | | | | | |
| | RT(AA) $\bar{X}$ | 236 | 274 | 267 | 322 | 276 | 275 |
| | S. D. | 40 | 59 | 40 | 60 | 38 | 56 |
| | S. E. of $\bar{X}$ | 1.7 | 2.5 | 1.7 | 2.5 | 1.6 | 1.0 |
| 70:30 | Alternations, | | | | | | |
| | RT(BA) $\bar{X}$ | 255 | 289 | 298 | 339 | 302 | 297 |
| | S. D. | 38 | 54 | 46 | 73 | 44 | 59 |
| | S. E. of $\bar{X}$ | 1.9 | 2.6 | 2.3 | 3.5 | 2.1 | 1.3 |
| | Difference, | | | | | | |
| | RT(BA)-RT(AA) | 19 | 15 | 31 | 17 | 26 | 22 |

greater repetition effect associated with the 70:30 condition, at this point, is likely to be misleading.

## The repetition function

Following the procedure introduced by Bertelson (1961) RT was plotted as a function of rank in a run of repetitions (0 = alternation; +1 = 1st repetition; +2 = 2nd repetition; etc.). The resulting plots for all subjects combined under both conditions are shown in Figure 2. Except for the initial drop associated with the difference between the 0 position and 1 position (i. e., the repetition effect) the trends for the two conditions are very similar. The mean RTs for position in run for each subject under the 50:50 condition are presented in Figure 3. The similarity of the individual trends displayed in Figure 3 is indicative of the stability of the higher-order sequential effects (particularly through the fourth-order) discussed in the present paper.

## Repetition functions for the individual components of the 70:30 condition

On the basis of the repetition function for the 70:30 condition presented in Figure 2, it would appear that most of the decrease in RT associated with repeated presentations of a given stimulus event can be attributed to the initial repetition and that further repetitions play a much lesser role in determining RT. However, when a similar analysis is made the individual components of the 70:30 condition it

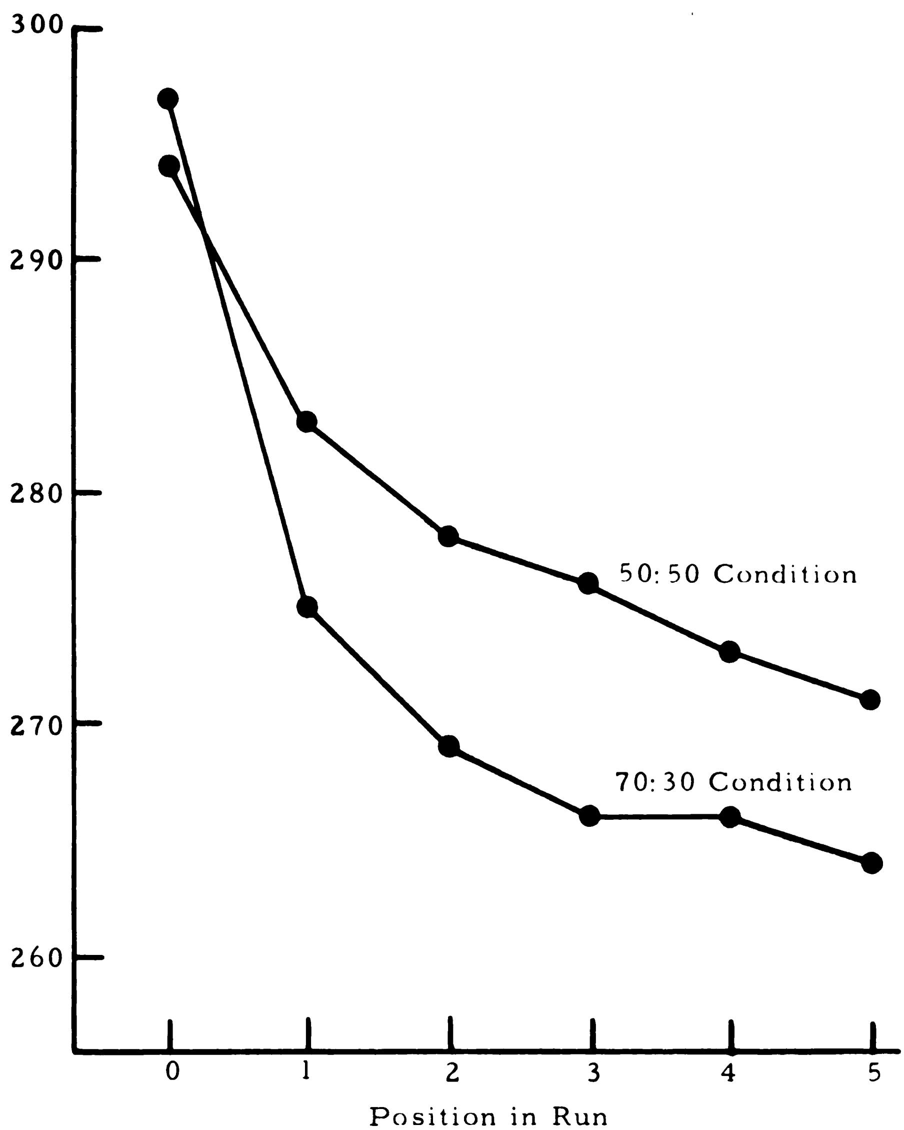


Figure 2. RT as a function of position in a run of repetitions for the 50:50 condition and the 70:30 condition.

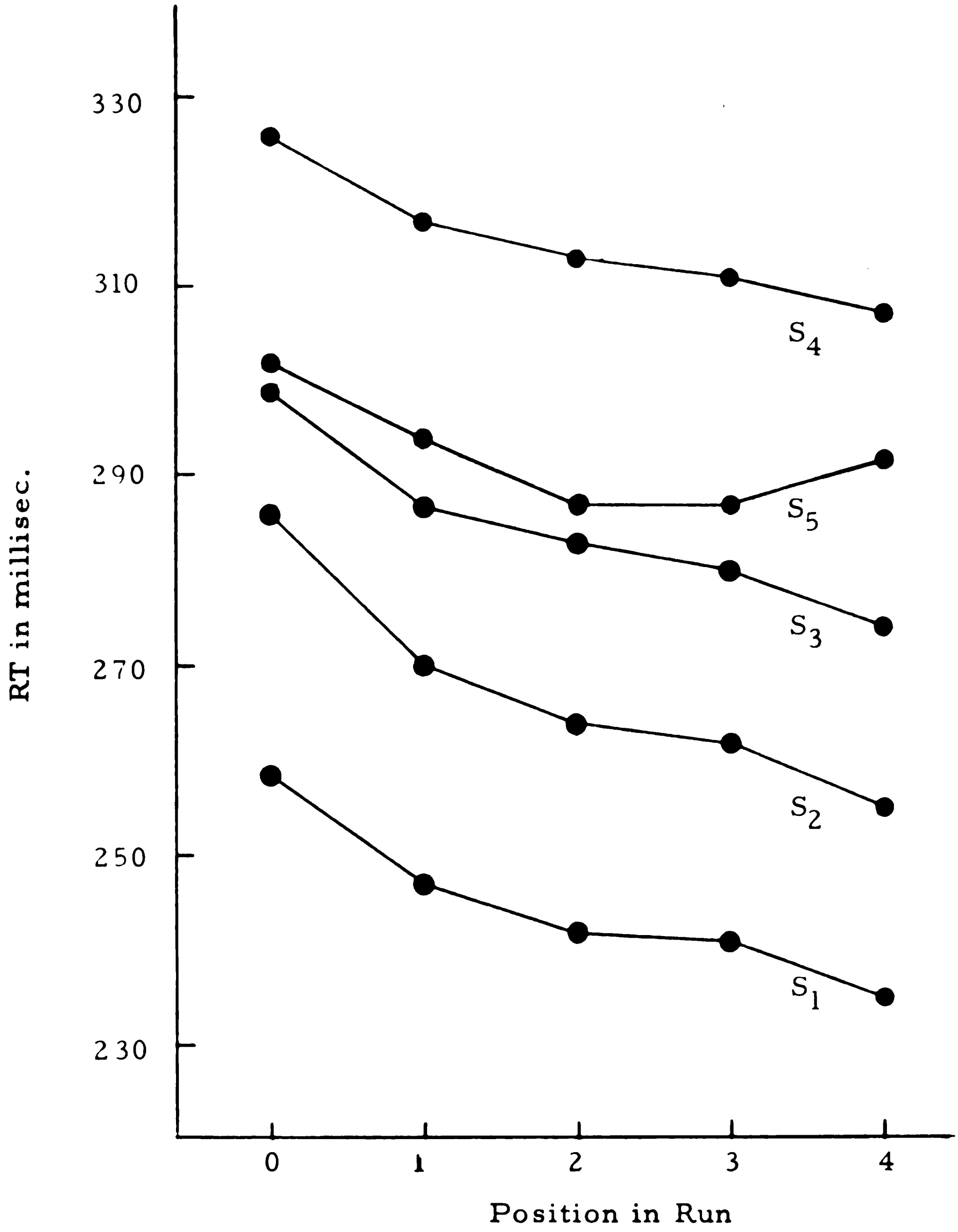


Figure 3. RT as a function of position in a run of repetitions for each of the five subjects under the 50:50 condition.

becomes clear that the greater repetition effect associated with this condition is an artifact produced by the somewhat common practice of averaging over the components which make up an experimental condition. Figure 4 shows the mean RTs for position in run for each component in the 70:30 condition separately as well as those for the components combined. It now becomes apparent that the large repetition effect for the 70:30 condition is merely due to the fact that while both components contribute equally to the average for an alternation (position 0), the 70 per cent component with its greater number of repetitions and faster RTs largely determines the overall mean RT for the initial repetition. Therefore, the sharp drop in the overall mean RT in the 70:30 condition is a reflection of this averaging process rather than the magnitude of the repetition effect. Failure to recognize this fact would lead one to overestimate the relative importance of the first repetition (i. e., the repetition effect) and underestimate the role of additional repetitions. For an example of how the process of averaging over the components of an experimental condition has produced this sort of misleading interpretation in previous research the reader is advised to see the study reported by Leonard *et al.*, (1966). These authors present a graph (Figure 3, page 137) which is very similar to Figure 3 in the present paper. Averaging over a five component experimental condition (i. e., a condition involving five stimulus signals, one of

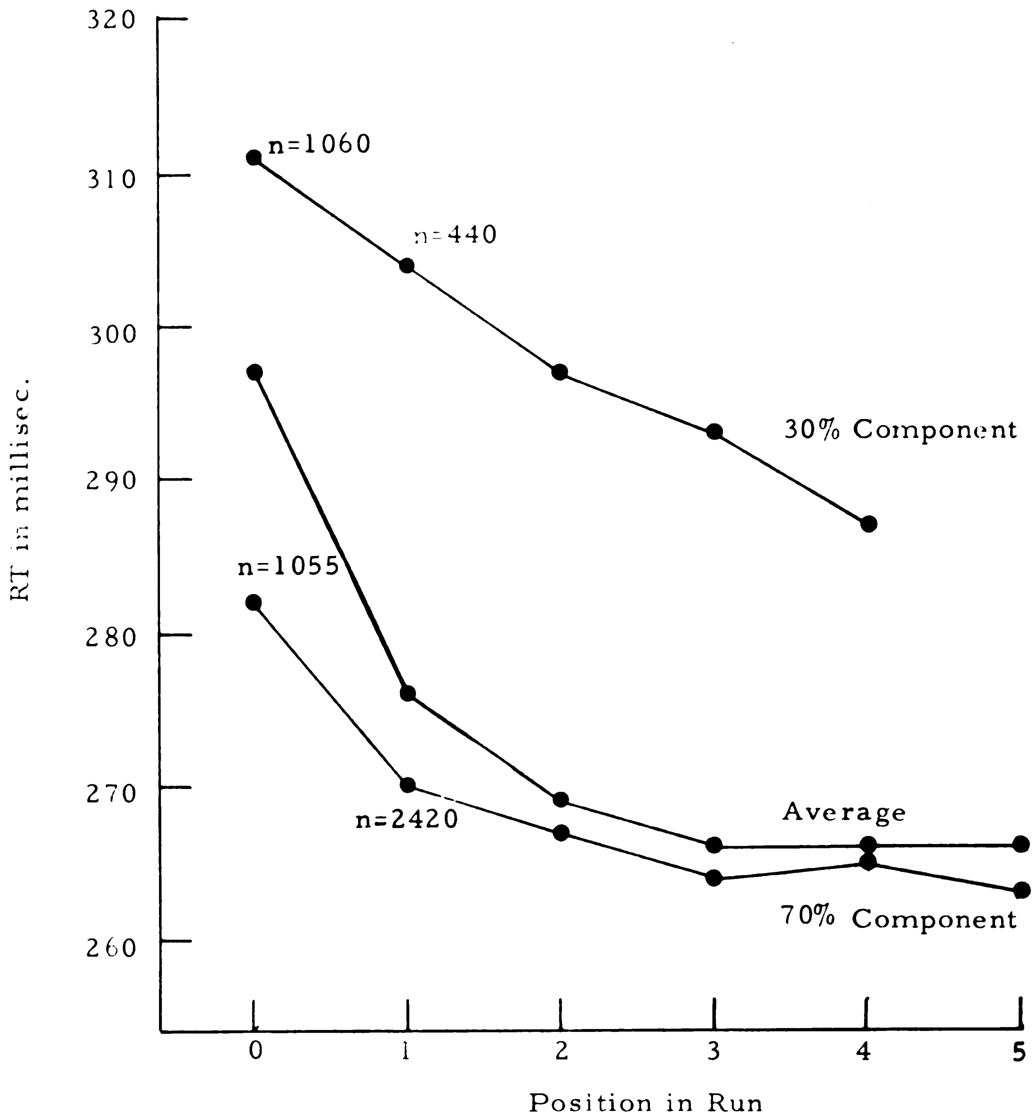


Figure 4. RT as a function of position in a run of repetitions for each component and overall average for the 70:30 condition.

which appeared 68 per cent of the time) produced what was interpreted by these authors as being a "strong repetition effect".

Returning to the 70 per cent component in Figure 4, it can be seen that RT is a decreasing negatively accelerated function of repetitions. However, the 30 per cent component produced a trend that is practically linear through 4 repetitions. The small number of observations for repetitions beyond 4 for the 30 per cent component makes it impossible to reliably assess the nature of the function beyond this point.

The interval analysis

The data from both two-choice conditions were analyzed for signs of the "recency effect", an increase in RT associated with an increase in the number of stimulus events that intervene between successive presentations of a given stimulus event. The mean RTs associated with intervals of increasing size, i.e., RT(AA), RT(ABA), RT(ABBA), RT(ABBBA), and RT(ABBBBA), for the 50:50 condition are shown in Figure 5. These results are very similar to those previously observed for a six-choice task (Falmagne, 1965) and an eight-choice task (Hyman, 1953), but not those reported by Hyman (1953) for a similar two-choice task (Hyman did not find a recency effect in the two-choice case).

The results of a separate interval analysis of the data for each component of the 70:30 condition as well as the data pooled

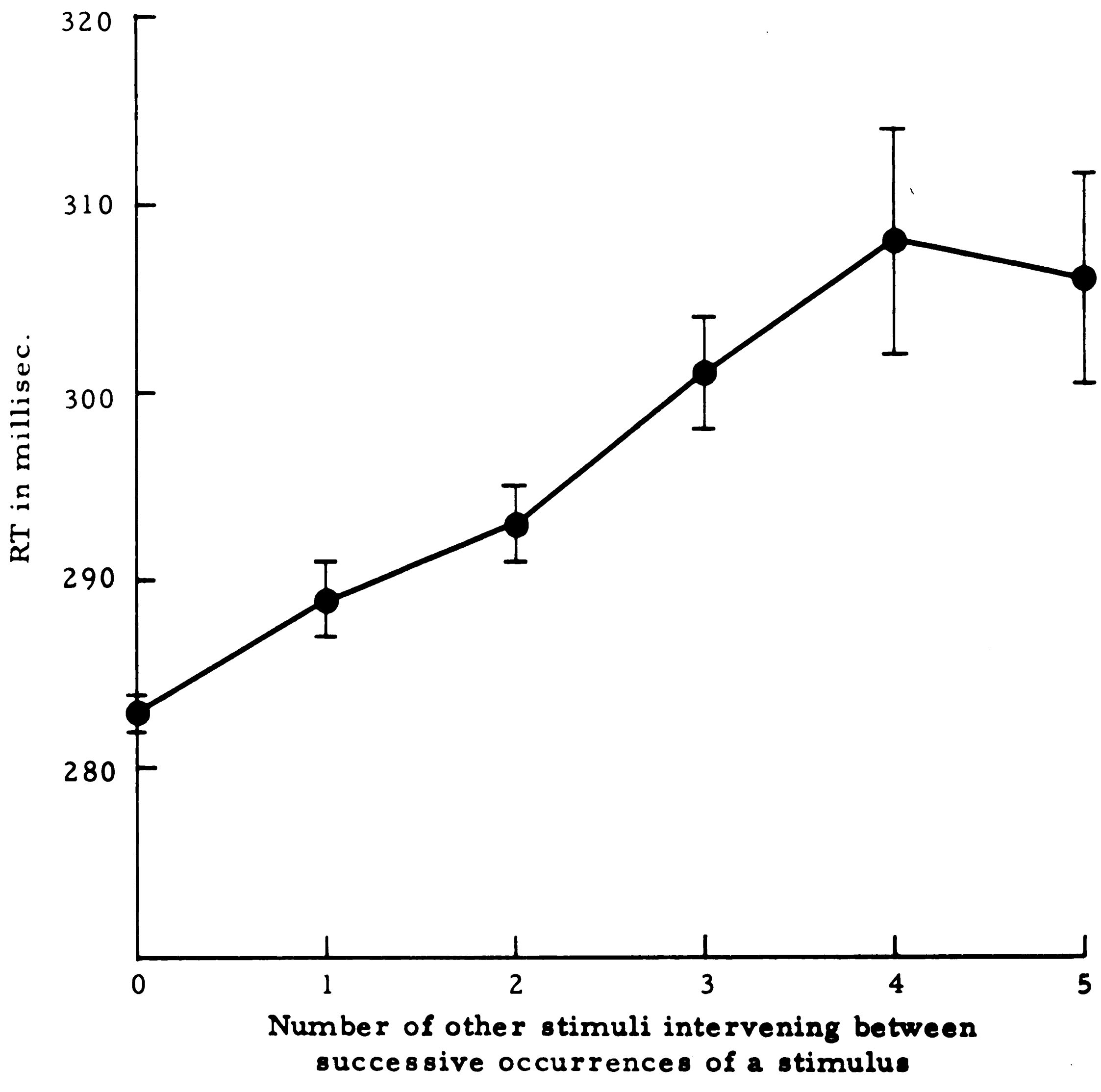


Figure 5. RT as a function of the number of other stimuli intervening between successive occurrences of a particular stimulus within a series for the 50:50 condition. (Vertical lines extend one standard error of the mean on either side of the plotted mean RTs.)

across components are presented in Figure 6. Once again the trend for the overall 70:30 condition gives a misleading picture. The averaging process produced a trend that does not represent a simple average of the trends for the separate components. For interval sizes of zero and one the overall trend is mainly determined by the 70 per cent component, but for larger intervals the overall trend becomes increasingly dependent upon the 30 per cent component.

Tree diagram analysis of the 50:50 condition

The results of the tree diagram analysis of the 50:50 condition data are presented in Figure 7. As indicated previously, this analysis associates a mean RT with every possible stimulus pattern through a given order (the fifth-order in this case). Perhaps the most striking result was the overall picture that emerged when the tree diagram analysis was applied to the data. The graph in Figure 7 clearly conveys the fact that stimulus patterns of a higher order than the popular second-order have a reliable effect on CRT. The results of this tree diagram analysis, represented in graphic form, also shed light on the nature of the repetition effect and some of the theoretical misconceptions associated with this popular second-order sequential effect.

It is generally believed that the repetition effect is the result of some sort of perceptual or response facilitation brought about by having seen or responded to the same stimulus event on

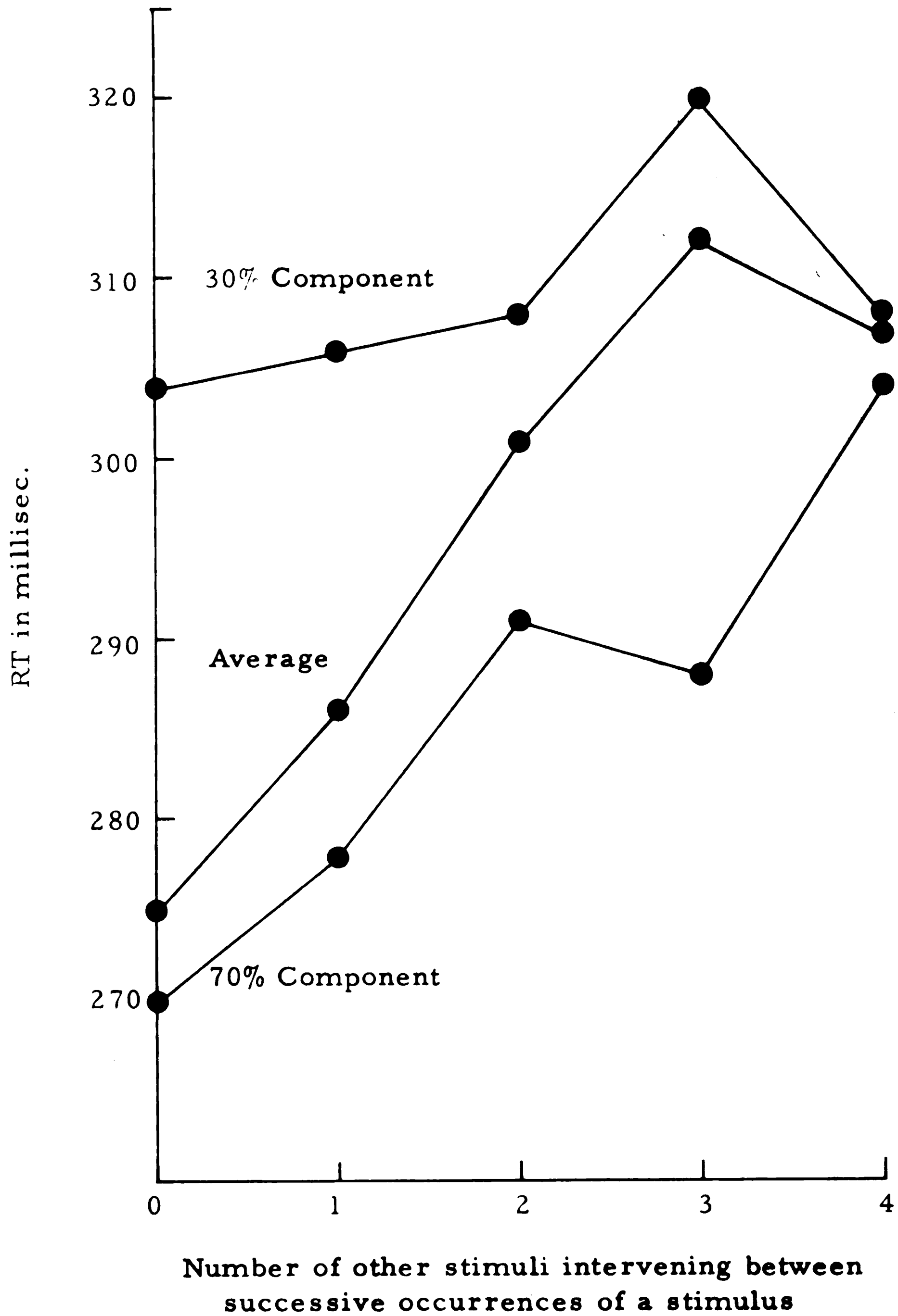


Figure 6. RT as a function of the number of other stimuli intervening between successive occurrences of a particular stimulus within a series for each component and the overall average of the 70:30 condition.

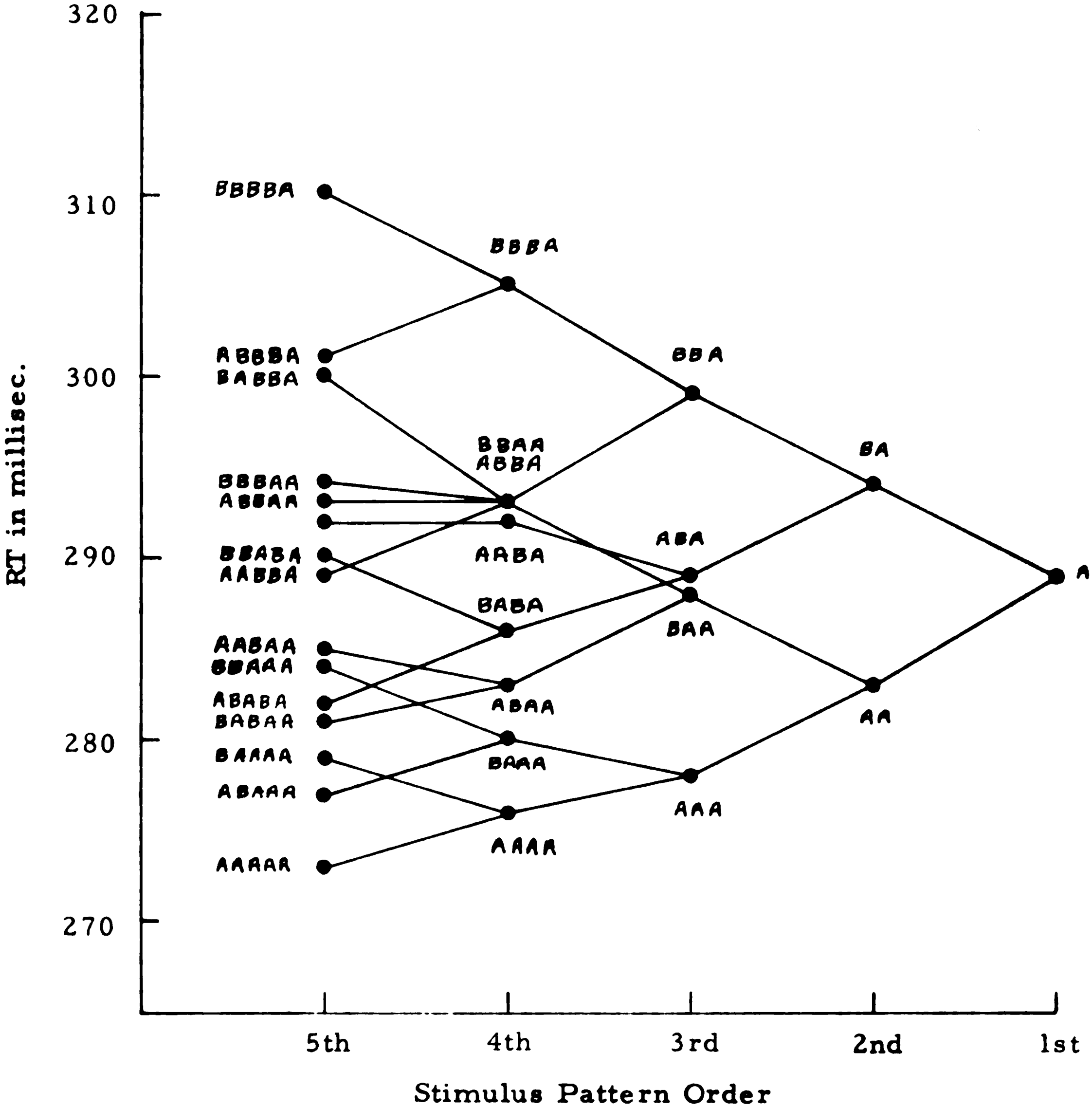


Figure 7. Tree diagram for the 50:50 condition.

the <u>immediately preceding</u> trial. A very simple test of this theoretical notion can be made by examining the mean RTs associated with the third-order components of the AA pattern (i. e., BAA and AAA). From the results reported in Figure 7 it can be seen that the decrease in RT associated with the AA pattern (the repetition effect) can be attributed mainly to the AAA pattern and its higher-order components, and that RT(BAA) is nearly the same as the overall mean RT for the stimulus series. The important finding is that, at least for the 50:50 condition, the repetition effect could not be associated with a single repetition of a stimulus event.

Examination of the mean latencies associated with the third-order components of the BA pattern revealed more information concerning the nature of the repetition effect, and provided another test of the popular one-trial memory models. Assuming that on trial n the subject is operating only on the information processed on trial n-1, there would be no reason to expect a difference between the mean latency associated with the ABA stimulus pattern and the mean latency associated with the BBA stimulus pattern. However, a paired <u>t</u> test indicated that there was a significant (.02 level) difference between RT(BBA) and RT(ABA). Like RT(BAA), RT(ABA) was practically equal to the overall mean RT making no contribution to the repetition effect.

Although the results shown in Figure 7 do not lend themselves well to a concise and comprehensive verbal description, they do appear to display a number of salient characteristics that are worthy of further discussion. For example, the upper branch of the tree structure in Figure 7 has definite theoretical implications. On the basis of the trend displayed in the upper branch it appears that the time required to process a given signal A is directly dependent upon the number of successive presentations of signal B that have immediately preceded the presentation of signal A. This relationship is best described by the equation $Y = 289.7 + 5.3\ X$ (for the range of X values represented in Figure 7). It would be interesting to compare the slope of this equation with those obtained in other experimental situations which employed two equiprobable signals. But, unfortunately, previous researchers have not made this type of analysis. In fact, previous researchers have not examined and reported RT(BBA), RT(BBBA), or RT(BBBBA).

Examination of the mean RTs for the fourth- and fifth-order stimulus patterns suggests that the means for stimulus patterns at a given order are related to the number of *A*s that appear in a pattern. For example, of the eight fourth-order patterns, the three lowest means were associated with patterns with at least three *A*s, while the three highest means were those for patterns with two or less *A*s. However, it is interesting to note that RT(BABA) was less than RT(AABA). It appears that the alternating pattern BABA represents a special case. The fifth-order stimulus patterns with the three lowest mean RTs were patterns which contained four or more _A_s, while the four highest means were associated with patterns which had two or less _A_s. All eight patterns with means below the overall mean contained at least three _A_s.

In general, it appears that the more times a given signal has been processed on the immediately preceding trials (at least four trials back), the less time it takes to process that signal. Conversely, the more times the alternate signal occurs immediately before the presentation of a given signal A, the more time it takes to process signal A. If the number of times the alternate signal occurs is held constant, at two for example, then two occurrences of the alternate event in succession have a more detrimental effect on the processing time for signal A than non-consecutive presentations of the alternate signal (e.g., RT(BBAA) was greater than RT(BABA)).

Tree diagram analysis of the 70:30 condition

The results of the tree diagram analysis of the data from the 70:30 condition are presented in Figure 8. Based upon previous results it was deemed necessary to make a separate analysis for the individual components of this particular condition. In general, the results of these analyses support the major findings from the

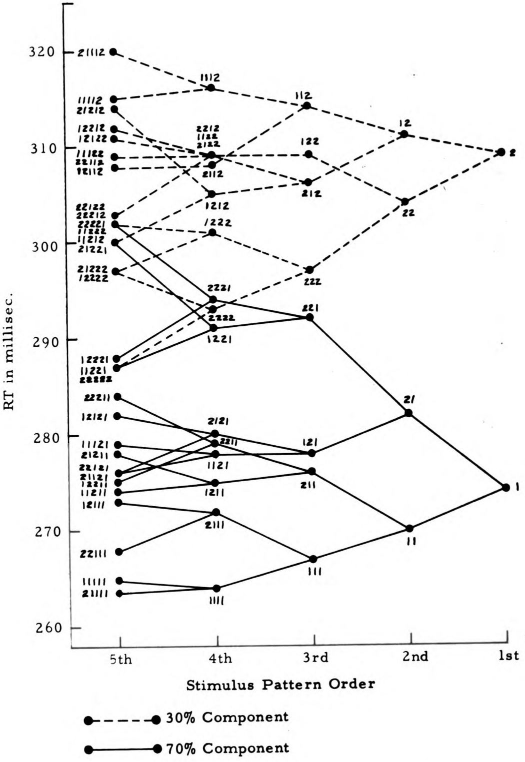


Figure 8. Tree diagrams for the individual components of the 70:30 condition.

50:50 condition regarding the importance of higher-order stimulus patterns in determining RT and the nature of the repetition effect. For example, the results for both components provide added support for the contention that the repetition effect cannot be attributed to a single repetition of a stimulus event. Once again the observed repetition effect was mainly a result of the faster RTs associated with at least three repetitions (111 or 222, but not 211 or 122), and the slower RTs associated with stimulus patterns in which a stimulus was immediately preceded by at least two presentations of the alternate stimulus event (e.g., 112 or 221, but not 212 or 121).

The linear equations that best describe the trends for the <u>lower</u> branch of the tree diagrams (the repetition function) for each component presented in Figure 8 appear to have different slopes. That is, the slope for the 30 per cent component appears to be greater than the slope for the 70 per cent component. These slopes were found for each subject and the differences were used in a paired *t* test. The results of this test showed that the slopes were significantly different (.05 level). This finding indicates that signal probability influences the amount of facilitation brought about by successive repetitions of the signal.

On the other hand, a similar comparison (paired *t* test) of the slopes for the linear equations for the <u>upper</u> branch of the tree diagrams showed that the slope for the 70 per cent component was significantly (.05 level) larger than the slope for the 30 per cent component. This finding indicates that successive presentations of the 30 per cent stimulus immediately preceding the presentation of a 70 per cent stimulus had a more detrimental effect on processing the 70 per cent stimulus than vice versa. Note that RT(2221) and RT(2222) are almost identical, in spite of the fact that the objective probability of a "1" following three "2s" is .70 while for a "2" following three "2s" it is .30. On the other hand, RT(2222) is 23 millisec. faster than RT(1112), in spite of the fact that the objective probability of a "2" following either three "2s" or three "1s" is the same. These findings illustrate the strength of the sequential effects, and the type of phenomena that an adequate model of CRT should be able to predict.

## Four-Choice Conditions

### The repetition effect

In determining the repetition effect for data collected from a CRT task involving more than two choices it is common practice to find the difference between the mean for repetitions and non-repetitions (i.e., stimulus events immediately preceded by a different stimulus). Non-repetitions are not sub-divided into additional categories on the basis of the characteristics of the particular pair of stimulus events involved, such as their probabilities, etc. For examples of the use of this procedure the reader is referred to the studies by Hyman (1953), Bertelson (1963), Bertelson (1965), and Kornblum (1967). When the procedure was applied to the four-choice data from the present experiment repetition effects of nearly the same magnitude were found for both conditions (i.e., 36 millisec. for the equiprobable four-choice condition, and 38 millisec. for the 40:20:20:20 condition). The results of this gross analysis (the very simplest type of sequential analysis of four-choice CRT data) indicate that the difference between the time required to process repetition signals and non-repetition signals under a four-choice condition is not affected by slight changes in the relative probabilities of the stimulus events.

When results of this analysis are compared to the results of the repetition effect analyses made for the two-choice data presented in Table 3 it can be seen that repetition effects of a greater magnitude are found for the four-choice conditions. Similar results have been reported for a variety of experimental situations (e.g., Kornblum, 1967; Bertelson, 1963).

## The repetition function

Repetition sequences represent one of the two particular cases of sequences that were considered by Falmagne in deriving the theorems of his model. The repetition function presented by

Falmagne differs from the usual repetition function that is produced by the position in run analysis introduced by Bertelson (1961). This difference is a result of a difference in the definition of what constitutes a repetition. In the position in run analysis, the sequence AA is defined as one repetition; the sequence AAA constitutes two repetitions, etc. However, Falmagne's <u>k-repetition sequence</u> can be defined as a sequence that begins with a non-repetition (i. e., BA) followed by a sequence of at least k consecutive repetitions. That is, a k-repetition sequence is defined as follows:

$$B_n A_{n+1} A_{n+2} \cdot \cdot \cdot A_{n+k+1}$$

In terms of data analysis this simply means that if one is interested in plotting RT as a function of repetitions from zero through four repetitions using Falmagne's method, he would plot RT(BA), RT(BAA), RT(BAAA), RT(BAAAA) and RT(BAAAAA) instead of RT(BA), RT(AA), RT(AAA), RT(AAAA) and RT(AAAAA). The results of both types of repetition analysis for the data from the 25:25:25:25 condition are presented in Figure 9. Although the two methods use different definitions of what constitutes a repetition, the resulting repetition functions were very similar. In order to make the results of repetition analyses compatible with those found in the two-choice conditions, the position in run analysis was adopted for the study of other repetition functions of interest in the four-choice conditions.

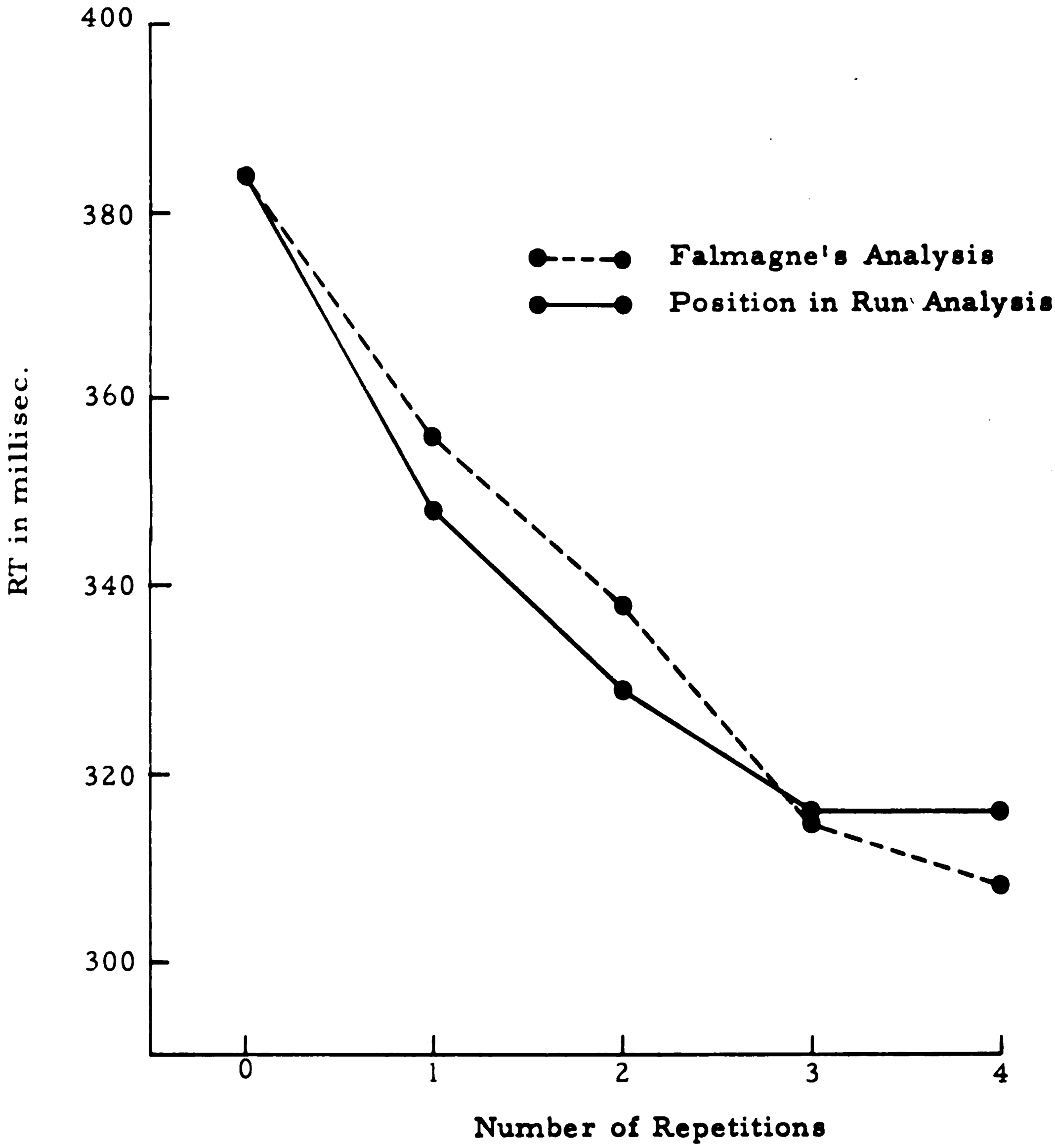


Figure 9. The results of two types of repetition analysis for the 25:25:25:25 condition.

The repetition functions for stimulus signal "1" under both four-choice conditions were delineated in order to determine the influence of increasing the probability of signal "1" from .25 to .40 on higher-order sequential effects. The resulting repetition functions are presented in Figure 10. A comparison of these functions yields some very interesting findings not revealed by the overused repetition effect analysis. It can be seen that the repetition effect for stimulus signal "1" is practically the same under both conditions (viz., 34 millisec. for the 25:25:25:25 condition and 35 millisec. for the 40:20:20:20 condition). However, an additional repetition led to a greater reduction in the mean RT to signal "1" when it was processed under the equiprobable condition than under the condition where it appeared with probability .40. This finding is analogous to the two-choice finding that greater reductions in processing time with successive repetitions were associated with the lower probability stimulus. But, unlike the linear reduction of CRT with successive repetitions found in the two-choice conditions, the trends for the four-choice conditions (particularly the 40:20:20:20 condition curve) appear to be curvilinear.

The repetition function curve for signal "1" under the 40:20:20:20 condition appears to level off at a faster rate than its counterpart for the 25:25:25:25 condition. Unfortunately, lack of

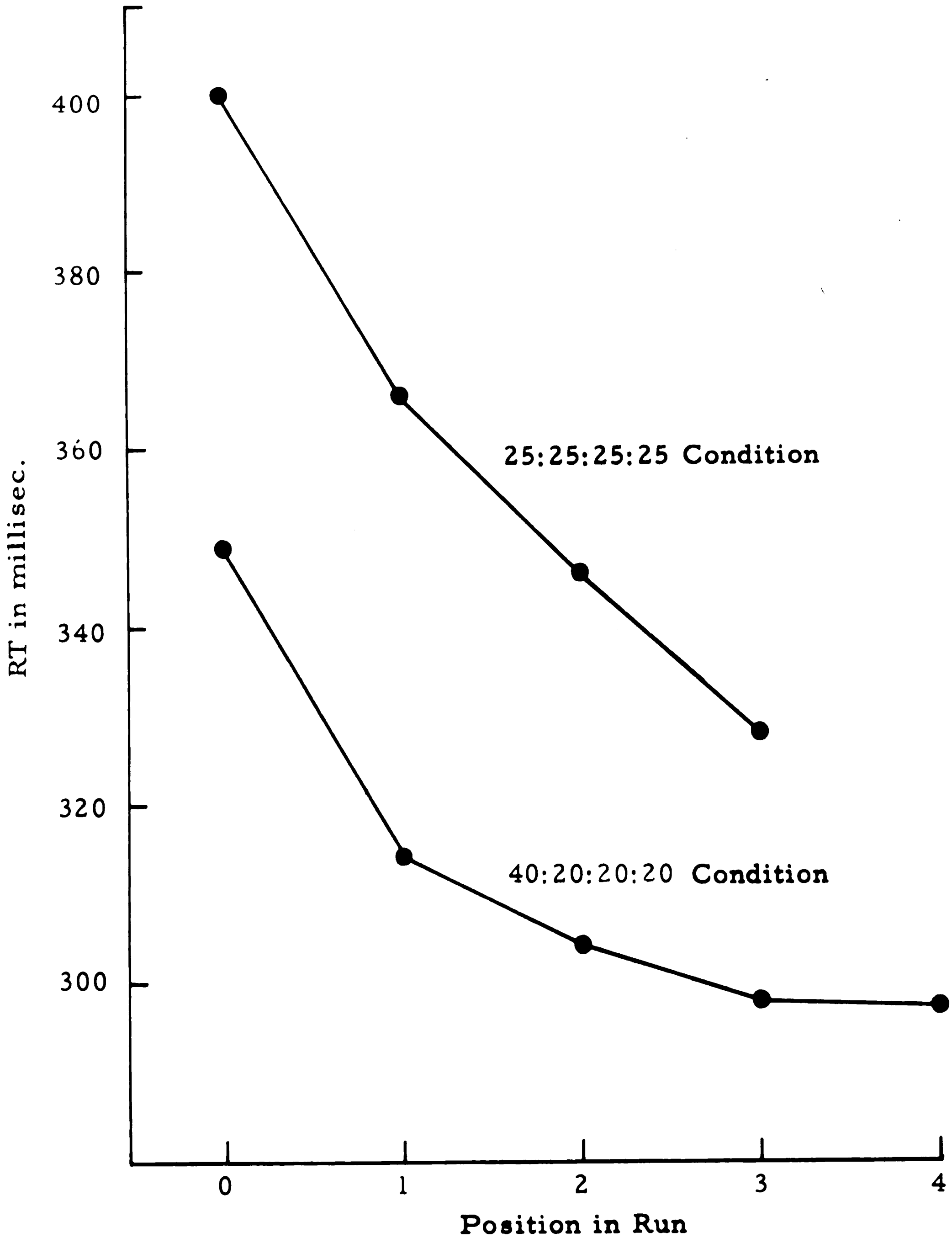


Figure 10. RT as a function of position in a run of repetitions of stimulus event "1" under the 25:25:25:25 condition and the 40:20:20:20 condition.

data on four repetitions of signal "1" under the equiprobable condition made it impossible to adequately compare the functions beyond three repetitions. The leveling off of the 40:20:20:20 condition curve could not be attributed to the fact that it was rapidly approaching the RT associated with the physiological limit. Examination of the results from the simple reaction condition showed that the mean simple reaction time for signal "1" was 248 millisec., which is about 50 millisec. lower than the apparent lower limit for this repetition effect curve.

Detailed tree diagram analysis of stimulus signal "1"

Instead of making a number of simplifying assumptions which would be needed to justify an overall sequential analysis of each four-choice condition (such as the one for the 50:50 condition presently in Figure 7), it was decided to start with a detailed tree diagram analysis of a particular stimulus event for each condition. In this way the validity of a number of assumptions that have been made by Falmagne (1965) and others in their data analysis can be examined directly. First, the results of the tree diagram analysis of stimulus signal "1" under the 25:25:25:25 condition are presented in Figure 11. This type of detailed analysis of the basic stimulus patterns did not permit adequate assessment of the mean RTs for

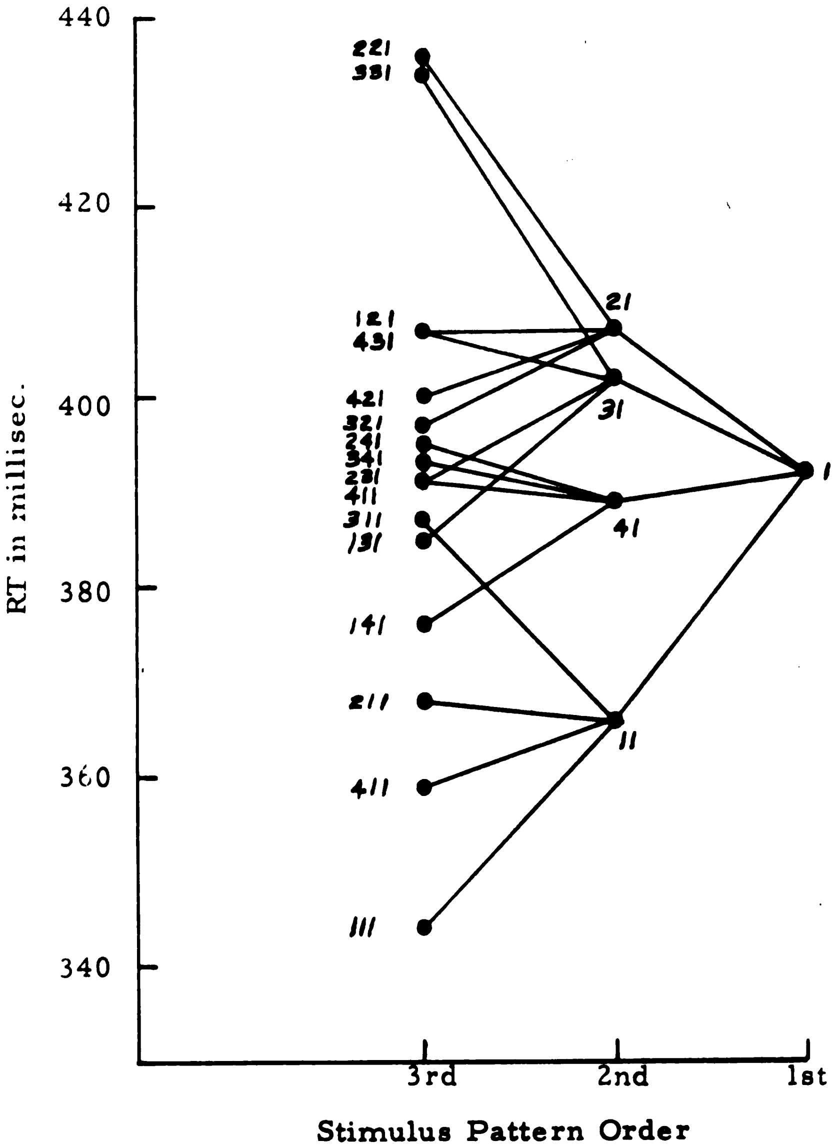


Figure 11. Tree diagram for stimulus signal "1" under the 25:25:25:25 condition.

all 64 fourth-order patterns. Therefore, the reported results are confined to the mean RTs associated with the 21 stimulus patterns through the third-order.

The results of this analysis, presented in graphic form, make it readily apparent that third-order stimulus patterns had an influence on RT, even a greater influence than was observed in either of the two-choice conditions. For example, it can be seen that the mean RT for stimulus signal "1" was much longer if it was immediately preceded by two presentations of signal "2" or signal "3" than if it was immediately preceded by two presentations of signal "1" (i.e., a difference of about 90 millisec.). The findings concerning the second-order sequential effects tend to cast doubt on the appropriateness of the customary procedure of pooling non-repetitions in arriving at a single value to represent "the repetition effect" for conditions that involve more than two choices. Examination of the mean latencies associated with the second-order stimulus patterns in Figure 11 indicates the existence of differences between the non-repetition patterns. Discussion of these differences is facilitated by the use of some new notation. Let $RT(A|B)$ represent the mean RT for stimulus event A given that it is immediately preceded by stimulus event B. Applying this notation to the differences between non-repetitions displayed in Figure 11 we would say that $RT(1|4)$ was less than RT(1|2) or RT(1|3). Examination of RT(1|4) showed that RT(1|4) was less than RT(1|2) or RT(1|3) for every subject. The same pattern of differences among the non-repetitions emerged when a tree diagram analysis was made for stimulus signal "1" under the 40:20:20:20 condition. The results of this analysis are presented in Figure 12.

Differences in mean RTs for different non-repetition patterns (e.g., RT(1|4), RT(1|2), and RT(1|3)) have not been examined and reported in previous literature. In view of the fact that such differences exist in the data for stimulus signal "1" where each of the non-repetition patterns were equiprobable, it is very likely that even larger differences exist in data from previous studies where the probabilities associated with the more numerous non-repetitions patterns were vastly different (e.g., the data from the studies conducted by Falmagne, 1965; Leonard et al., 1966; and Kornblum, 1967).

The results of a detailed examination of the second-order sequential effects for each stimulus event under the 40:20:20:20 condition are presented in Table 4. The data from one of the low probability stimuli (i.e., stimulus events 2, 3, or 4) from this table should illustrate, in a limited way, the questionable value of the results of the previous studies mentioned above if they have indeed averaged over non-repetitions components that are greatly

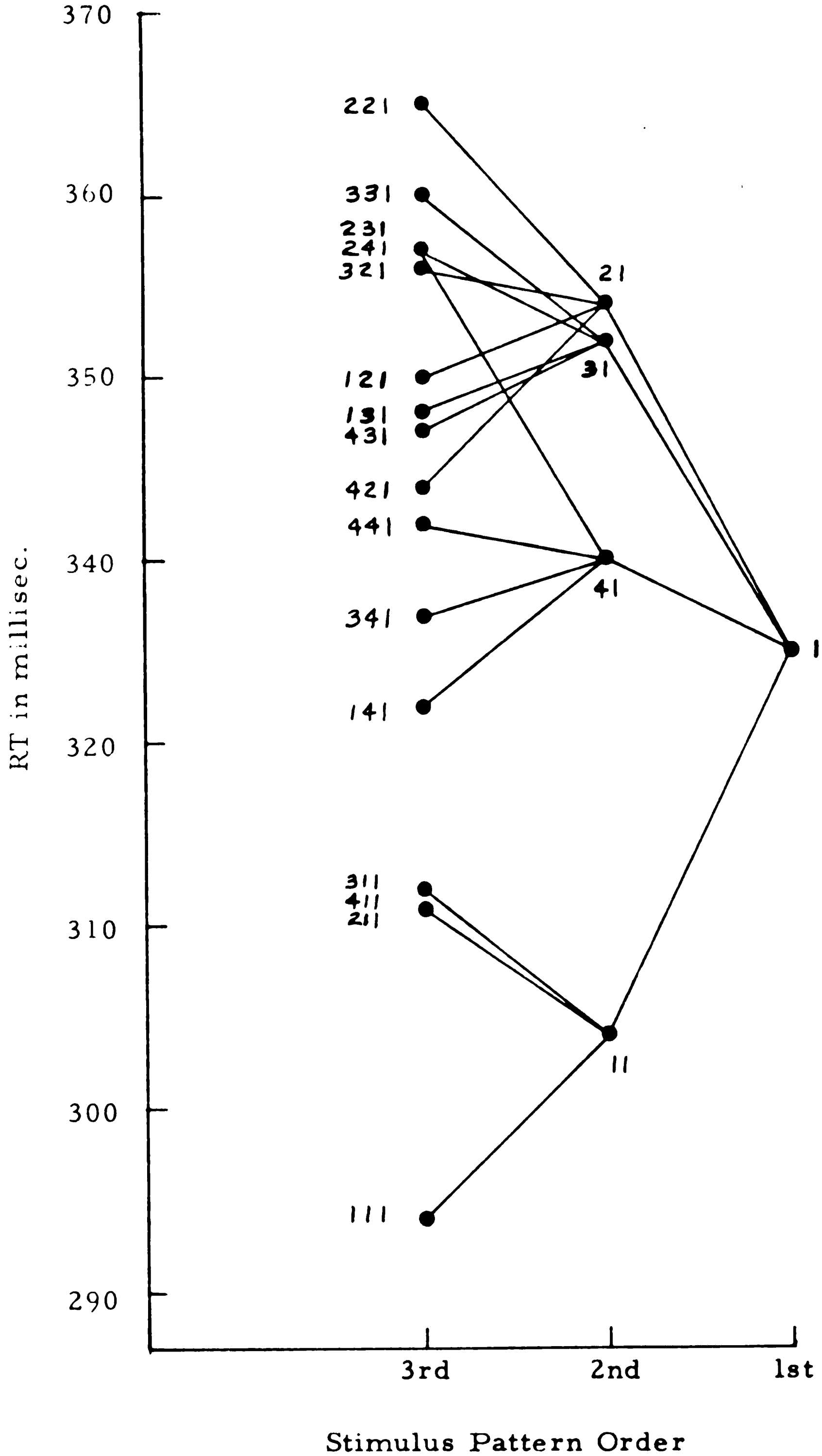


Figure 12. Tree diagram for stimulus signal "1" under the 40:20:20:20 condition.

Table 4. Mean RTs and SDs associated with all second-order stimulus patterns for each of the stimulus events under the 40:20:20:20 condition.

| Stimulus Event on Trial n-1 | | Stimulus Event on Trial n: 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| 1 | $\bar{X}$ | 314 | 341 | 378 | 380 |
| | SD | 54 | 67 | 76 | 77 |
| 2 | $\bar{X}$ | 354 | 311 | 345 | 379 |
| | SD | 73 | 53 | 58 | 72 |
| 3 | $\bar{X}$ | 352 | 341 | 329 | 386 |
| | SD | 70 | 64 | 61 | 80 |
| 4 | $\bar{X}$ | 340 | 351 | 352 | 344 |
| | SD | 62 | 67 | 77 | 58 |
| Column Marginals | $\bar{X}$ | 335 | 337 | 357 | 374 |
| | SD | 66 | 65 | 73 | 75 |

different in both mean latency and the weight they contribute to the average for non-repetitions. For example, let us examine the results reported for stimulus event "3". Using the customary repetition effect procedure the difference between the RT for repetitions and non-repetitions, or "the repetition effect", was found to be 33 millisec. However, a more detailed analysis based upon the mean RTs for the separate non-repetitions components shows repetition effects of 16 millisec., 23 millisec., and 49 millisec. for the (3|2), (3|4) and (3|1) non-repetition stimulus patterns, respectively. It can be seen that the repetition effect for stimulus event "3" was more than three times larger when it was immediately preceded by stimulus event "1" than when it was immediately preceded by stimulus event "2". This type of interaction would not have been revealed by any of the data analysis procedures described in the reviewed literature. These results illustrate the fact that the overall repetition effect derived from the conventional procedure can be very misleading if interpreted as a representative measure. No straightforward interpretation of this particular index of second-order sequential effects should be made unless one has evidence that the mean RTs for the various non-repetition stimulus patterns are equal. This becomes a particularly relevant consideration when a number of stimuli representing a wide range of stimulus probabilities make up a condition, such as the experimental condition used by Falmagne (1965). However, it appears as though Falmagne ignored this fact at every level of his sequential analysis.

At first glance one might contribute the observed differences between RT(3|2), RT(3|4) and RT(3|1) to the differences in the probabilities associated with the stimulus events that precede the stimulus event "3". That is, the mean RT for stimulus event "3" was relatively larger if it was immediately preceded by the high probability stimulus event "1" than if it was preceded by either of the two low probability non-repetition stimulus events "2" or "4".

However, examination of RT(3|1), RT(3|2) and RT(3|4) for the 25:25:25:25 condition found in Table 5 shows that RT(3|1) was also larger than RT(3|2) and RT(3|4). The differences in these RTs were somewhat smaller in the 25:25:25:25 condition than in the 40:20:20:20 condition. These findings indicate that a factor (or factors) other than stimulus probability are involved in the observed differences between mean RTs for non-repetition stimulus patterns.

Examination of the overall means for each stimulus event for both conditions (reported as the column marginals in Table 4 and Table 5) suggests a factor that might be operating in such a way as to produce some of the observed results. As would be expected from previous findings, increasing the probability of stimulus event "1" from .25 to .40 produced a decrease in mean RT for that particular event from 392 millisec. to 335 millisec. But, the finding of most interest in the present section concerns the observed changes in mean RT for stimulus events "2" and "3" that took place under the 40:20:20:20 condition.

Examination of the simple reaction time data for stimulus events "2" and "3" showed that they both had a mean RT of 241 millisec. The means for these stimulus events were also equal under the 25:25:25:25 condition. However, under the 40:20:20:20 condition a 20 millisec. difference between the means for these

Table 5. Mean RTs and SDs associated with all second-order stimulus patterns for each of the stimulus events under the 25:25:25:25 condition.

| Stimulus Event on Trial n-1 | | Stimulus Event on Trial n 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| 1 | $\overline{X}$ | 366 | 362 | 385 | 390 |
| | SD | 72 | 85 | 101 | 79 |
| 2 | $\overline{X}$ | 407 | 332 | 358 | 394 |
| | SD | 85 | 71 | 92 | 78 |
| 3 | $\overline{X}$ | 402 | 368 | 338 | 392 |
| | SD | 88 | 93 | 77 | 84 |
| 4 | $\overline{X}$ | 389 | 390 | 366 | 358 |
| | SD | 82 | 88 | 94 | 73 |
| Column Marginals | $\overline{X}$ | 392 | 363 | 363 | 384 |
| | SD | 83 | 87 | 93 | 80 |

events emerged. The direction of this difference (i. e., RT(2) was less than RT(3)) suggests that the spatial location of the signals was an influencing factor. That is, the difference between RT(2) and RT(3) might be explained in terms of the spatial correspondence of these signals to signal "1", the biased signal. Perhaps under the 40:20:20:20 condition the "search pattern" begins at the left with the highly probable signal and proceeds to the right. It would be interesting to see whether or not the difference between (RT(2) and RT(3) would reverse direction if signal "4" were the biased signal.

Detailed interval analysis for stimulus event "1"

It should not be concluded from the foregoing discussion that one need only exercise caution in averaging RTs for second-order non-repetition stimulus patterns. The results reported in the present section indicate that the interval analysis curves reported in the previous literature (viz., Hyman, 1953; and Falmagne, 1965) are also of questionable value as indicators of the underlying microstructure of the reaction processes. In introducing the interval analysis to study the recency effect in CRT data, Hyman (1953) presented interval analysis curves for his two, four, and eight alternative conditions. Later, Falmagne (1965) presented separate interval analysis curves for each of the six stimulus events employed in his one experimental condition.

Although Falmagne's analysis represented an improvement over the relatively gross analysis made by Hyman, a number of questionable simplifying assumptions are associated with Falmagne's data analysis procedures. In order to illustrate and test these assumptions Falmagne's procedure as well as a more detailed data analysis procedure were applied to the data for stimulus event "1". Using Falmagne's procedure one first would find RT(ABA) where A represents the stimulus event of interest (viz., stimulus event "1") and B represents any of the other possible stimulus events (viz., stimulus events "2", "3" and "4"). In the case under consideration RT(ABA) is the weighted mean of the means associated with the third-order stimulus patterns 121, 131, and 141.

Under the 25:25:25:25 condition RT(ABA) for stimulus event "1" was 389 millisec., which is only 3 millisec. lower than the overall mean for stimulus event "1". Strictly speaking, RT(121), RT(131) and RT(141) should all equal about 389 millisec. if this value is to be considered as representative of the RT associated with the stimulus pattern in which successive presentations of stimulus event "1" are separated by a presentation of another stimulus event. However, examination of the mean RTs associated with these stimulus patterns revealed substantial differences. The mean RTs ranged from 376 millisec. for the 141 pattern to 407 millisec. for the 121 pattern.

The next step in delineating the interval analysis curve for stimulus event "1" by Falmagne's procedure would be to determine RT(ABBA). The pooling procedure becomes even more questionable in this case, where we do not distinguish between patterns such as 1221, 1331, 1441 and the patterns 1231, 1241, 1341, 1321, 1421, and 1431. The mean RTs for these patterns were found to represent a wide range from 429 millisec. for the 1221 pattern to 377 millisec. for the 1341 pattern. The pooled mean, which would have been reported in the Falmagne type of analysis, was 393 millisec. Future models of CRT should be able to account for the findings regarding the microstructure of the data such as those reported in this section.

## DISCUSSION

Most of the current research on sequential effects in CRT performance has been focused on the repetition effect. The typical interpretation of the repetition effect implies that the RT on a given trial is largely determined by the stimulus event that appeared on the *immediately preceding* trial. That is, on the average, the RT to a signal that is the same as the signal that appeared on immediately preceding trial will be faster than the RT to a changed signal. Theoretical formulations based on findings concerning the repetition effect do not acknowledge the presence of higher order sequential effects. However, the results of a more comprehensive analysis of sequential effects reported here have clearly demonstrated that an adequate model of CRT must also account for third, fourth, fifth, and possibly higher-order sequential effects.

Most of the current models of sequential effects in CRT are based on the theoretical notion that the time required to process a given signal is relatively independent of the signals presented more than one trial back. The general structure of the tree diagrams presented in the present paper suggests that such models are unrealistic. If stimulus patterns beyond the popular second-order had no significant effect on CRT, we would not expect the tree structure resulting from a tree diagram analysis to branch in any systematic way beyond the point representing the nodes for the second-order stimulus patterns. However, the resulting tree structures displayed systematic patterns of branching and non-negligible sequential effects at every level examined (i. e., through the stimulus pattern order for which there was sufficient data). Furthermore, the resulting tree structures suggest that certain higher-order sequential effects are as important as the more popular repetition effect (e. g., third-order sequential effects, similar to the repetition effect in magnitude, were found under every experimental condition), and therefore, deserve similar study and treatment in any theoretical formulation which attempts to account for sequential effects in CRT.

Although higher-order sequential effects were reported as early as 1953 by Hyman, only two major studies of such effects have been reported since (Falmagne, 1965; and Leonard *et al.*, 1966). Only effects associated with a relatively small number of the possible higher-order stimulus patterns were subjected to analysis by both of these researchers (i. e., repetition stimulus sequences and sequences in which the successive presentations of a given stimulus are separated by intervals of varying size). The findings of the present study indicate that the higher-order sequential effects reported by Falmagne and Leonard *et al.* represent only a small piece of the picture that emerges when the entire microstructure of sequential effects are examined and displayed by means of a tree diagram. It appears that current approaches to the study of both second-order and higher-order sequential effects have been too fragmentary and have impeded the development of more comprehensive theoretical models by overemphasizing the importance of the small number of sequential effects examined. The most efficient approach to the study of sequential effects would seem to be a comprehensive approach that examines the entire microstructure of the data.

The results of the present study, in addition to demonstrating the feasibility of a more comprehensive approach to the study of sequential effects, contain a number of methodological implications. During the early phase of the present study possible sequential effects were obscured by strong practice effects and highly variable RTs within subjects. For example, under the 50:50 condition a relatively stable pattern of sequential effects (including the repetition effect) did not emerge until each subject was allowed to go through a practice period of 400 trials. This finding suggests that the results of a number of studies on sequential effects are of questionable value (especially in the formulation of a steady state model of CRT) because they are based upon so few observations per subject (e. g., Williams, 1966; Hale, 1967; and Bertelson, 1963). The more comprehensive approach to the study of higher-order sequential effects by means of a tree diagram analysis will demand the collection of even a larger amount of data. The results of the present study indicate that even 1,000-1,200 observations per subject under a given condition do not provide sufficient data to determine the stimulus pattern order at which sequential effects become negligible.

Another methodological implication derived from the results of the present study involves the common practice of collapsing or averaging over components which make up an experimental condition. A detailed analysis of data from the 70:30 condition demonstrated the fact that the usual practice of averaging over the two components in arriving at a single index of the repetition effect can lead to very misleading interpretations. Even a greater number of potential pitfalls were noted in the four-choice conditions. Detailed examination of four-choice data revealed evidence concerning the inappropriateness of a number of simplifying assumptions made by previous researchers in their analysis of data from experiments which involved more than two choices (e.g., The common practice of averaging across non-repetition components was found to be inappropriate, even in the equiprobable four-choice case.). The results of a number of previous studies, particularly those in which data from non-equiprobable stimulus events were collapsed (e.g., Leonard *et al.*, 1966), should be re-examined in the light of these findings. As a general rule for avoiding similar mistakes in future research on sequential effects one should start at the most detailed level of analysis and average over components only when the resulting average is meaningful.

Premature theorizing based on the repetition effect has been relatively ineffective in producing models with adequate explanatory and predictive power. Some relatively new lines of research may very well combine in such a way as to fill the current theoretical vacuum. Further detailed data analysis of the caliber reported in the present paper should prove useful in sharpening our theoretical formulations. Similar data from a number of experimental situations would allow us to specify more precisely the requirements that an adequate theoretical model must satisfy. Fortunately, because of the theoretical work of Falmagne (1965), we already have a good example of some of the things that a model ought to predict. Falmagne's mathematical model is capable of making relatively good predictions concerning many interesting aspects of CRT data. However, there is convincing evidence that the processes underlying choice reaction behavior are too complex to be accurately represented by such a two state model. The development of more sophisticated mathematical models would represent a challenging and perhaps rewarding approach. Finally, the type of detailed information that emerged from the tree diagram analysis introduced in the presented study appears to be well suited to the computer simulation approach. Perhaps future work along these lines will yield a concise and comprehensive description of CRT behavior in the form of a computer program.

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