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STIMULUS AND RESPONSE FACTORS DETERMINING THE RELATIVE FREQUENCY EFFECT IN CHOICE-REACTION TASKS

Three experiments were performed to determine the influence of the probability of occurrence of stimulus and response alternatives on choice reaction time (RT). With response probabilities equated, the choice RT for a stimulus was found to be longer the lower its probability of occurrence. This relative frequency effect was larger for less codable stimulus types (e.g., circles of varying size), than for more codable ones (e.g., colors and letters); but the magnitude of the effect was not related to confusability of the stimulus alternatives. With stimulus probabilities held constant, a relative frequency effect was also observed with variations in response probability. The effect produced by variations in stimulus probability is attributed to differential recency of recall of the stimulus-response translation rule. Recency had less influence when the stimulus-rule association was strong, as with highly codable stimuli. The effect produced by variations in response probability is attributed to processes occurring at the response selection stage of choice behavior.
STIMULUS AND RESPONSE FACTORS DETERMINING THE RELATIVE FREQUENCY EFFECT IN CHOICE-REACTION TASKS

by

Roger Blackman

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I

INTRODUCTION

A problem common to almost all areas of psychology concerns the nature of the processes involved in choice—the selection of one response from among a number of possible alternatives on the occurrence of a particular stimulus. Inferences about the processes that underlie choice have largely been based on evidence from tasks in which the subject is required to choose among a given set of alternatives according to certain instructions or prescribed rules. The typical dependent variables in such experiments are the speed and accuracy of choice. One of the simplest paradigms allowing measurement of these two variables is used in the choice reaction time (RT) task; the latter thus provides a convenient approach to the elucidation of choice processes.

The first use of RT as an index of the temporal properties of higher mental processes was made by Donders (1868). He distinguished three basic types of RT tasks. In the first, involving measurement of simple RT, the subject makes a specified response (R1) when a specified stimulus (S1) occurs. Since only one stimulus and one response are specified, neither discrimination between stimuli nor selection between responses is required. By including several alternative stimuli, and instructing the subject to withhold response to all but one of them (S1-R1, S2-no response, S3-no response, etc.), the necessity for stimulus discrimination is introduced, allowing measurement of selective RT. Finally, when there are two or more S-R pairs (S1-R1, S2-R2, S3-R3, etc.), response selection is also required and choice
or disjunctive RT is obtained.

Donders believed that appropriate subtractions of these three measures of RT would give pure estimates of the time taken for stimulus discrimination and for response selection. This aim was largely thwarted by not only the variability found in the early studies of choice RT, but also by the belief that choice could not be validly divided into components in this manner (e.g., Kühpe, 1893). More recent experiments, however, provide some support for the contention that the times taken by the components of choice are additive (Peterson, 1965; Posner & Mitchell, 1967; Sternberg, 1967; Taylor, 1966).

It was soon discovered that one of the major determinants of choice RT is the number of different S-R pairs from which one pair is selected on any individual trial (Merkel, 1885). In other words, the greater the subject's uncertainty about the next stimulus event, the slower he is in dealing with it. Although this finding was of obvious relevance to the understanding of choice behavior, further analysis was hindered by the difficulty of quantifying uncertainty. This obstacle was removed when Shannon and Weaver (1949) proposed their information theory, which was applied to the choice RT situation by Hick (1952). In this approach, the variable used to define the uncertainty associated with an event is the probability of occurrence of that event. Investigations of the effect on choice RT of varying probability of occurrence over a series of trials thus provide a direct and convenient way of studying the influence of uncertainty on choice behavior.
One finding arising from such experiments is that the more likely the occurrence of a particular S-R pair, and thus the less the subject's uncertainty about its occurrence, the shorter is the associated choice RT (e.g., Bertelson & Barzeele, 1965; Falmagne, 1965; Krinchik, 1963). What is not clear, however, is the locus of this effect in the sequence of decision processes comprising choice behavior. Greatly oversimplifying the problem, it may be stated thus: is the subject uncertain as to which stimulus is going to occur, or uncertain as to which response is going to be required, or both? The present investigation is basically an attempt to provide an answer to this question.

In the remainder of this chapter, experimental and theoretical contributions relevant to this problem are reviewed. Three original experiments are described in Chapter II. Chapter III is devoted to a discussion of the results and their implications for current models and theories of choice behavior.

Uncertainty and Choice RT

The value of information theory in the analysis of choice behavior is that it provides a way of clearly conceptualizing and measuring uncertainty about the occurrence of stimuli and responses. It will thus be helpful to clarify some of the basic features of information measures.

The uncertainty \( H_{S_i} \) about the occurrence of a particular stimulus is defined by \( H_{S_i} = -\log_2(p_i) \), where \( p_i \) is the probability of occurrence of stimulus \( S_i \). It will be observed that as the probability
of occurrence decreases, uncertainty increases. This relation also defines the information conveyed by the occurrence of the stimulus, the two terms uncertainty and information being interchangeable in this context. Uncertainty associated with a particular stimulus, as defined above, may be regarded as uncertainty as to the trial on which the stimulus will next occur. A different aspect of the subject's uncertainty may be considered--his uncertainty as to which of the alternative stimuli is going to occur on the present trial. In the latter case, one is concerned with average or overall uncertainty, and this is computed by averaging the uncertainties associated with each stimulus in the set: \( H_s = -\sum p_i \log_2(p_i) \). In the special case where each of \( n \) stimuli has the same probability of occurrence, the formula for average uncertainty becomes \( H_s = \log_2(n) \).

In the standard choice RT experiment, responses are paired to stimuli in a one-to-one fashion. If no errors are made, it follows that the set of formulae defining stimulus uncertainty applies also to response uncertainty (\( H_r \)). Another important measure is transmitted information (\( H_t \)), the information common to both stimulus and response sets. To understand how \( H_s \), \( H_r \) and \( H_t \) are interrelated, it will be helpful to consider two unlikely but possible situations in which the responses made are completely unrelated to the stimuli occurring. In the first case, the subject always makes the same response not matter which stimulus occurs. There is no uncertainty regarding the response to be made, and no information is transmitted; therefore, both \( H_r \) and \( H_t \) are zero. In the second case, the distribution of responses is the same as the distribution of stimuli, but the
subject does not know which response is to be paired with each stimulus, so that responses are correct only by chance. $H_t$ is again zero (an observer could infer nothing about which stimuli occurred if he only saw the responses), but $H_r$ is equal to $H_s$. If the frequency of errors is reduced, the proportion of transmitted information would increase until, with errorless performance, the three measures $H_s$, $H_r$ and $H_t$ would be identical.

There are three mathematically equivalent ways of manipulating stimulus uncertainty in the standard choice RT experiment: (a) by varying the number of equiprobable alternative stimuli; (b) by varying the sequential dependencies (conditional probabilities of occurrence) of the stimuli within the trial series; and (c) by varying the probabilities of occurrence of the different stimuli within the trial series. Next we shall consider the effects of each of these variables on choice RT.

Choice RT and the Number of Alternatives

Merkel (1885) established that choice RT lengthens as the number of equiprobable S-R pairs increases. Hick (1952) replotted Merkel's data using stimulus uncertainty rather than number of alternatives as the independent variable. He also replicated Merkel's experiment, and found that both sets of data were best described by a linear relation between choice RT and stimulus uncertainty. This provided support for the information theorist's model of the subject as a communication channel of limited capacity that transmits information at a fixed maximum rate. The greater the amount of information in the stimulus set,
and thus the greater the subject's average uncertainty, the longer
will be his average choice RT. It should be pointed out that, since
the S-R pairs are equiprobable, average uncertainty and the uncer-
tainty for any particular S-R pair are identical.

S-R compatibility. While Hick's findings received general sup-
port (Crossman, 1953; Hyman, 1953), it became clear that description
of the experimental situation solely in terms of information theory
was not sufficient to allow prediction of all aspects of performance
in a choice RT task. One important determinant of the effect of un-
certainty was found to be "S-R compatibility" (Fitts & Deininger, 1954;
Fitts & Seeger, 1953). No formal definition of compatibility has as
yet found general acceptance, but the attribute can be described with
reference to certain experiments. In some studies, choice RT was shown
to be independent of the number of alternative stimuli where the task
involved S-R relations that had been highly practised over the sub-
ject's lifetime. Such tasks include the naming of visually presented
numerals (Morin & Forrin, 1962, 1965; Mowbray, 1960); the vocal imi-
tation of auditorily presented words and nonsense syllables (Chistovich,
Aliakrinsky, & Abulian, 1960; Davis, Moray, & Treisman, 1961); and
the reading of visually presented words (Conrad, 1962; Pierce & Karlin,
1957; Sumby & Pollack, 1954). Similar results have been obtained for
tasks in which there is a high degree of spatial correspondence between
the stimulus and response dimensions. For example, no effect on choice
RT of varying the number of stimulus alternatives was found when tac-
tile stimuli were applied directly to the response finger (Broadbent,
1963; Leonard, 1959). With highly practised subjects, the same was true when the response keys were arrayed in a fashion similar to the stimulus lights (Mowbray & Rhoades, 1959; Spigel, 1965). Thus, when S-R combinations are inherently compatible, or become so with practice, the usual dependence of choice RT on the number of alternatives disappears.

In a variety of situations in which choice RT did lengthen as the number of alternatives was increased, the magnitude of the effect was shown to be a function of the compatibility of the particular stimulus and response dimensions used (Alluisi, 1965; Alluisi & Muller, 1958; Alluisi, Muller, & Fitts, 1957; Alluisi, Strain, & Thurmond, 1964; Brainard, Irby, Fitts, & Alluisi, 1962; Broadbent & Gregory, 1962, 1965; Fitts & Switzer, 1962; Griew, 1958a, 1964; Hirsch & Ogasawara, 1965; Hellyer, 1963; Morin & Grant, 1965; Muller, 1955; Rabbitt, 1967a). The lesser the S-R compatibility, the greater the effect of uncertainty. That is, the increment in choice RT due to an additional S-R pair increases as compatibility decreases. More recent studies have indicated that it is the nature of the translation of stimulus into response that is the critical factor in determining compatibility. For example, Costa, Horowitz, and Vaughan (1966) used identical sets of stimuli (printed numerals), held constant the mode of response (writing), but varied the translation rule (copy direct, write n-1, etc.). The size of the effect of average stimulus uncertainty depended on the nature of the translation rule, and they attribute this to "the availability of logical S-R translation rules as a
function of preexperimental experience" (p.895).

Locus of the effect of uncertainty. In a review article, Bricker (1955) advanced the opinion that choice RT is best predicted by transmitted information, a conclusion also reached by Crossman (1956). In all of the experiments cited so far, however, the tasks have involved a one-to-one pairing of stimulus and response, and error rates have been low. These two conditions necessarily result in the complete confounding of stimulus, response, and transmitted information. As a result, these studies provide no evidence as to the locus of the effect of uncertainty on choice RT.

Stimulus uncertainty. Stimulus uncertainty may be dissociated from the other two variables by various modifications of the choice RT paradigm. Posner (1962, 1964) has described tasks in which stimulus and response uncertainty are the same (assuming negligible errors) as information conserving tasks. He uses the term information reduction to refer to tasks in which response uncertainty (and therefore transmitted information) is necessarily less than stimulus uncertainty. Further, Posner has pointed out that information may be reduced by filtering or by condensing. The former term is used when the excess stimulus information is irrelevant to selection of the correct response; thus, each stimulus might have two attributes, either of which is sufficient to determine the response. Information is said to be condensed when all stimuli are relevant, but are paired with responses in a many-to-one fashion. For example, a four-two pairing might be used (S1-Ra, S2-Ra, S3-Rb, S4-Rb).
Archer (1954) and Morin, Forrin, and Archer (1961) have shown that subjects can filter out irrelevant stimulus information without increasing choice RT, even when it is physically and perceptually impossible to ignore the irrelevant aspects of the stimulus. Results reported by Gregg (1954) indicate that practice is an important prerequisite for such performance. Morin et al. also failed to find any impairment of performance when the extra stimulus information had to be condensed. After practice, their subjects could perform a four-two condensing task as quickly and as accurately as a two-two conserving task. The authors conclude that

"the rate at which information can be processed can be adequately accounted for in terms of formal information measures without reference to the perceptual demands of the task.... [The results] are consistent with the parsimonious position that RT is proportional to transmitted information" (Morin, Forrin, & Archer, 1961, p.95).

Doubts have been cast on this conclusion by Fitts and Biederman (1965), who attempted a replication of these findings. While they confirmed that the filtering of excess stimulus information did not affect performance, they found information condensing to take longer than conserving, and point to the atypical behavior of some subjects in Morin et al.'s experiment as the source of the discrepancy. Furthermore, using a more compatible response code, Fitts and Biederman found the four-two condensing task to take not only longer than a two-two conserving task, but also longer than a four-four conserving task, the same type of stimuli and responses being used in all cases. Schlesinger and Melkman (1966a) have also demonstrated that the requirement to condense excess stimulus information leads to increased choice RT.
Additional evidence for the existence of an effect of stimulus uncertainty in tasks requiring the condensing of information comes from studies of simple RT. Mowrer, Rayman, and Bliss (1940) found that simple RT increases when the subject is told to expect two alternative stimuli, although only one occurs. It has also been shown that when one response is made to one, two, four, or eight stimuli, simple RT increases with stimulus uncertainty (Bernstein, Schurman, & Forester, 1967; Bevan & Dukes, 1956; Griew, 1958b).

These findings suggest that performance is little affected when the added stimulus information is irrelevant to response selection. Where relevant stimulus information has to be condensed, however, the bulk of the evidence points to a definite effect of stimulus uncertainty, the degree of increase in choice RT depending on the extent of the subject's practice and the compatibility of the response coding.

Response uncertainty. Morin and Forrin (1963) employed a technique for isolating the effects of response uncertainty that involved a one-to-many pairing of stimuli (geometric shapes) to responses (nonsense syllables); this device, which Posner (1964) has described as "information creation", enabled response information to take values greater than those for stimulus and transmitted information. They found that increases in response uncertainty led to longer choice RTs. However, they urged their subjects to choose in an unbiased manner from the alternative responses to a given stimulus. They suggest that the observed increase in choice time may have reflected not increased response
uncertainty per se, but rather have stemmed from the subject's concern over randomizing his responses. A similar study using light flashes as stimuli and key-press responses (Schlesinger, 1964), in which the same result was obtained, is also open to this criticism.

More convincing evidence on the role of response uncertainty in choice behavior was obtained by Bernstein, Schurman, and Forester (1967), who used an information condensing task requiring key-presses to spatially distributed lights. They were able to assess the independent contributions of stimulus and response uncertainty to choice RT by allowing response uncertainty to take different values within fixed levels of stimulus uncertainty. They found that choice RT was a linear function of stimulus uncertainty when response uncertainty was held constant. The reverse was not true, however, since within any level of stimulus uncertainty choice RT was a step function of response uncertainty. That is, increasing the number of responses from one to two led to increased choice RT; further increases in response uncertainty had little or no effect on performance.

**Transmitted information.** An experiment that has directly tested the influence on choice RT of transmitted information, the other two variables being held approximately constant, is one performed by Hick (1952). With a constant number of equiprobable S-R pairs, he encouraged his subjects to reduce their choice RTs at the expense of increased error rates. He found that the loss in accuracy (and therefore transmitted information) was balanced by an increase in response speed, with the result that the rate of transmission of information remained
virtually unchanged. This was an important advance, since transmitted information has the unique property of combining speed and error data into a single measure. However, a more recent and better controlled study (Fitts, 1966), has shown that the rate of transmitting information is not constant for different error rates. Fitts found the rate to be maximum for an error frequency of about 10%, and to decrease for error frequencies above or below this level.

The evidence from these studies, in which the number of equiprobable alternatives was varied, indicates that, with certain exceptions, choice RT is a linear function of average uncertainty. The magnitude of the effect of uncertainty depends, in large measure, on the degree of S-R compatibility, very high compatibility sometimes resulting in the complete independence of choice RT and the number of alternatives. Attempts to determine the locus of the effect of uncertainty have failed to attribute it to any single stage of the choice process. Depending on the experimental conditions and the nature of the task, stimulus information, transmitted information, and response information have each been described as the appropriate predictor of choice RT.

Choice RT and Sequential Dependence

The second technique for manipulating uncertainty involves the varying of sequential dependencies within the stimulus series. In a randomly ordered series of two equiprobable stimuli (A, B), the sequential dependencies are unbiased. Thus, given an A on the previous trial, the probability of occurrence of A and of B on the present trial is equal, with the result that stimulus uncertainty is maximum. A departure from
randomness resulting in, say, more stimulus repetitions than changes from one trial to the next, leads to greater uncertainty associated with stimulus change; at the same time uncertainty regarding stimulus repetition is decreased. Since averaging uncertainties is equivalent to taking the geometric (not arithmetic) mean of the component uncertainties, the average uncertainty is reduced by any such deviation from randomness. Hyman (1953) showed that changes in choice RT do reflect, in general, these variations in stimulus uncertainty. In fact, he found that the linear function relating choice RT to average stimulus uncertainty when sequential dependencies were manipulated, was not significantly different from that obtained when the number of equiprobable alternatives was varied.

The method of varying uncertainty by changing sequential dependencies has attracted little interest. More attention has been paid to an apparently similar, but actually unrelated, trial-to-trial change in choice RT termed the repetition effect (Bertelson, 1961, 1963, 1965; Biederman, 1966; Kornblum, 1967; Shaffer, 1965, 1966, 1967; Welford, 1959; Williams, 1966). First observed by Hyman in that part of his experiment dealing with the number of alternatives, the repetition effect describes the difference in RT on trials where the stimulus is repeated, as compared with those on which it is changed from the previous trial. While it must be incorporated into any complete account of choice behavior, this effect is found when the number of repetitions and changes is equal; it is thus unrelated to uncertainty as defined by information theory, and is not of direct relevant to the present discussion.
Choice RT and Frequency Imbalance

The third method of varying uncertainty involves imbalance of the frequencies of occurrence of the alternative S-R pairs. Consider the simple case of two alternatives. As with sequential dependencies, the decrease in uncertainty caused by a rise in probability of one pair outweighs the increase in uncertainty about the pair of lower frequency. The result is that the greater the frequency imbalance, the less the average uncertainty, and this is reflected in shorter average RTs for the series as a whole, as Hyman (1953) showed. His finding that the three linear functions relating choice RT to average stimulus uncertainty were not significantly different, may be regarded as a demonstration of the psychological equivalence of these three mathematically equivalent methods of varying uncertainty. This provided an important extension of the generality of the information theory approach to the analysis of choice RT.

Two aspects of the effect of frequency imbalance on choice RT should be distinguished. One is a between-series effect, and is a change in average performance. The other is a within-series effect, consisting of changes in choice RT for particular S-R pairs according to their various frequencies of occurrence; this is called the "relative frequency effect" and may be described as a change in component performance. Since it is of direct relevance to the present investigation, experiments dealing with this effect will be discussed in detail in the following, separate section.
The Relative Frequency Effect

The distinction between average and component performance can not be made when all S-R pairs are equally probable, since the uncertainty associated with each component is the same as the average uncertainty for the whole series. Hyman did, however, compare these two aspects of performance when sequential dependencies and frequency imbalance were varied. In both cases he found the same result when the linear function relating choice RT to average stimulus uncertainty was used to predict RTs to the component S-R pairs making up each condition. Comparison of observed with predicted RTs showed the latter to be overestimates for the high uncertainty components, but underestimates for low uncertainty components. In other words, the slope of the function relating component stimulus uncertainty and choice RT was less than that for the function relating average stimulus uncertainty and choice RT, even though the same data were being described. This discrepancy presented serious difficulties for the informational analysis of choice behavior, and Hyman concluded that "if,... we are interested in the behavior of the components making up the conditions, we must find different laws and equations" (1953, p.194).

A similar finding was reported by Leont'ev and Krinchik (1963) for a simple two-alternative task involving key-press responses to light flash stimuli. They stated that "the empirical dependence of reaction time upon amount of individual information proved to be significantly different, both in nature and in the magnitude of the effect produced, from the relation of reaction time to the amount of average
information" (p.28).

Three studies by Kaufman and his co-workers provide further evidence for a discrepancy between average and component functions relating choice RT and uncertainty (Kaufman & Lamb, 1966; Kaufman & Levy, 1966; Lamb & Kaufman, 1965). In each case they determined the function relating choice RT to average uncertainty by varying the number of alternatives, and the function relating choice RT to component uncertainty by varying frequency imbalance. In one experiment (Kaufman & Lamb, 1966) they found the slope of the average uncertainty function to be greater than that of the component uncertainty function (in agreement with Hyman's results), but both other studies showed the reverse relation between the two functions. However, it can be argued that the critical comparison should be between the average and component functions derived from the same data. Calculations of the average uncertainty function for the frequency imbalance condition from the results reported in these three studies shows it to have a steeper slope in each case than the corresponding component function. In this respect, the findings are congruent with those of Hyman. Where they differ, however, is that in two cases (Kaufman & Levy, 1966; Lamb & Kaufman, 1965), the average functions for the number of alternatives and the frequency imbalance conditions did not coincide. In these two cases, the slope of the function for the number of alternatives condition was much flatter than in the studies of Hyman and Kaufman and Lamb. The flat slope probably reflects the use of well-practised subjects and a highly compatible task involving key-press responses to corresponding light stimuli. Kaufman and Lamb used nonsense syllable responses to lines of
different length, and obtained results very similar to those of Hyman.

Lamb and Kaufman suggest that "an explanation of the discrepancy between the two functions is that perceived relative frequency of occurrence, subjective probability, differs from the measured relative frequency of occurrence, objective probability" (1965, p.255). Thus a subject in the frequency imbalance condition may perceive an objective imbalance of 90/10 as though it were 70/30. If it is assumed that these two measures of probability coincide in the number of alternatives condition, then a discrepancy between the average (number of alternatives) and component (frequency imbalance) functions, of the form reported by Hyman, would be expected. Lamb and Kaufman rejected the hypothesis on the basis of their own results, since such a hypothesis led to the postulation of probabilities greater than unity. Again, however, it can be argued that their average (number of alternatives) function was not comparable with the component (frequency imbalance) function, and that the crucial comparison was between average and component functions derived from the same data. If only this discrepancy is considered, it remains plausible that it is related to some difference between subjective and objective probability. It is, indeed, supported by evidence of the subjective underestimation of proportion reported by Erlick (1964).

Another feature of these results is the non-linearity of the component function. The typical deviations observed--shorter RT to the low frequency component, and flatter slope for the higher frequency components--recall Leont'ev and Krinchik's description of their
component function as "logarithmic." Such a non-linearity was, perhaps, anticipated by Hick when he suggested that "the effective probabilities are very little affected by increasing inequality in the stimulus frequencies until something like a threshold is reached" (1952, p.25).

A reasonably successful attempt to eliminate this non-linearity, and the difference between the slopes of the average and component functions, was made by Stone and Calloway (1964). They obtained nonsense syllable responses to visually presented numbers in an experiment in which the independent variables were the number of alternatives, their frequency of occurrence, and the probability that a response would be required (as indicated by a simultaneous, auxiliary stimulus). They found component performance best described by an uncertainty measure which used effective, rather than objective, probability. This measure, which is mathematically complex, is basically a function relating objective probability, number of alternatives, and the probability of occurrence of the most likely event. The use of effective probability improved the linearity of the component function considerably, and the discrepancy between the average and component functions was greatly reduced. The only remaining substantial departures from linearity were for conditions in which the response sometimes had to be withheld. Apparently, a frequent requirement to inhibit response to a likely stimulus eliminated the reduction in RT usually associated with increased frequency of occurrence.

In summary, Hyman's findings that the linear functions relating
average choice RT to average stimulus uncertainty were not signifi-
cantly different for the three methods of varying uncertainty, de-
monstrated the generality of the informational analysis of choice
RT. However, further analysis of the data, and subsequent experiments
by other workers, revealed persistent discrepancies between the expect-
ed and obtained functions. Two separate types of discrepancy were ob-
served. The first was a difference between the average function for
the number of alternatives and that for the frequency imbalance condi-
tion (Kaufman & Levy, 1966; Lamb & Kaufman, 1965). This contradicted
Hyman's results, and probably reflected the combined influence of well
practised subjects and a highly compatible task, which led to a parti-
cularly "flat" function for the number of alternatives condition: A
more serious problem for the informational analysis of choice RT is
raised by a second difference; that between average and component
functions for the same experimental conditions (i.e., derived from
the same data). Such a discrepancy does not just limit the range of
applicability of informational analysis (as the influence of compati-
bility on the first type of discrepancy would appear to require); ra-
ther, it exposes a lack of internal consistency of informational mea-
sures that casts doubt on the validity and utility of the analysis of
choice RT in informational terms. This serves to emphasize the need
for a greater understanding of the effect of variables other than un-
certainty (as defined in information theory) on component performance.
Stone and Calloway, with their use of effective probability seem to
have made a promising start in this direction.
Locus of the relative frequency effect. As with the other techniques for varying uncertainty, the relative frequency effect has been used by some investigators in an attempt to establish the relative importance of stimulus and response processes in determining choice RT. If two stimuli (A, B) are paired with one response (R1), and a third stimulus (C) is paired with another response (R2), the relative frequencies of occurrence of A and B may be varied without affecting the frequencies of occurrence of R1 and R2. This device was used by LaBerge and Tweedy (1964), who instructed their subjects to press one key for a green stimulus light, and another key for both red and blue stimulus lights. In the training session, the three stimuli were presented with equal frequency until stable levels of responding had been attained. The ratio of blue to red stimuli (which shared the same response) was then changed to 5:1, and later to 1:5. The frequency of occurrence of the green stimulus, and that of each response, remained constant. Choice RTs for red and blue stimuli, very similar during practice, became significantly different when the stimulus frequencies were changed, longer RTs being associated with the less frequent stimulus. Changes in RT also paralleled the reversal of stimulus frequencies in the last part of the experiment. While this was taken as strong support for attributing the changes in RT to biases in stimulus frequencies, at least some of the variance, considering all RTs, was tentatively ascribed to the imbalance (3:2) in response frequency present throughout the experiment.

A similar technique was used by Schlesinger and Melkman (1966b), who paired four stimuli with two responses (S1-Ra, S2-Ra, S3-Rb, S4-Rb)
in a task requiring key-presses to spatially arrayed light stimuli. Since only cumulated RTs were recorded for each session, they were able to observe average, but not component, performance. Their results are of relevance here, however, in that they demonstrated improvement of performance with increasing stimulus frequency imbalance, when response frequencies were held equal.

Bertelson and Tisseyre (1966) exploited the same basic approach, associating two stimuli with probabilities of occurrence of 0.55 and 0.15 with one response ($p = 0.70$), and two other stimuli (0.15, 0.15) with a second response (0.30). This arrangement allowed them to examine separately the contributions to the relative frequency effect of substantial biases at the stimulus and response stages. As expected, the shortest choice RTs and fewest errors were recorded for the S-R pair whose stimulus and response frequencies were high. The finding that equally long RTs were given to low frequency stimuli whether the response frequency was high or low, led Bertelson and Tisseyre to conclude that "the relative frequency of response does not affect reaction time, and the only critical variable is the relative frequency of the stimulus" (p.1070).

The general lack of agreement regarding the locus of the effect of uncertainty on choice RT, evident in previous sections, also characterises experiments involving the relative frequency effect. Although using the same types of stimulus (visually presented letters) and response (key-presses), Dillon (1966) found results completely different from those of Bertelson and Tisseyre. Dillon saw his results as supporting
the view that "it is the requirement to give a rarely called-for response alternative which underlies the latency differences constituting the relative frequency effect" (p.329). He used a technique that involved pairing seven stimuli with one response, and an eighth stimulus with another response. The subjects were also given an auditory signal (a tone) on some trials, omission of the signal indicating that the response should be withheld. This latter innovation was designed to allow independent variation of stimulus and response frequencies. In three experiments, in which he successively covaried stimulus and response frequencies, varied stimulus frequency with constant response frequency, and vice versa, a significant relative frequency effect was only observed when response frequency was varied.

It should be noted that Dillon presented the "response demand" signal 0.5-0.7 sec. after the occurrence of the stimulus (unlike the simultaneous presentation used by Stone & Calloway). Judging from the results of other similar experiments, had a response always been required, the RTs would probably have averaged about 0.4-0.5 sec. It thus appears likely that Dillon's subjects had decided on the correct response before the arrival of the response demand signal, the latter merely triggering the response. Any variations in decision time would not then be reflected in the measured RTs. This argument gains credence when it is noted that in the experiment in which he failed to demonstrate a relative frequency effect, RTs measured from the onset of the response demand signal averaged about 140 msec. This is the value cited by Woodworth and Schlosberg as typical for simple RT to an auditory stimulus (1954, p.16).
When response frequency was varied, the average RT was nearer 200 msec., suggesting that long decision times were augmenting the "simple" RTs on some of the trials. That this was more likely on trials where the response frequency was low is apparent from the longer average RT for this component, thus indicating a relative frequency effect attributable to response frequency bias. However, his failure to demonstrate a relative frequency effect when only stimulus frequency was varied may well have been due to his measuring of RT from an arbitrary point 0.5-0.7 sec. after the start of the decision process.

Two factors which Stone and Calloway deemed of sufficient importance to include in their measure of effective probability are the number of alternatives and the probability of occurrence of the most likely stimulus. Dillon's study differed from previous work on both these points, the respective values of these two variables used by the different investigators being as follows: Schlesinger and Melkman, 4, 0.55; LaBerge and Tweedy, 3, 0.50; Bertelson and Tisseyre, 4, 0.55; Dillon, 8, 0.18. These and other differences make it difficult to draw general conclusions from the disparate results of these experiments.

It is clear that while informational measures are useful in describing average performance, they are demonstrably inadequate when component performance is considered. The most direct influence of uncertainty on component performance is evident in the relative frequency effect. Attempts to identify the locus of this effect, however, have yielded contradictory evidence. Some attribute it entirely to
stimulus frequency bias (e.g., Bertelson & Tisseyre, 1966), some to response frequency bias (e.g., Dillon, 1966), and yet others to both (e.g., LaBerge & Tweedy, 1964). A major obstacle to interpretation of these findings stems from the variety of experimental techniques and parameter values used by the different investigators. A greater understanding of the nature of the relative frequency effect, and thus of the underlying decision processes, would accrue from experiments that tested multiple hypotheses in a uniform experimental setting. The experiments carried out in the present investigation were designed with this in mind. Before introducing them, the general approach within which they are formulated will be discussed with reference to current theoretical views of the choice process.

Models of Choice RT

In one of the simplest models of choice behavior the subject is regarded as making successive discrete matches of the incoming signal with stored memories of all the possible alternatives, the appropriate response occurring when a successful match is made. Although this model predicts longer average choice times as the number \( n \) of alternatives increases, Hick (1952) rejected it when his results showed that choice RT increases linearly with \( \log_2 n \), rather than with \( n \). He suggested instead, that the subject makes successive dichotomous (binary) choices, each of the same duration. The first decision identifies the stimulus as lying within one half of the range of probabilities; the second decision as lying within one half of this half, and so on. This would allow reasonable prediction of the logarithmic relation,
but fails to account for the relative frequency effect, in which the number of stimuli is constant, but their relative frequencies of occurrence are varied.

Welford (1960) has put forward a modification of Hick's model that does allow incorporation of the relative frequency effect. Welford suggested that if the subject finds that the stimulus is not in the half he is examining, he then checks that it is in the other half before proceeding. The further assumption that more probable stimuli, as compared to the less probable ones, are more likely to be in the first half checked, allows prediction of the relative frequency effect, since less probable stimuli would require generally more "double-checking" than would probable ones. But even this modification of the discrete search model leaves it unsuitable for dealing adequately with such factors as values, payoff, and emphasizing speed versus accuracy.

Another set of models is based on the principle of sequential stimulus sampling. These derive partly from Wald's (1949) theoretical treatment of sequential decision making, and partly from the general theory of signal detection (Swets, Tanner, and Birdsall, 1961). The subject is regarded as taking successive samples of the stimulus; the likelihood of their being from a particular stimulus is recalculated after each sample. As a consequence of sampling variations and internal noise, the sequence of values computed in this manner should have the properties of a random walk, but should drift in a direction determined by the characteristics of the particular stimulus being
observed, the process being terminated when the likelihood values reaches a cut-off point. Values, payoffs, and speed versus accuracy are thought to exert their influence on the subject's criterion which determines this cut-off point. Increased probability of occurrence results in a greater initial likelihood value for the particular stimulus, with consequently fewer samples, and thus less time, being required before the cut-off point is reached.

Models of this type have been proposed by Audley (1960), Christie and Luce (1956), LaBerge (1962), Luce (1960), McGill (1963), Rapoport (1959), Restle (1960), and Stone (1960). Many of the early models (e.g., Stone) considered the relation of RT to the number of alternatives only for the case of a fixed number of samples, the number being decided in advance to give a desired level of error. The inflexibility of this arrangement was avoided in a development suggested by Laming (1962), in which each sample is followed by a decision to act or to take a further sample. The process of sampling continues until the accumulated information is sufficient, according to the criterion, to select a particular response. Especially with respect to time-error relations, this type of model is able to generate far more precise predictions than the search models favored by the earlier information theorists. Tests of these predictions have generally supported the underlying view of man as a statistical decision maker (Broadbent & Gregory, 1965; Fitts, 1964, 1966; Fitts, Peterson, & Wolpe, 1963). While the stimulus sampling model currently appears to be preferred to the search model (Broadbent, 1967a), Edwards (1965) has pointed out that a mathematical rationale for the former type has yet to be developed for the
case where the number of S-R pairs is greater than two.

Most model makers take the uncomplicated view that one type of model is sufficient, in principle, to account for choice behavior under all conditions. It is possible that different stages of the choice process are best described by different types of models. Fitts, et al., suggest that RT may be "the consequence of a two-stage process, which involves time for access to stored information followed by a statistical decision time" (1963, p.424). This view of choice behavior as a multi-stage process requiring, perhaps, the combination of different types of models for its explanation, points to the need for what might be called a "functional" approach to the problem, as described below.

Unlike the formal, mathematical descriptions of information theory, and the structural models of Welford and others, the functional view analyses the choice process into a number of stages: stimulus detection, stimulus identification, recall of stimulus-response translation rule, application of rule, response selection, and response production. These stages are justified initially on logical and intuitive rather than empirical grounds. However, it seems reasonable to assume that one stage must be completed before the succeeding one can occur. The utility of specifying independent stages for, say, application of rule and response selection, rests on the demonstration of a change in RT which can reasonably be attributed to one of the stages but not the other. Failure to produce such evidence would obviate their distinction, and it would be concluded that they represented merely different
descriptions of the same process. While this functional view is reminiscent of Donders' and Wundt's fragmentation of the choice process, the experimental approach it advocates is very different from the subtractive procedure used by these early investigators. The functional approach attempts to attribute changes in choice RT to particular stages of the process by examining the interaction of the change with variables which are presumed to influence a particular stage. Thus, if the size of the relative frequency effect is shown to be a function of stimulus discriminability, all other things being equal, it follows that at least part of the effect is occurring at the stimulus identification stage.

A corollary to this approach is that particular attention should be paid to the experimental conditions employed in these investigations. For example, the stimulus detection stage is of obvious importance when the stimulus is near threshold. It is unlikely, however, that the time taken at this stage contributes much to the variance in choice RT when the stimulus is well above threshold; and uncertainty about the time of its occurrence is minimal.

Finally, it must be stressed that the functional approach is considered to supplement rather than supplant the formal and structural descriptions of choice behavior. If successful, it will serve to identify experimental situations in which more precise tests may be made of the various models mentioned earlier.

The Present Investigation

The broad aim of the present investigation was to contribute to an
understanding of the processes involved in choice behavior. The purpose of the experiments reported in this thesis was to determine the points in the choice process at which uncertainty exerts the influence on choice RT manifested in the relative frequency effect.

When the number of equiprobable stimulus alternatives is varied, both discriminability of the alternatives and the probability of occurrence of any one stimulus also change. The considerable influence of the former variable has been demonstrated (Birren & Botwinick, 1955; Botwinick, Brindley, & Robbin, 1958; Crossman, 1953, 1955; Henmon, 1906). A stimulus that is from a set of eight alternatives can be considered to be less discriminable than when it is one of four alternatives; changes in information are thus confounded with changes in discriminability when the number of alternatives is varied. In order to avoid this problem, it was decided to choose one of the two techniques for varying uncertainty that do not involve changing the number, and therefore the discriminability of the stimulus alternatives. These two techniques are based on manipulation of sequential dependencies and of frequency imbalance. The one involving sequential dependencies makes analysis of the effect of uncertainty extremely difficult. Therefore the second technique (frequency imbalance) was used in the present investigation; it is considered to represent the most direct method of isolating the effects of the one variable (probability) which underlies all variations of uncertainty in choice RT experiments.

Having decided on the relative frequency effect as the phenomenon to be studied, the next step was to select the variables whose interaction
with the relative frequency effect was to be examined. It will be remembered that Hick suggested that a threshold of frequency imbalance might exist, below which no effect on choice RT would be observed. Since little attention has been paid to this important hypothesis, and since such a threshold, if it existed, might well be the source of some of the discrepant findings in this field, the degree of stimulus frequency imbalance was selected as one of the independent variables.

Most of the models of choice behavior are focused on the stimulus identification stage. Little consideration has been given, however, to the type of stimulus used in experiments in this area. Such varied stimulus types as spatially arrayed lamps, colored lights, letters, and lines of different length, have been used. Since they may well vary in their discriminability, this factor may also underlie some of the discrepant findings. It was therefore decided to make stimulus type another independent variable, particular interest being in the interaction of the relative frequency effect with the factor of stimulus discriminability. Since the amount of pre-experimental training given to subjects in the reported experiments varied widely, the degree of practice was included as a third independent variable in the present investigation.

In Experiments 1 and 2, the stage of the choice process of major concern was that involving stimulus identification. In order to allow clear observation of any relative frequency effect occurring at the early stages, the response frequencies in these two experiments were
kept equal. This eliminated any effect that may have occurred at or after the stage involving the application of translation rule. The effect occurring at these later stages was the major interest in Experiment 3. Although it is relatively easy to devise a simple modification of the basic RT paradigm, to allow stimulus frequency to be varied while response frequency remains balanced, it is difficult to obtain the reverse situation without introducing fundamental changes into the design and nature of the task. Two techniques that have been employed (one-to-many S-R pairing, and response demand signals) have each been criticised by those who have used them (Morin & Forrin, 1963; Stone & Calloway, 1964). Experiment 3 was therefore designed to allow a direct comparison of performance in two conditions, each having the same degree of stimulus frequency bias, but only one involving response frequency bias. A larger relative frequency effect when both stimulus and response frequencies were biased than when only stimulus frequency imbalance existed, would be evidence that at least part of the effect is attributable to changes in response frequency. To permit a distinction to be made between the response selection and production stages, choice RT in Experiment 3 was measured in two parts--decision time (DT) and movement time (MT).
II

THE EXPERIMENTS

Experiment I

The purpose of this experiment was to determine the effect on choice RT of three degrees or conditions of stimulus frequency imbalance, while response frequencies were kept equal. Four different stimulus types (circles of varying size, colors, letters, and spatially arrayed lamps) were used, each set containing three alternatives. The stimulus types, and the alternatives within them, were selected to provide a wide range of discrimination difficulty. In order to observe any changes due to practice, the basic experiment, using the same Ss, was repeated twice. Each S thus performed in all parts of a 3 (stimulus alternatives) by 3 (conditions of stimulus frequency imbalance) by 4 (stimulus types) by 3 (weekly replications) factorial design.

Method

Subjects. The Ss were four male undergraduate students aged between 17 and 21 years.

Apparatus. Four stimulus types were used, each set containing three stimulus alternatives.

(a) CIRCLES: Circular patches of white light with diameters of 11/32, 17/32, and 23/32 in.
(b) COLORS: 1½ in. square patches of colored light; red, green, and yellow.
(c) LETTERS: 5/8 in. high x 7/16 in. wide upper case letters; A, U, and T.
(d) LAMPS: 28 volt bulbs with 3/8 in. diameter translucent plastic covers; centres spaced 1½ in. apart.

The circles were displayed on a multiple stimulus projector (Grason-Stadler, Model No. 10657), and the letters and colors were displayed on a similar unit (Model No. 1070R-44-L). The brightness of the projected stimuli was approximately 27 ft-lamberts (measured with a spotlight meter). The lamps were mounted vertically on a metal unit. The projectors and the lamp unit were situated at eye-level on a large wooden screen placed about 2 ft. from S. A warning signal, in the form of a brief burst of clicks, was delivered to S through padded earphones; the latter also served to deaden extraneous noises. The response unit consisted of two button-operated microswitch keys, mounted on a 1½ in. high wooden platform on the table in front of S. The buttons, which had a diameter of ½ in., were centred 2 in. either side of the "home" key on which S rested his index finger between responses.

Stimulus presentation was controlled by a 12-channel magnetic tape programmer. This device enabled different stimuli to be presented for precise durations at precise intervals. Signals were prerecorded in the appropriate channels at the required positions on the tape, and on playback these signals activated the corresponding stimulus circuits.
A chronoscope (Hunter Klockounter, Model 120A, Series D) was triggered by stimulus onset and stopped by depression of either response button, allowing RT to be measured to the nearest millisecond. Signal lamps in each stimulus and response circuit permitted S to observe errors. S was seated in a dimly illuminated room facing the stimulus display board, while E monitored the programming and timing apparatus in an adjacent room.

**Experimental design.** In the first week S had one practice and four experimental sessions, each on successive days, a single stimulus type being used throughout a session. The order in which stimulus types were assigned to each S's four experimental sessions was determined by a semi-balanced Latin square. On any one day each S had a different stimulus type, and for each S a different stimulus type was used in each of the four experimental sessions. The stimulus type used in the practice session was the same as that used in S's last experimental session. With the exception of the practice session, two replications using the same Ss and experimental design were carried out over the following two weeks. This gave each S three weekly sessions with each of the four stimulus types, or a total of twelve experimental sessions.

A session contained 300 trials, 100 in each of the three conditions (low, medium, and high) of stimulus frequency imbalance. Table 1 shows the probability of occurrence of the three S-R pairs in the three conditions.

Stimulus A, which occurred on half the trials in each condition, was paired with response A. In the case of the circles and lamps, A
Table 1
Probability of Occurrence of each S-R Pair in
each Condition of Stimulus Frequency Imbalance

<table>
<thead>
<tr>
<th>Condition of Stimulus Frequency Imbalance</th>
<th>Stimulus A</th>
<th>BI</th>
<th>BD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>.50</td>
<td>.25</td>
<td>.25</td>
</tr>
<tr>
<td>Medium</td>
<td>.50</td>
<td>.35</td>
<td>.15</td>
</tr>
<tr>
<td>High</td>
<td>.50</td>
<td>.45</td>
<td>.05</td>
</tr>
</tbody>
</table>
was always the middle of the three stimuli; for the letters and colors it was T and yellow, respectively. For two Ss response A was pressing the left button, for the other two Ss it was pressing the right button. Stimulus BI, whose probability of occurrence increased from the low to the high conditions, and stimulus BD, whose probability of occurrence correspondingly decreased, were both paired with response B. For each stimulus type, the particular stimulus alternative designated as BI and BD were fully balanced over Ss and partially balanced over weeks.

The order of trials within each condition was randomized, with the following restrictions: (a) The sequential response probabilities, p(A following A) and p(B following A), were set equal to 0.5 in all conditions. (b) The sequential stimulus probabilities were balanced according to the different frequencies of occurrence of the stimuli in the three conditions. (c) The longest run of repeated stimuli or responses was four. These restrictions were applied, as nearly as possible, to each block of 20 trials. The 100 trials in each condition were split into three parts of 20, 40, and 40 trials. Part 1 was considered as practice, allowing S to accommodate to the particular stimulus frequency bias in the series, and the data from these trials were discarded. The order in which Parts 2 and 3 were given was varied. This feature, together with the alternating use of two different programs, and the varied order of conditions within a session, was considered sufficient to make it virtually impossible for S to learn what the sequence of stimuli or responses would be on any given set of trials.
Procedure. At the start of each session S was shown examples of the relevant stimulus type. A card depicting these stimuli, and indicating the relative frequency of occurrence of each S-R pair (in the form of a bar graph), could be seen by S throughout the session. To encourage S to be both fast and accurate, the following payoff scheme was adopted. One cent was awarded for each RT that was faster than $t$ sec. ($t$ being calculated from the results of the practice session so as to reward S on about 75% of the trials); a penalty of five cents was levied for each mistake. S was informed of his earnings before the following session. Rest breaks of 1 minute were given between each part, and of 5 minutes between each condition. The duration of each stimulus was 100 millisec. The warning signal was presented 1 sec. prior to the occurrence of the stimulus. With a constant inter-stimulus interval of 7 sec., a session lasted just less than 1 hour.

Data analysis. Data for trials on which S made an error were not included in the analysis of RTs; error data are presented separately. Inspection of the RT data indicated that many of the distributions were significantly positively skewed. Normality was most closely approached through use of a reciprocal transformation. The harmonic mean (the reciprocal of the arithmetic mean of the reciprocals) was therefore chosen as the best estimate of RT for each cell of the 3 by 3 by 4 by 3 matrix for each of the 4 Ss. The number of RTs contributing to each mean varied between 4 and 36 (except where omission of RTs for erroneous responses reduced these numbers), according to the
frequency of occurrence of the particular S-R pair. Unless otherwise specified, all analyses of choice RT reported in the next section used harmonic mean RT as the basic datum.

Results

The complete matrix of 432 harmonic means is shown in Table A, Appendix 1. The results are summarized in Figure 1, where harmonic mean RT, averaged over Ss, stimulus types, and weeks, is shown for each stimulus alternative in each condition of stimulus frequency imbalance. The probability of occurrence of the stimulus is indicated next to each point on the graph. It will be observed that the average RT for stimulus A was shorter than those for stimuli BI and BD in all conditions. Since the frequency of occurrence of stimulus A was always higher than that of either of the other two stimuli, this aspect of the results may be taken as evidence of a relative frequency effect. Further analysis revealed that while the shortest average RTs were associated with stimulus A for the colors, letters, and lamps, this was not the case for the circles. For the latter set of stimuli, unlike the others, stimulus A was much less easily discriminated than were stimuli BI and BD. Comparison of RTs for stimulus A with those for stimulus BD or BI is complicated by this factor.

More direct evidence of a relative frequency effect, unconfounded with differences in discriminability, is provided by a comparison of the results for stimuli BD and BI. It can be seen from Figure 1 that the average RT for stimulus BD increased as the probability of occurrence of the stimulus decreased. At the same time, the average RT for
Figure 1. Average harmonic mean RT in milliseconds for stimuli A, B1, and B2, in each condition of stimulus frequency imbalance in Experiment 1. The probability of occurrence of the stimulus is indicated on the graph.
stimulus BI showed a small overall decrease with increasing frequency of occurrence of the stimulus. These two changes are regarded as demonstrating the predicted effect on RT of an increasing difference in relative stimulus frequency. It is evident that the greater contribution to this relative frequency effect comes from the increment in RT for stimulus BD. Further inspection of the data showed the effect to be comprised almost wholly of this component in the first week; by the third week, however, the contribution of the two components (increment in RT for BD, and decrement in RT for BI) was approximately equal.

An analysis of variance (Winer, 1962, Chapter 7) was carried out on the harmonic mean RTs for stimuli BD and BI (omitting the data for stimulus A), with stimulus alternatives, stimulus types, conditions, and weeks, as the four factors. Each S contributed equally at all levels of each factor. The results of the analysis are shown in Table A, Appendix 2. The significant main effects for stimulus types indicates that S showed a characteristic speed of responding that differed for the various stimulus types. In fact, this effect is largely due to the longer RTs generally found for the circles than for the other stimulus types.

The longer RTs for stimulus BD than for stimulus BI observed in the medium and high frequency imbalance conditions gave rise to a significant main effect for stimulus alternatives. A more appropriate indicator of the relative frequency effect is the stimulus alternatives x conditions interaction. This was found to be highly significant.
The interaction between the relative frequency effect and stimulus type was of particular interest in this experiment. The significant stimulus alternatives x stimulus types interaction indicates that the overall difference in RT for the stimulus alternatives BD and BI was dependent on stimulus type. Again, a more appropriate test of this dependence is the triple interaction, stimulus alternatives x conditions x stimulus types. That this interaction was found to be significant is interpreted as evidence that the size of the relative frequency effect differed for the various stimulus types.

Since comparison of the RTs for stimuli BD and BI was planned, and since such comparisons are orthogonal, a t-test for correlated samples was considered an appropriate test of the significance of the difference RT\textsubscript{BD} - RT\textsubscript{BI} (denoted by ΔRT). As the direction of difference was predicted (RT\textsubscript{BD} > RT\textsubscript{BI}), the one-tailed version of the test was used. The average RTs for stimuli BD and BI, the difference (ΔRT), and the corresponding t-values indicating significance of this difference from zero, are shown in Table 2 for each stimulus type for the three conditions of frequency imbalance. The largest value of ΔRT found in the condition of low frequency imbalance (in which the probabilities of occurrence of stimuli BD and BI were equal) was 6 millisec., testifying to the adequacy of the balancing procedures used. While ΔRT for the circles is significantly different from zero in the medium imbalance condition, and even more so in the high imbalance condition, it is not significantly different from zero in any of the conditions for the letters. Intermediate results were obtained for the other
Table 2

Average Harmonic Mean RT in Milliseconds for Stimulus Alternatives BD and BI, the Difference (ΔRT), and the Corresponding t-values (Indicating Significance of the Difference from Zero), for each Stimulus Type in each Condition of Frequency Imbalance in Experiment 1.

<table>
<thead>
<tr>
<th>Stimulus Type</th>
<th>Condition of Frequency Imbalance</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT</td>
<td>ΔRT</td>
<td>t+</td>
<td>RT</td>
</tr>
<tr>
<td>Circles</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>510</td>
<td>5</td>
<td>0.50</td>
<td>551</td>
</tr>
<tr>
<td>BI</td>
<td>505</td>
<td></td>
<td></td>
<td>495</td>
</tr>
<tr>
<td>Lamps</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>412</td>
<td>2</td>
<td>0.39</td>
<td>411</td>
</tr>
<tr>
<td>BI</td>
<td>410</td>
<td></td>
<td></td>
<td>416</td>
</tr>
<tr>
<td>Colors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>449</td>
<td>6</td>
<td>0.68</td>
<td>451</td>
</tr>
<tr>
<td>BI</td>
<td>443</td>
<td></td>
<td></td>
<td>444</td>
</tr>
<tr>
<td>Letters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>410</td>
<td>-4</td>
<td>-0.70</td>
<td>417</td>
</tr>
<tr>
<td>BI</td>
<td>414</td>
<td></td>
<td></td>
<td>424</td>
</tr>
</tbody>
</table>

+ df = 11
* p < .05
** p < .01
*** p < .001
two stimulus types in the high imbalance condition, but for neither type was a relative frequency effect discernible in the medium imbalance condition.

The insignificant main effect for weeks suggests that 8 reached a stable level of responding within the first week. However, further analysis of the data revealed noticeably different trends of the relative frequency effect with practice for the different stimulus types. The results for the conditions of medium and high frequency imbalance are shown in Tables 3 and 4, respectively, for each of the three weeks. In the medium condition, $\Delta$ RT for the colors, lamps, and letters was negligible, but for the circles it was substantial. In the condition of high stimulus frequency imbalance, a relative frequency effect was noticeable for the colors, lamps, and letters in the first week, but $\Delta$ RT decreased with practice. By the last week, in fact, the relative frequency effect for the letters had disappeared. On the other hand, there was no overall decrease in the much larger relative frequency effect observed for the circles.

Excluding practice, a total of 11,520 responses were recorded. Of these, 82 were incorrect, representing an error frequency of just over 0.7%. The distribution of errors in each condition is shown in Table 5; the values in parentheses are the expected number of errors assuming a random distribution. A chi-square test revealed no significant difference between the observed and expected distributions of errors ($\chi^2 = 5.66, p > .10$). The number of errors for each stimulus type was as follows: circles, 35; lamps, 24; colors, 13; and letters,
Table 3

Average Harmonic Mean RT in Milliseconds for Stimulus Alternatives BD and BI, the Difference (ΔRT), and the Corresponding t-values (Indicating Significance of the Difference from Zero), for each Stimulus Type and Week in the Condition of Medium Frequency Imbalance in Experiment 1.

<table>
<thead>
<tr>
<th>Stimulus Type</th>
<th>Week 1</th>
<th></th>
<th>Week 2</th>
<th></th>
<th>Week 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT</td>
<td>ΔRT</td>
<td>t⁺</td>
<td>RT</td>
<td>ΔRT</td>
<td>t⁺</td>
</tr>
<tr>
<td>Circles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>573</td>
<td>46</td>
<td>1.93</td>
<td>567</td>
<td>90</td>
<td>2.37*</td>
</tr>
<tr>
<td>BI</td>
<td>527</td>
<td></td>
<td></td>
<td>477</td>
<td></td>
<td>481</td>
</tr>
<tr>
<td>Lamps</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>435</td>
<td>-13</td>
<td>-0.65</td>
<td>418</td>
<td>9</td>
<td>0.55</td>
</tr>
<tr>
<td>BI</td>
<td>448</td>
<td></td>
<td></td>
<td>409</td>
<td></td>
<td>392</td>
</tr>
<tr>
<td>Colors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>473</td>
<td>3</td>
<td>0.25</td>
<td>445</td>
<td>5</td>
<td>0.91</td>
</tr>
<tr>
<td>BI</td>
<td>470</td>
<td></td>
<td></td>
<td>440</td>
<td></td>
<td>423</td>
</tr>
<tr>
<td>Letters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>416</td>
<td>-5</td>
<td>-0.39</td>
<td>416</td>
<td>-20</td>
<td>-1.39</td>
</tr>
<tr>
<td>BI</td>
<td>421</td>
<td></td>
<td></td>
<td>436</td>
<td></td>
<td>414</td>
</tr>
</tbody>
</table>

* df = 3
* * p < .05
Table 4

Average Harmonic Mean RT in Milliseconds for Stimulus Alternatives BD and BI, the Difference (ΔRT), and the Corresponding t-values (indicating significance of the difference from Zero), for each Stimulus Type and Week in the Condition of High Frequency Imbalance in Experiment 1.

<table>
<thead>
<tr>
<th>Stimulus Type</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT</td>
<td>ΔRT</td>
<td>t⁺</td>
</tr>
<tr>
<td>Circles</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>597</td>
<td>66</td>
<td>3.26*</td>
</tr>
<tr>
<td>BI</td>
<td>531</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lamps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>510</td>
<td>69</td>
<td>3.41*</td>
</tr>
<tr>
<td>BI</td>
<td>441</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Colors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>494</td>
<td>51</td>
<td>2.18</td>
</tr>
<tr>
<td>BI</td>
<td>443</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Letters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>446</td>
<td>32</td>
<td>2.80*</td>
</tr>
<tr>
<td>BI</td>
<td>414</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

⁺df=3
*=p < .05
Table 5

Number of Errors for each Stimulus Alternative in each Condition of Stimulus Frequency Imbalance in Experiment 1 (figures in parentheses indicate expected number of errors assuming random distribution).

<table>
<thead>
<tr>
<th>Condition of Frequency Imbalance</th>
<th>Stimulus Alternative</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>BI</td>
<td>BD</td>
<td>Total</td>
</tr>
<tr>
<td>Low</td>
<td>14 (14)</td>
<td>7 (7)</td>
<td>6 (7)</td>
<td>27</td>
</tr>
<tr>
<td>Medium</td>
<td>14 (14)</td>
<td>7 (10)</td>
<td>8 (4)</td>
<td>29</td>
</tr>
<tr>
<td>High</td>
<td>13 (14)</td>
<td>12 (12)</td>
<td>1 (1)</td>
<td>26</td>
</tr>
<tr>
<td>Total</td>
<td>41</td>
<td>26</td>
<td>15</td>
<td>82</td>
</tr>
</tbody>
</table>
10. The small number of errors precluded detailed analysis of the RTs for incorrect responses. However, it was noted that on 45 of the 82 error trials, the RT was shorter than the harmonic mean RT for the corresponding correct responses.

Discussion

The first of the two main hypotheses tested in Experiment 1 concerned the form of the relative frequency effect. It was suggested that there might be a threshold level of frequency imbalance below which choice RT is independent of the frequency of occurrence of the stimulus. The present results for the colors, letters, and lamps support this hypothesis, because with none of these stimulus types was a relative frequency effect observed in the condition of medium frequency imbalance, whereas such an effect was found, at least initially, in the condition of high frequency imbalance. For the circles, choice RT was found to be a linear function of the degree of stimulus frequency imbalance. This absence of a threshold effect was probably due to the lower discriminability of the circles which increased the range of frequency imbalance over which an effect would be observed. This point will be discussed more fully at a later stage.

It will be remembered that Dillon (1966) and Bertelson and Tisseyre (1966), both using key-press responses to letters, found contradictory evidence as to the existence of an effect of stimulus frequency imbalance on choice RT. The difference in probability of occurrence between the "high" frequency stimulus and the "low" frequency stimulus used by
Dillon was 0.12; the corresponding difference in Bertelson and Tisseyre's experiment was 0.40. In the present study, the differences in probability of occurrence of stimulus BI and BD were 0.20 and 0.40 in the conditions of medium and high frequency imbalance, respectively. The present results are therefore consonant both with the results of Dillon, who found no relative frequency effect with a probability difference of less than 0.20, and with the results of Bertelson and Tisseyre, who did observe an effect for a probability difference of 0.40. It appears that the discrepancy between their findings can be explained in terms of a threshold of frequency imbalance required for obtaining the relative frequency effect.

The results for the circles in the present experiment provide support for the second main hypothesis: that the relative frequency effect is a function of the particular type of stimulus used. It was suggested that the critical variable in this regard was stimulus discriminability. If the number of errors made and the characteristic RT may be taken as indices of the difficulty of discrimination, then the relative frequency effect was indeed related to stimulus discriminability. The largest effect was found for the circles, the stimulus type with which were associated the greatest number of errors and the longest RTs. Fewest errors and the shortest RTs were recorded for the letters, the stimulus type showing the smallest relative frequency effect.
Up to this point, no attempt has been made to define stimulus discriminability. It will have been noticed, however, that in the foregoing arguments the term is used to refer jointly to two distinct properties of the stimulus. The first is confusability, the degree to which one stimulus alternative is confused with other members of the set. The second property, which will be termed codability, refers to the facility with which S can codify or label stimulus alternatives of a particular type. Since circles of varying size are regarded as being less easily coded than are letters, confusability and codability were confounded in Experiment 1. Experiment 2 was therefore designed to allow the dissociation of these two aspects of stimulus discriminability.

Experiment 2

In order to distinguish the influence on the relative frequency effect of stimulus confusability from that of stimulus codability, the sets of stimuli chosen for this experiment included three that were of the same type (codability), but whose members differed in their degree of similarity (confusability). Two sets of circles were selected whose members were of such sizes that the stimulus alternatives in one set were less confusable than the stimulus alternatives in the other. To obtain a third set, in which the stimulus alternatives would be even less confusable, the middle sized circle in the "easy" set was replaced by a square of approximately the same size. This set will be referred to as the circles-square set. It
was predicted that, if confusability was the determining factor, then the relative frequency effect would be greatest for the "difficult" (more confusable) set of circles than for the other two sets. If, however, codability was the critical attribute, then no difference in the relative frequency effect for the two sets would be observed.

A fourth set of stimuli consisted of letters whose confusability was much greater than that of the letters used in Experiment 1. Increase in confusability was achieved by choosing letters that looked more alike, and by reducing the brightness of the stimuli. If confusability was critical, then the relative frequency for this set should be much greater than that observed for the letters in the first experiment. If codability was of paramount importance, then the relation between the relative frequency effect for the letters and that for the circles should be similar in both experiments.

Method

Subjects. The Ss were eight male undergraduate students, aged between 17 and 24 years.

Apparatus. Four stimulus sets were used, each containing three alternatives:

(a) CIRCLES (easy): Circular patches of white light, diameters 3/32, 14/32, 32/32 in.

(b) CIRCLES (difficult): Circular patches of white light, diameters 11/32, 14/32, 17/32 in.

(c) CIRCLES-SQUARE: Same as (a), but with middle circle replaced by 13/32 in. square patch.
The remainder of the stimulus, response, and programming apparatus was the same as that used in Experiment 1.

**Experimental design.** The basic experimental design was the same as that used in the previous experiment, except that only one weekly replication was performed. For the easy and difficult circles, stimulus A was always the middle-sized circle; for the circles-square set it was the square, and for the letters it was the letter O.

The experimental procedure and the method of data analysis were the same as in Experiment 1.

**Results**

The matrix of 576 harmonic means is shown in full in Table B, Appendix 1. The results of the experiment are summarized in Figure 2, where harmonic mean RT, averaged over Ss, stimulus sets, and weeks, is shown for each stimulus alternative in each condition of stimulus frequency imbalance. The similarity of these results to those obtained in Experiment 1 is striking. Again, the speed of response to stimuli BD and BI was a function of their probability of occurrence, and the shortest average RTs were associated with stimulus A. The latter result was found to be true for all sets except the difficult circles.

The results of the analysis of variance of the RTs for stimuli BD and BI are shown in Table B, Appendix 2. As expected, the main effect for stimulus sets was highly significant, reflecting the longer RTs
Condition of stimulus frequency imbalance

Figure 2. Average harmonic mean RT in milliseconds for stimulus A, BI, and BD, in each condition of stimulus frequency imbalance in Experiment 2. The probability of occurrence of the stimulus is indicated on the graph.
obtained for the difficult circles and letters than for the other two stimulus sets.

The main effect for stimulus alternatives was significant in this experiment, as was the more direct indication of the relative frequency effect—the stimulus alternatives x frequency imbalance conditions interaction. It was found that, as in Experiment 1, the decrement in RT for stimulus BI increased with practice, while at the same time the increment in RT for stimulus BD became smaller. These changes from Week 1 to Week 2 are thought to underlie the significant conditions of frequency imbalance x weeks interaction.

Table 6 shows the average RTs for stimuli BD and BI, the difference (Δ RT), and the corresponding t-values (indicating significance of the difference from zero), for each stimulus set for each condition of frequency imbalance. The relative frequency effect is similar for the easy circles, the difficult circles, and the circles-square set, being significant for all these sets in the medium and high frequency imbalance conditions. The relative frequency effect for the letters, on the other hand, was smaller, and was significant only in the high frequency imbalance condition.

The results for the conditions of medium and high frequency imbalance are shown in Tables 7 and 8, respectively, for each week. In the first week, a significant relative frequency effect was observed for all sets except the letters in the medium condition; no significant effects were found in the second week. The pattern was the same in the high frequency imbalance condition, with significant relative
Table 6

Average Harmonic Mean RT in Milliseconds for Stimulus Alternatives BD and BI, the Difference (ΔRT), and the Corresponding t-values (Indicating Significance of the Difference from Zero), for each Stimulus Set in each Condition of Stimulus Frequency Imbalance in Experiment 2.

<table>
<thead>
<tr>
<th>Stimulus Set</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT</td>
<td>ΔRT t+</td>
<td>RT</td>
</tr>
<tr>
<td><strong>Easy Circles</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>473</td>
<td>11 0.96</td>
<td>484</td>
</tr>
<tr>
<td>BI</td>
<td>462</td>
<td></td>
<td>445</td>
</tr>
<tr>
<td><strong>Difficult Circles</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>560</td>
<td>16 0.97</td>
<td>572</td>
</tr>
<tr>
<td>BI</td>
<td>544</td>
<td></td>
<td>534</td>
</tr>
<tr>
<td><strong>Circles-Square</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>440</td>
<td>12 0.96</td>
<td>461</td>
</tr>
<tr>
<td>BI</td>
<td>428</td>
<td></td>
<td>426</td>
</tr>
<tr>
<td><strong>Letters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>542</td>
<td>-6 -0.41</td>
<td>572</td>
</tr>
<tr>
<td>BI</td>
<td>548</td>
<td></td>
<td>555</td>
</tr>
</tbody>
</table>

+ df = 15
** p < .01
*** p < .001
Table 7

Average Harmonic Mean RT in Milliseconds for Stimulus Alternatives BD and BI, the Difference (ΔRT), and the Corresponding t-values (Indicating Significance of the Difference from Zero), for each Stimulus Set and Week in the Condition of Medium Stimulus Frequency Imbalance in Experiment 2.

<table>
<thead>
<tr>
<th>Stimulus Set</th>
<th>Week 1</th>
<th>Week 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT</td>
<td>ΔRT</td>
</tr>
<tr>
<td>Easy Circles</td>
<td>BD</td>
<td>490</td>
</tr>
<tr>
<td></td>
<td>BI</td>
<td>434</td>
</tr>
<tr>
<td>Difficult Circles</td>
<td>BD</td>
<td>604</td>
</tr>
<tr>
<td></td>
<td>BI</td>
<td>551</td>
</tr>
<tr>
<td>Circles-Square</td>
<td>BD</td>
<td>464</td>
</tr>
<tr>
<td></td>
<td>BI</td>
<td>426</td>
</tr>
<tr>
<td>Letters</td>
<td>BD</td>
<td>562</td>
</tr>
<tr>
<td></td>
<td>BI</td>
<td>576</td>
</tr>
</tbody>
</table>

+ df = 7
* p < .05
*** p < .001
Table 8

Average Harmonic Mean RT in Milliseconds for Stimulus Alternatives BD and BI, the Difference (ΔRT), and the Corresponding *p*-values (Indicating Significance of the Difference from Zero), for each Stimulus Set and Week in the Condition of High Stimulus Frequency Imbalance in Experiment 2.

<table>
<thead>
<tr>
<th>Stimulus Set</th>
<th>Week 1</th>
<th>Week 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT</td>
<td>ΔRT</td>
</tr>
<tr>
<td>Easy Circles</td>
<td>BD</td>
<td>542</td>
</tr>
<tr>
<td></td>
<td>BI</td>
<td>421</td>
</tr>
<tr>
<td>Difficult Circles</td>
<td>BD</td>
<td>625</td>
</tr>
<tr>
<td></td>
<td>BI</td>
<td>552</td>
</tr>
<tr>
<td>Circles-Square</td>
<td>BD</td>
<td>496</td>
</tr>
<tr>
<td></td>
<td>BI</td>
<td>420</td>
</tr>
<tr>
<td>Letters</td>
<td>BD</td>
<td>616</td>
</tr>
<tr>
<td></td>
<td>BI</td>
<td>556</td>
</tr>
</tbody>
</table>

* df = 7
* p < .05
** p < .01
*** p < .001
frequency effects in both weeks for all sets except the letters; a
significant effect was found for the latter only in the first week.

Of a total of 15,360 responses, 367 (2.4%) were incorrect. The
distribution of these errors for the stimulus alternatives in each
condition is shown in Table 9, the expected number of errors assuming
random distribution being shown in parentheses. A chi-square test
showed the observed and expected distributions to be significantly
different ($\chi^2 = 29.27, p < .001$). It can be seen that this is
largely due to the fewer errors than expected for stimulus A, and
the greater number than expected for stimulus B1, in the medium and
high frequency imbalance conditions. The number (and percentage) of
errors for each stimulus set was as follows: easy circles, 48 (1.3%);
difficult circles, 204 (5.3%); circles-square 50 (1.3%); letters 74
(1.9%). The RT for each error was compared with the harmonic mean RT
for the corresponding correct responses. The ratio of fast:slow er-
rors was approximately 2:1 for the easy circles, circles-square, and
letters, but 1:1 for the difficult circles.

Discussion

The purpose of Experiment 2 was to examine the interaction of
the relative frequency effect with two aspects of stimulus discrimi-
niability—confusability and codability. The major finding is that
the size of the relative frequency effect was very similar for all
three stimulus sets containing circles. Yet, judging from the num-
ber of errors and the RTs for each set, the confusability for the
set of difficult circles was much greater than that for the other two
Table 9

Number of Errors for each Stimulus Alternative in each Condition of Stimulus Frequency Imbalance in Experiment 2 (figures in parentheses indicate expected number of errors assuming random distribution).

<table>
<thead>
<tr>
<th>Condition of Frequency Imbalance</th>
<th>Stimulus Alternative</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>A (58, 63)</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>B (32, 31)</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>D (33, 31)</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>123</td>
</tr>
<tr>
<td>Medium</td>
<td>A (43, 63)</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>B (53, 43)</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>D (22, 19)</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>118</td>
</tr>
<tr>
<td>High</td>
<td>A (45, 63)</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>B (83, 55)</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>D (7, 6)</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>135</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>146</td>
</tr>
</tbody>
</table>
sets. It can therefore be concluded that, for circles of varying size, stimulus confusability is not an important determinant of the relative frequency effect.

Comparison between the results of Experiments 1 and 2 must be made with caution, since different S's were used and the number of replications varied. Comparison of practice effects is further complicated by the fact that, in Experiment 2, some of the circles appeared as stimulus alternatives in more than one set. This may account for a discrepancy between the results of the two experiments. In Experiment 1, where the interval between sessions with the same stimulus type was one week, no practice effect was observed for the circles. In Experiment 2, however, a decrease in size of the relative frequency effect was found for all sets between Weeks 1 and 2. The failure of the effect for the circles to "recover" between sessions in the second experiment may have been due to S's more concentrated experience with the circles.

The results for the letters in Experiment 2, if less compelling than those for the circles, point in the same direction. The confusability of the letters was increased by choosing a set whose forms were more similar than those used in Experiment 1, and by reducing their intensity. These changes resulted in RTs for the letters that were about as long as those for the difficult set of circles. However, the frequency of errors for the letters was only slightly greater than that for the set of easy circles. It is possible that some of the increase in RT for the letters in the second experiment resulted
from a decrease in stimulus detectability, and, therefore, that only part of the increase was due to their greater similarity of form. Nevertheless, the relative frequency effect for the letters, and its relation to that for the circles, were similar in the initial stages of the two experiments. Again, this suggests that stimulus codability, and not confusability (or even detectability), was the critical factor underlying the difference in relative frequency effect for the circles and letters.

It will be noted that, in the second week of Experiment 2, the difference between the relative frequency effect for the letters and circles was slight. In the first experiment, on the other hand, the difference was substantial in each of the three weeks. Although Ss in the first experiment had greater experience of the task, they had less concentrated experience with the circles than did the Ss in Experiment 2. It may be concluded that it is experience with particular stimuli, rather than practice on the task per se, that is crucial in reducing the difference between the effects for the various stimulus types.

The results of Experiments 1 and 2 may be summarized as follows:

1. The relative frequency effect due to stimulus frequency imbalance was much greater for the circles than for the colors, lamps, or letters.

2. With colors, lamps, and letters, there appeared to be a threshold level of frequency imbalance below which choice RT was independent of the probability of occurrence of the stimulus. For circles, however,
choice RT was an approximately linear function of stimulus frequency imbalance.

3. In Experiment 1, little change with practice was observed for the circles; for the other stimulus types, the relative frequency effect decreased with practice. With more concentrated practice (Experiment 2), a similar decrease was found for the circles.

4. The above differences between circles and the other stimulus types were little affected by changes in the confusability of the stimulus alternatives. The differences may be attributed to the lower codability (difficulty of labeling) of the circles.

Further discussion of these results, and of the inferences that may be drawn from them regarding the locus of the relative frequency effect, will be deferred until after presentation of the results of Experiment 3.

Experiment 3

The main purpose of Experiment 3 was to compare the influence of stimulus frequency imbalance with that of response frequency imbalance on choice movement time (MT) and decision time (DT) (the two components of RT). Four stimuli were paired with two responses in a two-to-one fashion (S1-Ra; S2-Ra; S3-Rb; S4-Rb). Three conditions of stimulus and response frequency imbalance were used: In the control condition, all S-R pairs occurred with equal frequency. In the stimulus imbalance (SI) condition, stimuli S1 and S3 each occurred nine times as often as stimuli S2 and S4; this left response
frequencies unchanged from the control condition. In the stimulus plus response frequency imbalance (SRI) condition, stimuli S1 and S2 each occurred nine times as often as stimuli S3 and S4; this led to response Ra occurring nine times as often as response Rb.

Comparison of the results for the control and SI conditions allowed determination of the effects of stimulus frequency imbalance on choice MT and DT. Comparison of the SI and SRI conditions allowed observation of the additional effects of response frequency imbalance.

Method

Subjects. The Ss were ten male and eight female undergraduate students, aged between 17 and 25 years.

Apparatus. Two sets of stimuli were used, each set containing four alternatives:

(a) CIRCLES: circular patches of white light with diameters of 11/32, 17/32, 23/32, and 32/32 in.
(b) LETTERS: 1 in. high by 5/8 in. wide upper case letters; F, N, K, and A.

The circles and letters were displayed on multiple stimulus projectors (Grason-Stadler, Model Nos. 10657 and E458003, respectively).

The home-key was connected to a second chronoscope in order to allow the separate measurement of DT (the time between onset of the stimulus and release of the home-key), and MT (the time between release of the home-key and depression of a response-key). The remainder
of the stimulus, response, programming, and timing apparatus was the same as that used in Experiment 1 and 2.

Experimental design. The 18 Ss were randomly assigned to six equal-sized groups. Groups 1-4 received the circles, while Groups 5-6 had the letters. The S-R pairings and high-low frequency combinations in the SI and SRI conditions for each group are shown in Table 10. S1, S2, S3, and S4 refer to circles of increasing size, or to the letters, F, N, K, and A, respectively. It will be seen from Table 10 that Groups 1 and 2 shared one S-R pairing, while Groups 3 and 4 shared a different arrangement. Furthermore, Group 1 had high-low frequency combinations in the SI and SRI conditions that were the reverse of those for Group 3. The same relation held between the frequency combinations for Groups 2 and 4. For the letters, Group 5 had high-low frequency combinations in the SI and SRI conditions that were the reverse of those for Group 6. This design was considered adequate to ensure that, for both circles and letters, confusability of stimulus alternatives had no differential effect on the overall results for the SI and SRI conditions.

Each S had five consecutive daily sessions with the same S-R pairing and high-low frequency combination. The first session was regarded as practice and the results were not included in the analysis. Experiment 3 may therefore be regarded as a 4 (stimulus alternatives) by 3 (conditions of frequency imbalance) by 4 (sessions) by 4/2 (groups receiving circles/letters) by 3 (Ss within groups) factorial design.
Table 10

Stimulus-Response Pairing and High (H) or Low (L) Frequency of Occurrence of each S-R pair in the Stimulus Frequency Imbalance (SI) and Stimulus plus Response Frequency Imbalance (SRI) Conditions, for Groups 1-4 (Circles) and Groups 5-6 (Letters) in Experiment 3.

<table>
<thead>
<tr>
<th>Group</th>
<th>Condition of Frequency Imbalance</th>
<th>Stimulus-Response Pairing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>S1 - Ra</td>
</tr>
<tr>
<td>1</td>
<td>SI SRI</td>
<td>H</td>
</tr>
<tr>
<td>2</td>
<td>SI SRI</td>
<td>L</td>
</tr>
<tr>
<td>3</td>
<td>SI SRI</td>
<td>H</td>
</tr>
<tr>
<td>4</td>
<td>SI SRI</td>
<td>H</td>
</tr>
<tr>
<td>5</td>
<td>SI SRI</td>
<td>L</td>
</tr>
<tr>
<td>6</td>
<td>SI SRI</td>
<td>H</td>
</tr>
</tbody>
</table>
Procedure. Two new stimulus programs were devised according to the same restrictions as were applied in Experiments 1 and 2. The only other change from the procedure used previously was a decrease in the inter-stimulus interval from 7 to 5 sec.

Data analysis. Since both DT and MT distributions showed positive skew, the harmonic mean was again chosen as the best estimate of the times for each cell of the factorial design. Unless otherwise specified, harmonic mean was the basic datum used in the analyses of DT and MT reported in the next section. Times for trials on which an error occurred were treated separately.

Results

Decision time. The complete matrices of harmonic mean DTs (576 for the circles, and 288 for the letters) are given in Tables C and D in Appendix 1. The results, combined over sessions for all six groups, are summarized in Figure 3, which shows the average harmonic mean DTs for the control condition, and for the high and low frequency S-R pairs in the SI and SRI conditions. In the SI condition, the average relative frequency effect due to stimulus frequency imbalance was 41 millisecond. Comparison with the control condition indicates that this is approximately equally attributable to an increment in DT for the low frequency S-R pairs, and to a decrement in DT for the high frequency pairs. The results for the SRI condition show that the introduction of response frequency imbalance increased the average relative frequency effect to 60 millisecond. Comparison with the results for the control condition demonstrates that, in contrast to the effect of stimulus frequency imbalance, response frequency imbalance leads to an
Condition of frequency imbalance

Figure 3. Average harmonic mean DT in milliseconds for the control condition, and for the high and low frequency S-R pairs in the SI and SRI conditions of frequency imbalance, for all groups in Experiment 3.
overall reduction in DT. The average DTs for both high and low frequency pairs in the SRI condition were shorter than that for the control condition.

While initial analyses of variance of the harmonic mean DTs for the circles and for the letters revealed no significant main effect for groups, some of the interactions including this factor were found to be significant. Differences between the results for the various groups appeared to be related to the differences in confusability of the S-R pairs. In order to eliminate this factor from the analysis, the results for the control condition were used to "correct" the results for the other two conditions. That is, the DT for each pair in the control condition was subtracted from the DT for the corresponding pair in the SI and SRI conditions.

The results for each group are shown in Table II. Values are given for the average DTs in the control condition, and for the high and low frequency S-R pairs in the SI and SRI conditions. Also shown are the differences in DT for the low and high frequency pairs (\( \Delta DT \)), and the corrected difference (\( \Delta DT' \)), the latter being calculated after subtraction of the control DTs from those in the other two conditions. It will be seen that correction substantially reduced the range of difference values, but had little effect on the overall mean value. The larger value of \( \Delta DT' \) for the letters than for the circles was unexpected in view of the results of the first two experiments. However, comparison of results for the groups receiving letters with those for the groups receiving circles is rendered suspect by the
Table 11

Average Harmonic Mean DT in Milliseconds for the Control Condition, and for the Low and High Frequency S-R Pairs in the Stimulus Frequency Imbalance (SI) Condition and the Stimulus plus Response Frequency Imbalance (SRI) Conditions, the Difference (ΔDT) and the Corrected Difference (ΔDT'), for each Group in Experiment 3.

<table>
<thead>
<tr>
<th>Group</th>
<th>Frequency of S-R Pairs</th>
<th>Control</th>
<th>Stimulus Imbalance</th>
<th>Stimulus plus Response Imbalance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>DT</td>
<td>ΔDT</td>
<td>ΔDT'</td>
</tr>
<tr>
<td>1</td>
<td>Low</td>
<td>365</td>
<td>392</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>338</td>
<td>314</td>
<td>-5</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>2</td>
<td>Low</td>
<td>320</td>
<td>319</td>
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<td></td>
<td></td>
<td>37</td>
</tr>
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<td>314</td>
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<td>37</td>
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<tr>
<td>3</td>
<td>Low</td>
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<td>45</td>
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<tr>
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<td>High</td>
<td>388</td>
<td>397</td>
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<td>65</td>
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<tr>
<td>4</td>
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</tr>
<tr>
<td>6</td>
<td>Low</td>
<td>419</td>
<td>448</td>
<td>428</td>
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</tr>
<tr>
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<td>High</td>
<td>387</td>
<td>448</td>
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<td></td>
<td>High</td>
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</tr>
</tbody>
</table>
finding that the average DT in the control condition was shorter for the latter set of Ss. This finding, which was contrary to predictions based on previously observed performance with these two types of stimulus, makes it difficult to regard the two sets of Ss as comparable samples from the same population.

Separate analyses of variance (Winer, 1962, Chapter 7) were performed on the corrected difference scores for the circles and for the letters. The results of these analyses are shown in Tables C and D in Appendix 2. The main effect for stimulus alternatives was highly significant in both analyses, demonstrating the significance of the overall relative frequency effect on choice DT. The significant main effect for conditions of frequency imbalance, found for both circles and letters, reflects the shorter DTs that were generally obtained when response frequency imbalance was added to stimulus frequency imbalance in the SRI condition. The difference in size of the relative frequency effect for the SI and SRI conditions is represented by the interaction between stimulus alternatives and conditions of frequency imbalance. This term was found to be significant for both stimulus types, confirming the increase in magnitude of the relative frequency effect with the introduction of response frequency imbalance. The only other significant term in the analyses was the main effect for sessions for Ss receiving letters. This reflected an overall decrease of DT with practice in the SI and SRI conditions relative to the DT recorded in the control condition.

Is the relative frequency effect due to a large difference in DT on a few trials, or to a smaller difference in DT on many trials?
The answer to this question may be found by comparing the distribution of DTs for the high and low frequency S-R pairs. These are shown in Figure 4 for the SI and SRI conditions, in the form of cumulative frequency curves for the combined results for both stimulus types. Untransformed DTs were used in compiling these distributions. While the DT for the low frequency pair was longer than that for the high frequency pair at all cutting points in both conditions, this difference was slightly more marked for the longer DTs. Furthermore, the reduction in DT with the addition of response frequency imbalance was greater for the high frequency than the low frequency S-R pairs.

Movement time. The complete matrices of harmonic mean MTs are shown in Tables E and F in Appendix 1. The same analyses were applied to the MTs as were used for the DTs. Figure 5 summarizes the results; harmonic mean MTs, averaged over all sessions and groups, are shown for the control condition, and for the high and low frequency S-R pairs in the SI and SRI conditions of frequency imbalance. Comparison of results for the control and SI conditions reveals an average effect due to stimulus frequency imbalance of 18 millisec.; this was almost entirely due to an increment in MT for the low frequency S-R pairs. Addition of response frequency imbalance in the SRI condition increased the average relative frequency effect to 25 millisec. In contrast to the effect on DT, however, addition of response frequency imbalance did not also lead to an overall decrease in MT.

Corrected difference scores were obtained by subtracting the harmonic mean MTs for the control condition from those in the other two
Figure 4. Cumulative frequency distributions of untransformed DTs in milliseconds for the high and low frequency S-R pairs in the SI and SRI conditions of frequency imbalance in Experiment 3.
Figure 5. Average harmonic mean MT in milliseconds for the control condition, and for the high and low frequency S-R pairs in the SI and SRI conditions of frequency imbalance, for all groups in Experiment 3.
conditions. Table 12 shows these results for each of the six groups. It will be seen that correction tended to reduce the range of values of $\Delta$MT with little affect on the mean value. Analyses of variance were performed on the difference in harmonic mean MT for the control condition and the other two conditions; the results for the groups receiving circles and letters are shown in Tables E and F, respectively, in Appendix 2. For both stimulus types, the main effect for stimulus alternatives was highly significant, thus demonstrating the significance of the overall relative frequency effect on choice MT. Although the main effect for conditions of frequency imbalance, and its interaction with stimulus alternatives, were significant for the letters, it was the interaction of these terms with groups that was significant for the Ss receiving circles. For Groups 1 and 3, the relative frequency effect was greater in the SI condition than in the SRI condition; the reverse was true for Groups 2 and 4. No simple basis for this dichotomy can be offered.

The following terms in the analysis for letters were also significant; sessions x groups, sessions x stimulus alternatives, and the interaction of the latter term with groups. Inspection of the data indicates that the trend underlying these effects is the reverse of that found for DT. In the latter case, practice led to a decrease in overall DT relative to that in the control condition. For MT, on the other hand, practice appeared to lead to an increase in MT relative to the control level. The change is complicated, however, in that it occurs for only one of the groups (5), and for one of the
Table 12

Average Harmonic Mean MT in Milliseconds for the Control Condition, and for the Low and High Frequency S-R Pairs in the Stimulus Frequency Imbalance (SI) and Stimulus plus Response Frequency Imbalance (SRI) Conditions, the Difference (\(\Delta DT\)) and Corrected Difference (\(\Delta DT'\)), for each Group in Experiment 3.

<table>
<thead>
<tr>
<th>Group</th>
<th>Frequency of S-R Pairs</th>
<th>Control MT</th>
<th>Stimulus Frequency Imbalance MT</th>
<th>(\Delta MT)</th>
<th>(\Delta MT')</th>
<th>Stimulus plus Response Frequency Imbalance MT</th>
<th>(\Delta MT)</th>
<th>(\Delta MT')</th>
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<tbody>
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<td>1</td>
<td>Low</td>
<td>109</td>
<td>147</td>
<td>43</td>
<td>35</td>
<td>113</td>
<td>8</td>
<td>12</td>
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<td></td>
<td>83</td>
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<td></td>
</tr>
<tr>
<td>4</td>
<td>Low</td>
<td>103</td>
<td>117</td>
<td>18</td>
<td>14</td>
<td>130</td>
<td>36</td>
<td>37</td>
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<td></td>
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<tr>
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<td>124</td>
<td>16</td>
<td>19</td>
<td>118</td>
<td>13</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>108</td>
<td>104</td>
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<td>Low</td>
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</tr>
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<tr>
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<td>14</td>
<td>142</td>
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<td>27</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>102</td>
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<td></td>
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<tr>
<td>Average (Letters)</td>
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<td>105</td>
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<td>20</td>
<td>19</td>
<td>145</td>
<td>47</td>
<td>37</td>
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<td>High</td>
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<td>98</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Average (All Groups)</td>
<td>Low</td>
<td>106</td>
<td>123</td>
<td>18</td>
<td>19</td>
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<td>High</td>
<td>105</td>
<td>102</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
stimulus alternatives (low frequency). The small number of Ss per group suggests that caution should be exercised in interpreting interactions involving the group factor.

Cumulative frequency distributions of untransformed MTs for the high and low frequency S-R pairs in the SI and SRI conditions of frequency imbalance are shown in Figure 6. There was little difference between the MT distributions in the lower half of the range. For longer MTs, however, the discrepancy between the distributions for the low and high frequency S-R pairs was marked. All distributions exhibited a substantial positive skew, indicating that the MTs recorded in this experiment may be described as comprising mostly short latencies with a few long ones. These long MTs were relatively more common for the low frequency pairs than for the high frequency pairs, and MT, on average, was little affected by the introduction of response frequency imbalance.

Joint MT-DT functions. It is of interest to know the relation between the observed changes in MT and DT. Table 13 shows the coefficients of product-moment correlation of MT with DT for the control condition, and for the high and low frequency S-R pairs in the SI and SRI conditions of frequency imbalance. These correlations were determined individually for the high and low frequency pairs in each session; they were then averaged over sessions and Ss using Fisher's Z transformation. The only coefficients that differ appreciably from zero are the negative values obtained for the low frequency S-R pairs in the SI and SRI conditions of frequency imbalance.
Figure 6. Cumulative frequency distributions of untransformed MTs in milliseconds for the high and low frequency S-R pairs in the SI and SRI conditions of frequency imbalance in Experiment 3.
Table 13

Coefficients of Product-Moment Correlation of DT with MT for the Control Condition, and for the High Frequency and Low Frequency S-R Pairs in the SI and SRI Conditions of Frequency Imbalance in Experiment 3.

<table>
<thead>
<tr>
<th>Condition of Frequency Imbalance</th>
<th>Control</th>
<th>SI</th>
<th>SRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of S-R Pairs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>.05</td>
<td>.01</td>
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</tr>
<tr>
<td>Low</td>
<td>-.04</td>
<td>-.13</td>
<td>-.44</td>
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</table>
Errors. The observed and expected distributions of errors for the control condition, and for the high and low frequency S-R pairs in the SI and SRI conditions are shown in Table 14. A chi-square test showed the two distributions to be significantly different ($\chi^2 = 66.0, p < .001$). The total of 208 errors represented an error frequency of 1.2%. Of these, a greater proportion than would be expected by chance occurred in the control condition. Also, more errors than expected were recorded for the low frequency S-R pairs, while less than expected were found for the high frequency pairs. This was true of both the SI and SRI conditions of frequency imbalance. The speed of erroneous responses was compared with that of the corresponding correct responses, allowing the DTs and MTs on trials involving errors to be classified as fast or slow relative to the speed of the correct responses. The results are shown in Table 15. With regard to both MT and DT, there were slightly more fast than slow errors in the control and SI conditions. In the SRI condition, however, most errors for the high frequency S-R pairs were associated with relatively long MTs and DTs, whereas the reverse was true for the low frequency pairs.

Discussion

These results are in general agreement with the findings of the two previous experiments with regard to the effect of probability of occurrence of the stimulus on the speed of choice response. The absence of any systematic difference in size of the relative frequency
Table 14

Number of Errors for the Control Condition and for the Low and High Frequency S-R Pairs in the SI and SRI Conditions of Frequency Imbalance in Experiment 3 (figures in parentheses indicate expected number of errors assuming random distribution).

<table>
<thead>
<tr>
<th>Condition of Frequency Imbalance</th>
<th>Control</th>
<th>SI</th>
<th>SRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of S-R Pairs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>90 (69)</td>
<td>43 (62)</td>
<td>37 (62)</td>
</tr>
<tr>
<td>Low</td>
<td>16 (7)</td>
<td>22 (7)</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>90</td>
<td>59</td>
<td>59</td>
</tr>
</tbody>
</table>
Table 15

Dichotomy of Errors According to the Speed of the Erroneous Response (Fast/Slow) compared with the Average Speed of the Corresponding Correct Responses, for MT and DT, for the Control Condition and for the High and Low Frequency S-R pairs in the SI and SRI Conditions of Frequency Imbalance in Experiment 3.

<table>
<thead>
<tr>
<th>Condition of Frequency Imbalance</th>
<th>Control</th>
<th>SI</th>
<th>SRI</th>
</tr>
</thead>
<tbody>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Frequency of S-R Pairs</td>
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<tr>
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<td>Fast</td>
<td>Slow</td>
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<tr>
<td>MT</td>
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<td>41</td>
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</tr>
<tr>
<td>MT</td>
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<tr>
<td>MT</td>
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</tr>
<tr>
<td>DT</td>
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<tr>
<td>MT</td>
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</tr>
<tr>
<td>MT</td>
<td>17</td>
<td>5</td>
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</table>
effect for the circles and for the letters may have been due, in part, to S's more concentrated experience with the stimulus alternatives in Experiment 3. The results of the previous experiments indicated that this aspect of practice tended to reduce the differences in size of effect for the various stimulus types.

The introduction of response frequency imbalance increased the size of the relative frequency effect on choice DT. More striking, perhaps, was the resulting overall reduction in DT. Not only was average DT for the high frequency S-R pairs greatly reduced with the introduction of response frequency imbalance, but even the average DT for the low frequency pairs was shorter than that recorded in the control condition, despite the higher probability of occurrence of both stimulus and response in the latter case.

These differences were observed over the whole range of DTs. For MT, however, differences were largely confined to the longer latencies, these being relatively more numerous for the low frequency than for the high frequency S-R pairs. It seems likely that most of the long MTs resulted from S changing his response in mid-course. Considering the very simple movement required for a response, it is difficult to see how else they could be explained. Certainly S is aware on most occasions when he has made an error. This is clear from the research of Rabbitt (1966, 1967b), and was confirmed in the present investigation by informal questioning of S. It follows that S must recheck his decisions after reaching them. If he detects an error in time, a correction can be applied; this would lead to a
greatly increased MT for these corrected errors. That such long MTs were more numerous for the low frequency than for the high frequency pairs, suggests that the likelihood of reaching the wrong decision is a function of the probability of occurrence of the S-R pair. This is supported by the data on uncorrected or committed errors; a greater proportion of committed errors than expected were observed for the low frequency pairs, and less than expected were observed for the high frequency pairs.

The results also suggest that erroneous decisions were generally associated with fast decision times. For corrected errors, this is reflected in a negative correlation of MT with DT for the low frequency S-R pairs; for committed errors, it is seen in the preponderance of fast DTs for the low frequency pairs. The implications of this interpretation of the observed changes in MT for future studies of choice RT are considered to be important. If only correct decisions are of interest, a more precise estimate of choice time would be obtained by using the data on MT to identify and eliminate these corrected errors. Similarly, a clearer picture of time-error relations would be provided by investigation of this hitherto neglected aspect of response. Few existing studies have involved the measurement of both DT and MT, although Hilgendorf (1966) has shown that the effect of number of alternatives on choice RT is much more pronounced for MT than for DT. These results for MT also have important implications for work relating to the form of the choice RT distribution (Hohle, 1965; McGill & Gibbon, 1965; Snodgrass, Luce, & Galanter, 1967; Taylor, 1965a, 1965b).
Whether one is interested in correct or incorrect decisions, the present results suggest that separate measurement of decision and movement times would allow a more accurate assessment of choice processes.

The results of Experiment 3 may be summarized as follows:

1. Stimulus frequency imbalance resulted in longer DTs and MTs for the S-R pairs with the lower probability of occurrence. This was true for both circles and letters.

2. The addition of response frequency imbalance to stimulus frequency imbalance led to an increase in magnitude of this relative frequency effect on DT.

3. The introduction of response frequency imbalance also resulted in a substantial overall reduction in DT, compared with that recorded in the control condition in which stimulus and response frequencies were each balanced.

4. Observed differences in MT were interpreted as reflecting the occurrence of erroneous decisions which were corrected after initiation of the response, but before its completion.

5. The proportion of errors, both corrected and committed, was found to be a function of the probability of occurrence of the S-R pairs.
III

GENERAL DISCUSSION

The main purpose of the present investigation was to determine the nature and locus of the relative frequency effect on choice RT. This was done by examining the interaction of the effect with variables presumed to exert their influence at particular stages of the choice process. The existence or absence of an interaction with one of these variables would establish or eliminate the corresponding stage as a locus of the relative frequency effect. The following discussion is divided into two main sections. One deals with the influence on choice RT of stimulus frequency imbalance, and the interaction of this effect with variables such as stimulus confusability, codability, and practice. The second section concerns the effects on choice behavior of response frequency imbalance.

Stimulus Frequency Imbalance

Experiments 1 and 2 showed that the effect on choice RT of stimulus frequency imbalance was independent of the confusability of the stimulus alternatives. Consider first the implications of this finding for two different types of models of choice behavior that emphasize the stimulus identification stage of the choice process.

Discrete search models. In this type of model, the S in a choice RT experiment is regarded as making successive decisions as to the identity of the stimulus; the order in which these decisions is made is determined, in part, by the relative probabilities of occurrence of
the stimuli. Thus, S's strategy in the first two experiments might be represented by the following sequence: "If stimulus A occurs, press button A; if stimulus BI occurs, press button B; if stimulus BD occurs, press button B." Since each decision takes a certain amount of time, and the successive decisions are made in the order of probability of occurrence of the stimuli, the average RTs for stimuli A, BI, and BD should, other things being equal, be inversely proportional to their probability of occurrence. This would explain the relative frequency effect obtained in Experiments 1 and 2.

Differences in the magnitude of the effect for the various stimulus types may be explained by assuming that the time taken for each decision increases with greater confusability of the stimulus alternatives. This would lead to a greater relative frequency effect with increasing confusability. Furthermore, the decrease in magnitude of the effect with practice might be interpreted as reflecting S's increasing ability to adopt a more efficient strategy: "If stimulus A occurs, press button A; otherwise, press button B." It is plausible that S would learn to use this strategy with greater facility when the stimuli were letters than when they were circles. This would account for the smaller relative frequency effect, and its greater change with practice, for the letters than for the circles.

However, the fundamental assumption underlying these propositions is that the relative frequency effect is a reflection of the order in which attempts are made to identify the stimulus. Therefore, since greater confusability leads to increased time per decision, it should
also magnify the relative frequency effect. That this was found not to be the case is evidence against the discrete search models of choice behavior. Thus the above interpretation of the observed relative frequency effect is untenable.

**Stimulus sampling models.** As Edwards (1965) has pointed out, application of the stimulus sampling model to situations involving more than two S-R pairs has yet to be fully developed. However, considering the case for two alternatives, it appears that this type of model also predicts an interaction between the effect of stimulus frequency imbalance and stimulus confusability. The effect on RT of probability of occurrence of a stimulus is represented in the stimulus sampling model by a bias in S's initial likelihood value, or expectation, that favors identification of the more probable stimulus. Confusability is regarded as one of the determinants of the number of samples required before a decision is reached. Because of the bias in initial likelihood, confusability should have a greater effect on RT for the low frequency stimulus than on that for the high frequency stimulus. If the relative frequency effect is measured as the difference in RT for the low and high frequency stimuli, as it was in the present investigation, then increased confusability should lead to an increase in the magnitude of the effect. That this was not the case argues against the stimulus sampling model, at least in its explanation of the relative frequency effect.

**The functional approach.** Clearly, neither the discrete search model nor the stimulus sampling model is able to account for the
observed failure of substantial changes in stimulus confusability to influence the magnitude of the relative frequency effect. Since both these types of models are focused on the stimulus identification stage of the choice process, it seems reasonable to consider the possibility that the relative frequency effect occurs at some other stage.

In the functional approach, outlined in the introduction, the choice process is regarded as comprising six stages: stimulus detection, stimulus identification, recall of translation rule, application of rule, response selection, and response production. Since stimuli BI and BD shared the same response and had the same translation rules, the stages including and after application of the rule need not be considered as the source of the effect. Because the stimuli were mostly of high intensity, and temporal uncertainty was minimal, the stimulus detection stage also appears an unlikely source of the effect. With the stimulus identification stage ruled out by the results of Experiments 1 and 2, recall of the translation rule is left as the locus of the relative frequency effect. Put simply, it seems that the effect occurs not when S asks "which stimulus is it?," but rather when, having identified the stimulus, he then asks "what do I do about it?" He takes longer, on average, to answer the latter question the lower the probability of occurrence of the stimulus.

Because average RT was the same for stimuli BI and BD when they occurred with equal frequency, it can be assumed that the translation rules were recalled with equal speed in that condition. This means that the relative frequency effect cannot be attributed to differences
in strength of association between the stimuli and the rule for BI and BD. It is more plausible to regard the effect as a recency phenomenon. That is, the more recently the stimulus-rule association was used, the more quickly the rule can be recalled. This would also explain the finding by Hyman (1953) that the RT for a given S-R pair became longer the greater the number of intervening trials involving other S-R pairs. Evidence from studies in which selective RT was measured suggests that it is not the time elapsed since the previous use of the rule that is the critical variable (Brebner & Gordon, 1962, 1964a, 1964b; Mowbray, 1962, 1964). Rather, it is the number of intervening events (trials) involving other stimulus-rule associations that appears to be the important factor.

While recency is considered here to be the prime determinant of differences in choice RT, there are situations in which S's short-term expectancies appear to influence his choice behavior. Thus, with only two S-R pairs in a task involving discrete trials, Williams (1966) and others have shown that S responds more quickly when the stimulus is changed from that used on the previous trial, than when it is the same. Also, there is evidence that S's choice behavior is affected by what has been called the "gambler's fallacy"--the non-random time course of his expectancy of a randomly occurring rare event (Dale, 1966; Jarvik, 1951).

If the interpretation of the relative frequency effect as a recency phenomenon is correct, it follows that more attention should
be paid to the role of memorial factors in choice behavior. One such factor is stimulus codability.

**Stimulus codability.** To explain the differences between the results for the various stimulus types in the first two experiments, an appeal was made to a stimulus attribute termed "codability." If we assume that the strength of the stimulus-rule association is greater the more codable the stimulus type, a basis can be found for explaining the obtained results. With highly codable types, such as colors and letters, recency has little additional effect, especially when differences in probability of occurrence are small. The effect of recency is greater, however, and is observed for smaller degrees of stimulus frequency imbalance, when the stimulus-rule association is weak; this is the case with stimulus types of low codability (e.g., circles of varying size).

This view is also consistent with the observed results of practice on the relative frequency effect. In Experiment 1, in which the interval between sessions with the same stimulus type was one week, little change with practice in the magnitude of the effect was found for the circles, whereas a decrease was found for the other stimulus types. In Experiment 2, where practice was more concentrated, a decrease was also observed for the circles. The implication which may be drawn from these findings is that the critical aspect of practice is experience with the particular stimuli (or with the stimulus-rule associations), rather than with the task per se. Thus the effect of recency on choice RT diminishes as the stimulus-rule
associations become more strongly established; and that more concentrated practice is required for this to occur with stimulus types of low codability than with highly codable types.

It was suggested previously that codability be regarded as referring to the facility with which $S$ can label or codify the stimulus. This is the sense in which Brown and Lennenberg (1954) used the term. They found that the length of a color name (measured by words or syllables) was positively correlated with the latency of the naming response, and with the inter- and intra-personal reliability of naming. A factor-analysis of these measures yielded a single factor which they named codability. They then established that codability was strongly related to $S$'s ability to recognize colors.

Two further aspects of their work are worth noting. First, codability accounted for more variance in the recognition task as the response was delayed and the task complicated to increase the importance of the storage (memory) factor. Second, while they found that recognition scores were related to the similarity (confusability) of the colors, they showed that the correlation between codability and confusability was zero. Although Brown and Lennenberg demonstrated differences between stimuli of the same type, their attribute of codability is obviously very similar to that used to distinguish different stimulus types in the present investigation.

Considering the verbal labels associated with the stimuli used in Experiments 1 and 2, it may be noted that for two of the types, colors and letters, $S$ had had extensive practice in associating the
verbal labels with the particular stimulus alternatives. In the case of the circles of varying size, on the other hand, such experience was lacking. On these grounds, one might put the lamps, which varied in spatial location, in the same category as the circles. The results for the lamps, however, were more similar to those for the colors and letters than to those for the circles. This suggests that S can learn to codify some types of stimuli in spatial rather than verbal terms, and that spatial codification is easier than that in terms of size.

Response Frequency Imbalance

The results of Experiment 3 demonstrated the existence of a relative frequency effect on DT with a response frequency imbalance in the ratio 9/1. Since the translation rules for all S-R pairs in this experiment were equivalent, it may be concluded that this effect took place at the response selection stage. It is not possible to make a valid comparison of the magnitude of the effects occurring at the recall of translation rule and response selection stages, from the results obtained in the present investigation. The probability of occurrence of the "high" frequency stimulus was never greater than 0.45, whereas that of the high frequency response was 0.9. Furthermore, only two response alternatives were used, while the number of stimulus alternatives was never less than three. Nevertheless, the present investigation provides unequivocal evidence of the independent existence of effects related both to the probability of occurrence of the stimulus and to that of the response; further studies
are required to assess the relative size of these two effects.

Most models of choice behavior have concentrated on the stimulus reception aspect of the choice process. The demonstration, in Experiment 3, of a significant influence of response frequency on choice RT, contributes to the growing body of evidence in this and related fields indicating the importance of response processes in determining the characteristics of choice behavior. Broadbent (1967b) has shown this for response bias in the recognition of words of varying frequency; Reynolds (1966) has offered an explanation of the psychological refractory period in terms of response competition; and Berlyne (1957), Kornblum (1965), Morin, Forrin, Troxell and McPherson (1965), and Peterson (1965b) have obtained results showing that response competition and compatibility have significant effects on choice RT. It is likely that our understanding of choice behavior would benefit considerably from investigation of the effect of response frequency similar to those that have been concerned with the influence of the probability of stimulus occurrence on choice RT.

The results of the present investigation demonstrate the value of the functional approach to these problems. This approach not only allowed examination of the existence and magnitude of the effect of probability of occurrence of both stimulus and response on choice RT, but also permitted assessment of the loci of these effects in the sequence of processes comprising choice behavior.
IV

SUMMARY

If a subject is instructed to make one of a set of previously specified responses to the presentation of each of a set of corresponding stimuli, his reaction time (RT) for a given stimulus-response pair is found to be a function of the probability of occurrence of that pair. The higher the probability of occurrence, the shorter the associated choice RT. This well-established phenomenon, known as the relative frequency effect, was used in the present investigation to elucidate the processes involved in choice behavior. Specifically, an attempt was made to determine the locus of this effect in the sequence of events involved in making the choice (namely; stimulus detection, stimulus identification, recall of the stimulus-response translation rule, application of the rule, response selection, and response production).

In Experiment 1, two visually presented stimuli were paired with one key-press response, while a third stimulus was paired with another such response. The two responses were required equally often, but stimulus probability was varied by presenting the first two stimuli in different proportions. A relative frequency effect was found, in the form of longer RTs for the less frequently occurring stimulus, this effect being larger the greater the stimulus frequency imbalance. Several different stimulus types were used: circles of varying size, colors, letters, and spatially arrayed lamps. The relative frequency effect
was much greater, and was observed for smaller degrees of stimulus frequency imbalance, for the first of these stimulus types than for the other three.

Experiment 2 was designed to determine whether the effect of stimulus type on the magnitude of the relative frequency effect was related to differences in confusability of the stimulus alternatives within each set. The stimuli used in this experiment included two sets of circles, the sizes of the members of one set being much more confusable than those of the members of the other set, and a set of letters which were more confusable than those used in the first experiment. For neither type of stimulus was the relative frequency effect related to stimulus confusability. Since this factor was presumed to influence the stimulus identification stage of the choice process, the finding eliminated this stage as a source of the effect. Because the stages of stimulus detection, application of translation rule, response selection, and response production were held constant, it appears that the observed relative frequency effect was determined at the time when the subject had to recall the translation rule. It is suggested that the effect is basically a recency phenomenon; the more recently the stimulus has evoked the rule, the more quickly the rule can be recalled. Differences in magnitude of the effect for the various stimulus types were related to differences in stimulus "codability," this attribute determining the strength of association between stimulus and translation rule. The association is typically stronger for highly codable stimulus types, such as letters and colors,
than for less easily coded types, such as circles of varying size.

In Experiment 3, two stimuli were paired with each of two responses. Stimulus frequency imbalance existed in two of the conditions employed, whereas response frequencies were equated in one but differed in the other. Comparison of the results for these two conditions showed that both stimulus and response probability were determinants of choice RT. Separate measurement of decision time (DT) and movement time (MT) indicated that response frequency imbalance influenced the response selection stage, rather than the response production stage. Observed changes in MT were attributed to the occurrence of erroneous decisions that were corrected during the execution of the response.

Thus the relative frequency effect may arise from two sources. In the case of stimulus frequency imbalance it originates in the recall of the translation rule, and in the case of response frequency imbalance it arises from the response selection process. Presumably, when stimulus and response are paired in a one-to-one fashion, as in the typical choice RT experiment, both of these effects occur when the probability of occurrence of the S-R pairs is varied.
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APPENDIX 1

Harmonic Mean Latencies
Table A

Harmonic Mean RTs in Milliseconds for each Week, Stimulus Alternative (A, BI, and BD), and Stimulus Type, for each S in Experiment 1.

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<th>Week 3</th>
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Table B

Harmonic Mean RTs in Milliseconds for each Week, Stimulus Alternative (A, BI, and BD), and Stimulus Type, for each S in Experiment 2.

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Table C

Average Harmonic Mean DTs in Milliseconds for each Session, Stimulus Alternative, and Condition of Frequency Imbalance, for the Ss in the Four Groups receiving Circles in Experiment 3. (SA1, SA2, SA3, and SA4 refer to circles of increasing size).

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Table D

Average Harmonic Mean DTs in Milliseconds for each Session, Stimulus Alternative, and Condition of Frequency Imbalance, for the Ss in the Two Groups receiving Letters in Experiment 3. (SA1, SA2, SA3, and SA4 refer to the letters F, N, K, and A respectively).

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(SA1, SA2, SA3, and SA4 refer to the letters F, N, K, and A respectively).
Table E

Average Harmonic Mean MTs in Milliseconds for each Session, Stimulus Alternative, and Condition of Frequency Imbalance, for the Ss in the Four Groups receiving Circles in Experiment 3.

(SA1, SA2, SA3, and SA4 refer to circles of increasing size).

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Table F

Average Harmonic Mean MTs in Milliseconds for each Session, Stimulus Alternative, and Condition of Frequency Imbalance, for the Ss in the Two Groups receiving Letters in Experiment 3. (SA1, SA2, SA3, and SA4 refer to the letters F, N, K, and A respectively).

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APPENDIX 2

Analysis of Variance Tables
Table A

Analysis of Variance (Winer, 1962) of Harmonic Mean RT as a Function of Stimulus Alternatives (B₁, B₂), Stimulus Types, Conditions of Frequency Imbalance, and Weeks in Experiment 1.

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*p < .05
**p < .01
***p < .001
Table B

Analysis of Variance (Winer, 1962) of Harmonic Mean RT as a Function of Stimulus Alternatives (BA, BD), Stimulus Sets, Conditions of Frequency Imbalance, and Weeks in Experiment 2.

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*p < .05

**p < .01

***p < .001
Table C

Analysis of Variance (Winer, 1962) of DT Difference Scores as a Function of Stimulus Alternatives, Conditions of Frequency Imbalance, Sessions, and Groups (1-4), for the Ss receiving Circles in Experiment 3.

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<tr>
<td>Within Ss</td>
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**p < .01

***p < .001
Table D

Analysis of Variance (Winer, 1962) of DT Difference Scores as a Function of Stimulus Alternatives, Conditions of Frequency Imbalance, Sessions, and Groups (5-6), for the Ss receiving Letters in Experiment 3.

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*p < .05

***p < .001
Table E

Analysis of Variance (Winer, 1962) of MT Difference Scores as a Function of Stimulus Alternatives, Conditions of Frequency Imbalance, Sessions, and Groups (1-4), for the Ss receiving Circles in Experiment 3.

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<tr>
<td>Within Ss</td>
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**p < .01
***p < .001
Table F

Analysis of Variance (Winer, 1962) of MT Difference Scores as a Function of Stimulus Alternatives, Conditions of Frequency Imbalance, Sessions, and Groups (5-6), for the Ss receiving Letters in Experiment 3.

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*p < .05  
**p < .01  
***p < .001