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PREDICTING HUMAN PERFORMANCE IV: CHOICE REACTION TIME

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A quantitative analysis of the visual choice reaction time literature indicated that somewhat different functions and phenomena hold after extensive practice (at least 3000 trials) as compared to before that. These functions are developed for the number of alternatives and for different S-R combinations.

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PREDICTING HUMAN PERFORMANCE IV
CHOICE REACTION TIME

INTRODUCTION

This study is the fourth of a series which attempts to develop empirical models or relationships for predicting human performance. In an earlier study (Teichner and Krebs, 1972) we investigated simple "switching" performance, i.e., that performance which involves a discrete response to a single stimulus. The present analysis is concerned with the more complex type of switching task which involves more than one stimulus and more than one response (cf., Teichner and Olson, 1971). The dependent measure, the choice reaction time (CRT), is the time elapsing between the onset of a signal and the initiation of a response to it.

The present efforts, restricted to tasks using visual signals, investigated the effects of the following specific variables: Number of different alternative stimuli and responses, level of practice, stimulus probability, length of foreperiod, stimulus-response (S-R) coding and/or S-R compatibility, and unequal S-R mapping. Although other variables, might also produce effects on CRT, it was hoped that their effects would be small compared to the effects of the variables studied, and that their contribution to the inter-experimental error would be tolerable at the present stage of understanding.

THEORETICAL SUMMARY

How man makes choices or decisions is a question with roots in philosophy and is, perhaps, one of the major questions that man has asked about himself. Scientific psychology has approached the question by devising laboratory arrangements in which the events about which decisions are to be made (stimuli) can be manipulated and the decisions (responses) can be observed. Some of the observations made are of the correctness of the responses according to predetermined criteria. Others are observations of the speed with which decisions are made. The second, known as a disjunctive, or complex, or choice reaction time experiment, has had a long, and still very active, research interest. It is the choice reaction time experiment with which this paper is concerned.

The hope of the CRT experimental model is that an analysis of decision times will help isolate the processes which determine how decisions are made. Such processes involve identification of the stimulus and selection of the

response appropriate to it. Clearly, all of the problems studied by psychologists are subsumed by these two interests. Our particular purpose in this study was not to try to cope with all of those problems, but rather to attempt to find basic empirical relationships in the CRT literature which can act as constraints on the theoretical models that might be developed for them.

An early theoretical approach to the CRT task was that of Donders (1868-69)[1] who proposed that the latency involved in choice reactions is the sum of three temporal components: (1) Simple reaction time (RT) (2) The time required for stimulus categorization, and (3) The time required for response selection. These processes were hypothesized to be distinct, sequential and non-overlapping. The a-reaction represents the sum of various neural transmission lags, and for any stimulus energy condition was assumed to be a constant which could be estimated by RT. In order to assess the time required for the other two processes, he developed two experimental paradigms. In one, the b-reaction, each stimulus is associated with a response. This arrangement is often referred to as the "choice reaction time" experiment. In the other, the c-reaction, several stimuli are presented but response is required only to one of them. This arrangement is often called a "selective reaction time". The c-reaction requires only stimulus categorization since only one response is involved, whereas the b-reaction requires both stimulus categorization and response selection. Donders proposed estimating the time taken for response selection by subtracting the c-reaction time from the b-reaction time. This subtractive logic, the constancy of RT, and the assumption of non-overlapping, serial phases constitutes the essence of Donders's theory.

More recent theory tends to pursue the logic of Donders's model. In fact, as Smith (1968) points out, current theorists tend to push Donders's logic even farther to include multiple stages or comparisons within each of the three processes. Donders, himself, extended the a-reaction to include a set of constant, neural and muscular lags in series. Christie and Luce(1956)and Sternberg (1966) have proposed that stimulus categorization alone subsumes several steps executed in serial order. In addition to stimulus categorization and response selection Welford (1968) has proposed an intermediate translation stage.

1. For an informative and amusing description of Donders's publication history and misfortunes see Brožek (1970).

Although which subprocesses must be postulated is still an open question, current theoretical interest seems to be focused more on whether or not such processes or stages are executed in a parallel or serial fashion. A recent model of simple reaction time proposed by Teichner and Krebs (1972) suggests that even that comparatively simple task may require the assumption of three component processes operating in a serial-parallel arrangement.

The more complex CRT models have tended to concentrate on subprocesses within a major stage. Of considerable interest has been the stimulus categorization stage about which much of the serial-parallel debate has centered. For example, Hick's (1952) model views all stimulus identification activities as a series of subdecisions whereas Neisser (1963) favors a model in which activities associated with identifying the stimulus are carried out in parallel.

Stimulus categorization models have been of two major types, template-matching and feature-testing. In the template-matching model, the subject compares replicas of the stimuli presented with alternative stored representations or templates. Hick (1952) considered various models by which these comparisons might be performed either serially or in parallel. As Smith (1968) notes, however, little is said in these models about how the matching process might be carried out or what the nature of a template might be. In general he reports that such models have been weak in their ability to account for a variety of experimental findings.

One of the feature-testing models (Hick, 1952) proposes that the subject stores lists of features associated with each of the N possible stimuli. When a stimulus is presented, the subject makes a series of dichotomous tests related to one of the features. Each subdecision reduces the number of alternatives by half until the correct alternative is found. Consequently, CRT should be related to the number of possible stimulus alternatives in terms of the amount of stimulus information. A second general type of feature-testing model uses sequential stimulus sampling and/or statistical decision concepts (Edwards, 1965; Fitts, 1966; Stone, 1960). While these models are relevant to the development of a general theory of decision-making of which CRT may be viewed as a part, they deal with more complex issues than those which we wish to consider here. That is, this study is concerned with the temporal characteristics of errorless choices. In general those choices have faster CRTs than do error reactions although a speed-accuracy trade-off is a critical factor (Fitts, 1966).

Both kinds of stimulus categorization models are concerned with how the subject identifies or encodes the stimulus prior to response selection. Neither model has been addressed to the problem of response selection, as such, although in some elaborations which have been proposed (cf. Norman, 1970), the problem is approached Equally important, with regard to CRT, no available form of either model appears to provide a basis for predicting the actual latency of stimulus categorization.

Additional quantitative models of CRT have been suggested, the most recent being one proposed by Lappin and Disch (1972) who treat CRT within the theory of signal detection. While such approaches may provide fruitful results, they have only a limited applicability to the literature with which we shall be concerned. Again, this is related to our interest in errorless performance. In fact, most CRT studies have been concerned with the latency of error free performance, and have excluded error CRTs from their analyses.

INDEPENDENT VARIABLES

Number of Alternative Stimuli

The CRT, as a measure reflecting decision-making phenomena, has been of interest at least since Merkel (1885) demonstrated that CRT increases as the number of possible alternative signals that could be presented (N_A) increases. All of the theories discussed above would predict such an increase assuming stimulus categorization to be a serial process or at least some component of it to be sequential in nature. What has been unresolved is the quantitative relationship between an increase in N_A and the increase in CRT, and, more specifically, whether this relationship is linear or logarithmic.

One of the earliest quantitative models was that of Hick (1952) who proposed that:

$$CRT = a \log_2 (N_A + 1) \qquad (1)$$

where a is a constant representing simple RT and $\log_2 N_A$ is the amount of stimulus information assuming equiprobable alternatives. The +1 in the equation is a correction added to N_A to account for uncertainty about the time of occurrence of the signal (i.e., it represents the alternative of "no signal"). Note that when $N_A = 1$, CRT = a which is RT.

Equation 1 has come to be known as Hick's law. It assumes that the gain in information transmitted between stimulus and response is directly proportional to the amount of stimulus information (given a noiseless transmission), and that the increase in CRT reflects that gain.

An alternative equation was suggested by Miller (1951), Hyman (1953) and Bricker (1955) who proposed that

$$CRT = a + b \log_2 N_A \qquad (2)$$

where a represents simple RT and b $\log_2 N_A$, the time required for identification and choice. In a comparison of the two formulas Welford (1968) concluded that Equation 1 provides a better approximation of the available data.

Stimulus-Response Compatibility

While a number of investigators have demonstrated an increase in CRT as a function of increasing N_A, the slope of this increase has been shown to be sensitive to a number of factors. One of these is that relationship between stimuli and their associated responses which has been called "stimulus-response compatibility" (Fitts and Seegar, 1953). Stimulus-response compatibility has been manipulated in a variety of ways. One such manipulation involves the use of different spatial relationships between each S and its R. For example, in a task where the subject is presented with two lights and two keys both arranged horizontally so that the left light corresponds to the left key, the relationship is assumed to be compatible. If the S-R code is reversed so that the left light is associated with the right key, CRT tends to be larger. The second arrangement is considered to have less compatibility between S and R. The difference between the two arrangements tends to diminish with practice suggesting that negative transfer from an accustomed relationship produced the incompatibility, Smith (1968).

A second, theoretically more interesting, type of compatibility problem is associated with the nature of the physical stimulus and the kind of response required to it. Brainard, Irby, Fitts and Alluisi (1962) investigated all possible combinations of two stimulus types (lights or digits) and two responses (keypress or vocal). Their findings indicated that the highest rates of information transmission were obtained with the digit-vocal condition and the lowest with the light-vocal condition. Results for the other two conditions fell between these two extremes. According to Welford (1960, 1968) this result points strongly to some type of translation mechanism or stage between the stimulus categorization and response selection stages. Fitts (1964), Fitts and Posner (1967), and Welford (1968) conclude that the slope relating CRT to N_A is a function of S-R compatibility. The stronger the S-R relationship, the shorter the time required for the

translation stage and, thus, the higher the rate of information transfer. Compatibility, in turn, is assumed to have developed from pre-laboratory experience: that is, naming digits is a more familiar task than pressing keys in response to lights.

Effects of Practice

At any given level of N_A, one effect of practice is to reduce CRT. Such effects have been found to continue even after extensive practice. Seibel (1962) found continued reductions in a 5-choice task after more than 20,000 trials as did Hale (1969) in a 3-choice task. Mowbray and Rhoades (1959) found a continuing practice effect through 45,000 trials for both 2- and 4-choice conditions. As would be expected, the largest drop in CRT occurred early in practice with smaller improvements occurring later in the extended series. Welford (1968) has suggested that the practice gains reported were due to inadequate control of the number of responses made per signal in most studies which have varied both N_A and N_T. The question of an $N_A \times N_T$ interaction is still apparently open.

Fitts (1964) has noted an interactive effect between practice and S-R compatibility on the reduction of the slope of the N_A function. An assumption that has been made (e.g., Broadbent and Gregory, 1965) is that compatibility of particular S-R relationships reflects prior practice and thus these two variables are essentially reflecting the same process. One problem is that compatibility has been defined typically in terms of events which occur prior to the investigation, and which are, therefore, uncontrolled and difficult to study. This is demonstrated in the results of an experiment reported by Morin and Forrin (1965) which was designed to test the hypothesis that compatibility is the result of practice. Two groups of children, first and third graders, were tested on a numeral-naming task. The assumption was that the older group would have had more pre-experimental experience than the younger one at this task and, thus, that the slope of CRT vs N_A would be smaller. The results showed nearly a zero slope between CRT and N_A for both groups, suggesting that their hypothesis was incorrect. There was a large degree of variability in the results, however, which implies that grade level may not be a direct index of practice. Such findings suggest that assumptions regarding pre-laboratory experience may not be particularly valid in any specific instance.

Welford (1968) suggests that it is the translation mechanism between S

and R which is influenced most by familiarity. If the translation process is minimized so that the association between each S and its appropriate R becomes "wired in", the effect of increasing N_A should be reduced and eventually, with enough practice, be reduced to zero. This argument suggests a series of parallel channels which can be preset to await a stimulus event. Any given event would activate only one of these channels. Thus, the subject would be performing a set of simple reaction time tasks in parallel. The only effect of increasing N_A would be to increase the temporal uncertainty of any particular S-R subset.

Differential S-R Mapping

In Donders's (1868) original model, the selective reaction paradigm involved the presentation of several different stimuli in a task where the subject was required to respond only to one of them. This many-to-one mapping procedure was designed to provide a measure of stimulus categorization time. Such selective responding tasks have been employed by many investigators (e.g., Nickerson and Feehrer, 1964; Brebner and Gordon, 1962, 1964; Broadbent and Gregory, 1965) to study the process of stimulus categorization. The general results indicate that as the number of different stimuli is increased, CRT increases even though no response selection is involved in such a task. One implication of such findings is that stimulus factors play the primary role in the CRT vs N_A relationship. In contradiction, a study by Forrin and Morin (1966) comparing choice and selective reactions reported the latter to be even longer than the choice reaction. The suggestion was made by them that response inhibition to the non-critical items had an effect on response to the critical one. If so, then response factors must play a more important role then has been supposed. Other investigators, (e.g., Mowbray, 1964; Taylor, 1966) have not found supporting results except when N_A was eight or more.

A variation of the selective reaction is the paradigm in which all signals are critical (i.e., are responded to) but in which there are fewer kinds of responses than signals. Morin, Forrin, and Archer (1961) varying the S-R ratio from 4-1 through 4-4, obtained results which suggested that the primary factor was number of responses. The results of an experiment by La Berge and Tweedy (1964) suggested that it is the probability of particular S-R relationships which influences CRT. Using 3:2 mapping, but varying the relative probability of each of the three stimuli, they found that CRT depended

upon the probabilities of individual signals even though the frequency of the two responses was equal.

Another indication of the importance of stimulus factors in the many-few mapping task is provided by Hinrichs and Krainz (1970). Prior to each trial the subjects were asked to predict which stimulus would occur. In situations where the predicted stimulus occurred, response times were faster than in the case where the prediction was incorrect. An interesting finding in this latter situation was that equal CRTs were found even when the actual stimulus was associated with the same response as the incorrectly predicted one. Such results imply that even when the subject is set to make a particular response, stimulus factors may exert an overriding influence.

Stimulus Probability

One interpretation of the increase in CRT with N_A is related to the decrease in the probability of occurrence of any one stimulus as N_A increases if, as in most studies, all stimuli appear with equal frequency for any given level of N_A. Studies in which stimulus probability was manipulated (e.g., Hyman, 1953; Bertelson and Barzelle, 1960; Mowbray, 1964; Lamb and Kaufman, 1965; Kaufman, Lamb and Walter, 1970; Kaufman and Levy, 1966) have demonstrated that, for a constant N_A, higher probability stimuli are associated with smaller CRTs than those occurring with lower probability. The notion that the effects of stimulus probability are independent of the relationship between N_A and CRT is questionable considering the results of Broadbent and Gregory (1965) who showed that CRT to a stimulus occurring on 75 per cent of the trials was greater when it was part of a four-alternative set than when it was part of a two-alternative set.

Effects of Foreperiod Length

In general, increases in the length of the foreperiod (i.e., the interval between a warning signal and stimulus onset) have been considered to result in an increase in CRT. Hick (1952) attributed this to uncertainty concerning the time of arrival of the signal. He theorized that temporal uncertainty effectively added one to the number of alternatives in terms of its effect on CRT. The literature is not completely consistent in its findings about this variable, however. Brainard, Irby, Fitts and Alluisi (1962) found essentially no differences in performance between a CRT task in which the foreperiod was two seconds and a self-paced task in which the next stimulus was presented 0.15 second following a response. Those differences which were present seemed

to occur mostly at lower levels of N_A (i.e., 2) rather than at higher levels (i.e., 8). They found that CRT was slightly longer for the longer foreperiod at lower levels of N_A. These results were reversed for the 8-choice condition.

Gottsdanker and Way (1966) studied the effects of both random and constant foreperiods ranging from 1.05 to 1.80 second. Over this limited range they found little effect for the random foreperiod, but a consistent increase in CRT as foreperiod increased under the constant condition. In fact, the mean CRT for the random condition was less than for the constant interval. Such results are contrary to what might be expected from Hick's (1952) temporal uncertainty hypothesis. The variable condition should result in more uncertainty, not less, and, accordingly, CRTs should have been longer.

Foreperiods which are very short, especially those which are close to zero as in self-paced tasks, have been found to result in slightly longer CRTs. Borger (1963) discussed this in terms of the psychological refractory period such that two stimuli which occur too close in time are more difficult to separate as distinct. Welford (1960) also suggests that such effects are related to a minimal processing time for the separation of two events.

Physical Parameters of the Stimulus

Little attention has been paid to the effects of duration, size, and intensity of the signals in CRT tasks. In most studies the signal is terminated by the response and the stimulus energy characteristics are not even specified. One study by Christ (1970) in which duration of the stimulus was varied from 50 to 150 msec. found no significant difference in CRT across these durations. Another (Kaswan and Young, 1965) reported that CRT varies with stimulus intensity. This variation and the lack of variation due to stimulus duration are attributable to the interactive effects of intensity and duration on the simple reaction time component (Teichner and Krebs, 1972). We see no basis for expecting a decrease in either the choice reaction or selective reaction as well. However, important variations in CRT among studies could be due to energy factors and, therefore, should be controlled.

METHOD

A literature search was conducted of the studies published since 1950 which reported CRT as the dependent measure. A few important papers published earlier than 1950 were also included. These studies were then evaluated according to the following criteria before they were accepted for further use:

1. Stimuli had to be presented visually.

2. The stimulus situation contained no visual noise or other masking or distracting elements.

3. Only simple, highly overlearned signals could be used as stimuli. Stimuli falling within this category included single light flashes, single digits or letters, colors, and common geometric shapes (e.g., circle, triangle or square).

4. Response had to be intended to the onset of the signal and CRT measured from the initiation of the signal to the initiation of the response. If a keypress or other manual response was used, the movement required either had to be minimal (e.g., the subject's fingers rested on the response keys) or data had to be provided which allowed CRT to be corrected for movement time.

5. Viewing of the stimulus display was restricted to central binocular vision.

6. Position uncertainty was acceptable within visual limits if the signals were position-coded, and if the subject was always aware of the code.

7. The subjects were young normal adults.

8. CRTs of incorrect responses were excluded.

9. The procedures and general experimental design were acceptable.

On the basis of these criteria, 59 studies were accepted as providing data for further analysis.

Data Handling

Information descriptive of the physical characteristics of the stimulus and response apparatus as well as the procedural aspects of the study was recorded. In addition, the data from each study, as reported by the author, were extracted. All information and data were converted to common units of measurement: CRT, foreperiod duration, and stimulus duration in seconds, absolute number of stimuli and responses (rather than e.g., bits), target luminance in millilamberts, and stimulus size in degrees of visual angle. The following information was coded and placed on punched cards:

1. Identifying code number of the study.
2. Number of different stimuli.
3. Type of stimulus.
4. Type of response.
5. Length of foreperiod.
6. Log_{10} total number of trials.
7. Stimulus probability.

8. An indication of whether all stimuli were equally probable.
9. Type of task (serial or discrete).
10. Results.

A separate card was used to record each data point reported in each study. The only exception to this was in the case where data for individual subjects were reported separately. These data were averaged and reported as a single measure.

Having organized the data and descriptive information in this way permitted considerable flexibility in analyzing the results by computer. Any particular subset of data alike in specified ways could be selected and analyzed apart from the other data. Comparisons related, for example, to the effects of particular S-R combinations could be made merely by specifying two digits indicating the code for that combination. An additional advantage of using the computer was that it was possible to generate computer plots and thus have access to rapid and accurate graphic displays of the data.

As in previous efforts within this series, the approach used in handling the data was an iterative one. The first step was to plot all data on a common graph, the initial working hypothesis being that only one major variable was systematically related to the dependent measure, CRT. This graph was then examined for trends suggesting the influence of other major variables. Such examination led to a series of subsequent hypotheses which were then tested by plotting subsets of the data. A variable was considered to be important (i.e., a major variable) only to the extent that it produced a trend across studies conducted at different parametric values. Such an approach does not of course exclude the possibility that other sources of variability exist which either have not been specified or have not been varied parametrically.

RESULTS AND DISCUSSION

A rather large dispersion of points was found in the initial plot of CRT vs H_A. That variability appeared to be influenced importantly by two factors: 1) an extremely wide range of practice across studies, i.e., from 64 trials per subject in a study by Taylor (1966), to 63,000 trials per subject in one by Leonard (1958). 2) the particular type of stimulus-response (S-R) relationship.

Four different S-R combinations have been used extensively: (1) the

subject is presented with a digit (sometimes a letter) and responds by identifying the digit aloud, thus triggering a voice key; (2) the subject responds to a digit by depressing one of several buttons or keys manually; (3) the subject is presented with an array of lights and required to respond by depressing the appropriate key; (4) the subject responds to an array of possible lights by vocally identifying the position of the light in the array. Of these four combinations (digit-voice, digit-key, light-voice, light-key) only the digit-key and light-key have been studied over a wide range of practice levels. That being the case, it was possible to compare the effects of the four S-R combinations only at relatively low practice levels. Such an evaluation is provided in Figure 1 which presents the mean of the CRTs of different studies which have used the four arrangements. The lines in the figure are intended only to illustrate the average trend.

Figure 1 suggests that the light-key combination tends to produce the shortest CRT, at least at relatively low practice levels, and for $N_A \leq 4$. For $N_A \geq 5$, the digit-voice combination appears superior on the average. In fact, the digit-voice combination appears to be independent of N_A, whereas the other combinations appear to be directly proportional to $\log_2 N_A$. These results are in general agreement with Fitt's (1964) analysis of the portion of the data which he used and except for the higher CRT at lower N_A of the digit-voice combination, with the conclusions of Welford (1968).

Digit (or letter)-naming is highly developed in the adult population. We see little basis for assuming that the differences among the other three combinations reflect familiarity differences. There do appear to be differences among them in regard to differential S and R coding. The light-key combination uses the same code (position) for both S and R. In a sense the subject has only to touch an extension of the position-coded light. On the other hand the digit-key combination requires a translation from a verbal to a position code and the light-voice from a position to a verbal code. The advantage of the digit-key over the latter is presumably due to the fact that the subject already knows the (verbal, numeric) code. This explanation implies an S-R incompatibility defined on the basis of S-R coding differences. Presumably, the fewer translations required, the better the performance, at least at the relatively low levels of practice represented in Figure 1.

Figure 2 presents CRT for the digit-key combination as a logarithmic function of practice trials (N_m) with N_A as a parameter. The lines are

least-square fits. They are acceptable first approximations considering the variability displayed. It is suggested by the trends that at a sufficient level of practice each N_A curve will asymptote at the same minimal CRT. We have arbitrarily selected the minimum as .20 second. The suggestion of an eventual independence between CRT and N_A is supported by our previous observations of Figure 1.

Figure 2 shows that the CRT function can be expressed in general as:

$$CRT = K \log_{10} N_T + a \qquad (3)$$

where N_T is the number of trials, K is the slope constant, and a is the Y-intercept.

For the digit-key lines of Figure 2 at the indicated N_A:

$$N_A = 2,\ CRT = -.099 \log_{10} N_T + .725 \qquad (3a)$$

$$N_A = 3,\ CRT = -.156 \log_{10} N_T + 1.050 \qquad (3b)$$

$$N_A = 4,\ CRT = -.169 \log_{10} N_T + 1.145 \qquad (3c)$$

$$N_A = 8,\ CRT = -.217 \log_{10} N_T + 1.540 \qquad (3d)$$

It is clear that both the slope and intercept constants are functions of N_A. Figure 3 presents plots of the intercept constant as a function of N_A and of $\log_2 N_A$. The curves, fitted by eye, are reasonable. The logarithmic relationship is:

$$a = .425 \log_2 N_A + .295 \qquad (4)$$

From which, when $N_A = 1$, a = .295 which is an estimate of simple reaction time when $N_T = 1$.

Figure 4 presents a fit of the slope constant of Equation 3. The function is:

$$K = -.07 \log_2 N_A - .029 \qquad (5)$$

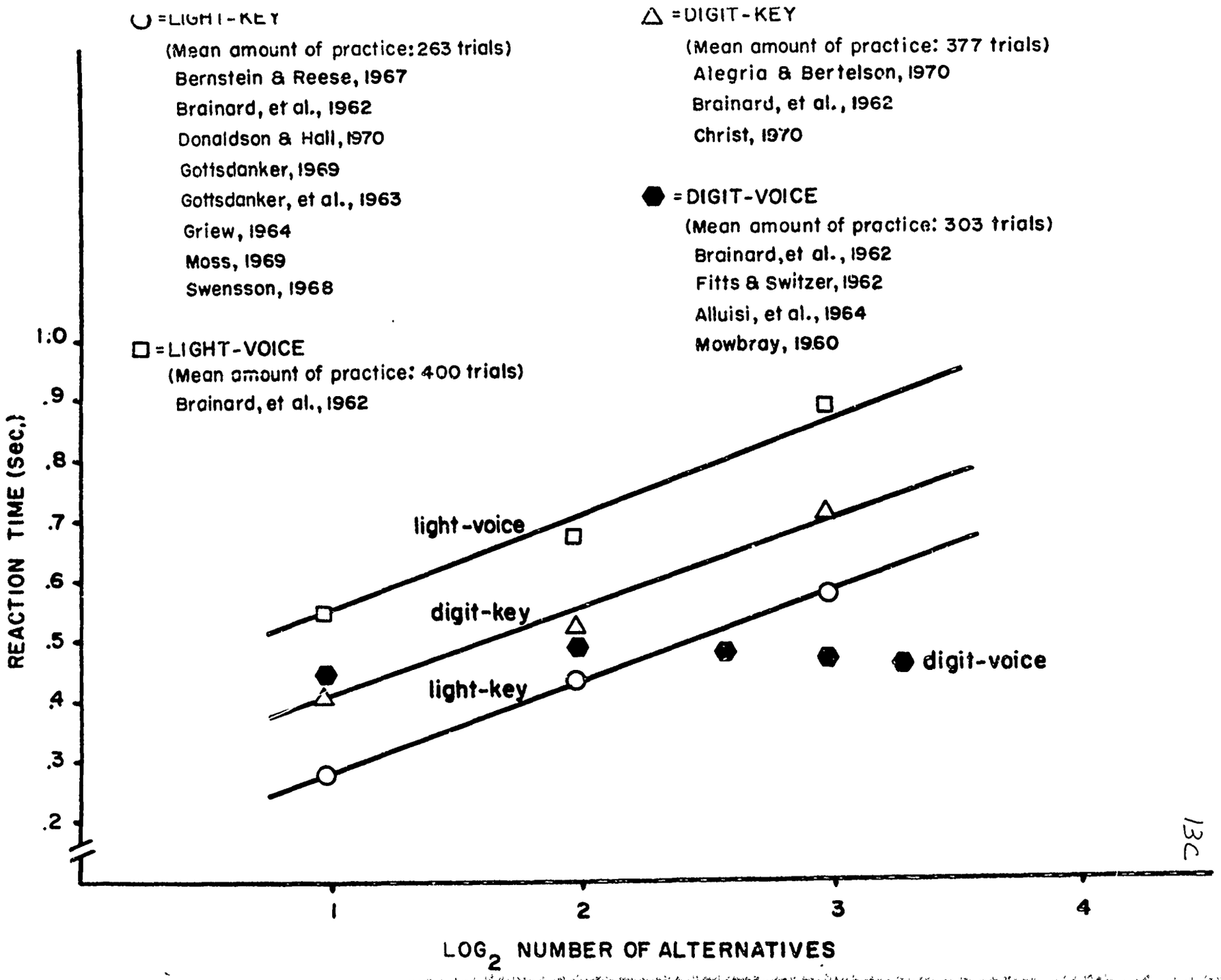
One implication of Equation 5 is that when N = 1, K is very close to zero, a desirable result. Using Equations 4 and 5 to obtain parameters for Equation 3 provides the following estimates of the simple reaction time: $N_T = 1$, RT = .295; $N_T = 100{,}000$, RT = .150. These are acceptable estimates.

Figure 5 presents CRT as a function of practice for the light-key combination. An important liberty was taken with the data of Seibel (1962) in developing this figure. In comparison to the rest of the data in the literature, Seibel's CRTs were consistently far less than even the two-choice results. Since the trend of his data is similar, and since as Figure 4 shows, the slope of that trend is similar to the other trends, we assumed a constant error (or more sensitive equipment?) in his data of .22 second. Correction by that

13B

FIGURE 1

Choice reaction time as a function of $\log_2 N_A$ (i.e. bits) for equiprobable alternatives at low practice levels. Data points are the mean of the indicated studies.

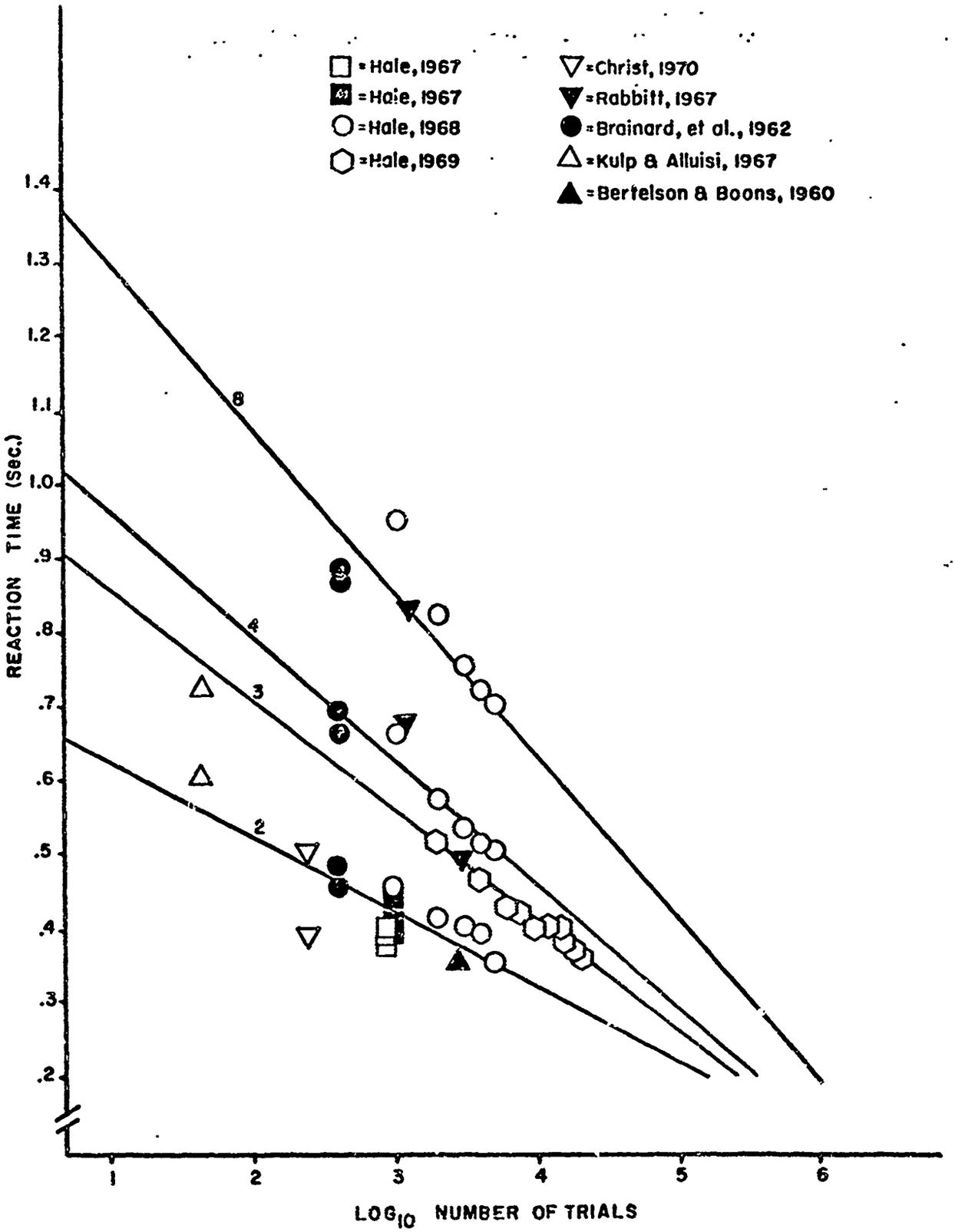

○ = LIGHT-KEY
(Mean amount of practice: 263 trials)
Bernstein & Reese, 1967
Brainard, et al., 1962
Donaldson & Hall, 1970
Gottsdanker, 1969
Gottsdanker, et al., 1963
Griew, 1964
Moss, 1969
Swensson, 1968
□ = LIGHT-VOICE
(Mean amount of practice: 400 trials)
Brainard, et al., 1962
△ = DIGIT-KEY
(Mean amount of practice: 377 trials)
Alegria & Bertelson, 1970
Brainard, et al., 1962
Christ, 1970
● = DIGIT-VOICE
(Mean amount of practice: 303 trials)
Brainard, et al., 1962
Fitts & Switzer, 1962
Alluisi, et al., 1964
Mowbray, 1960
REACTION TIME (Sec.)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
light-voice
digit-key
light-key
digit-voice
1
2
3
4
LOG2 NUMBER OF ALTERNATIVES

13C

13-D

FIGURE 2

Choice reaction time as a function of practice for the digit-key task. The parameter is the number of equiprobable alternatives.

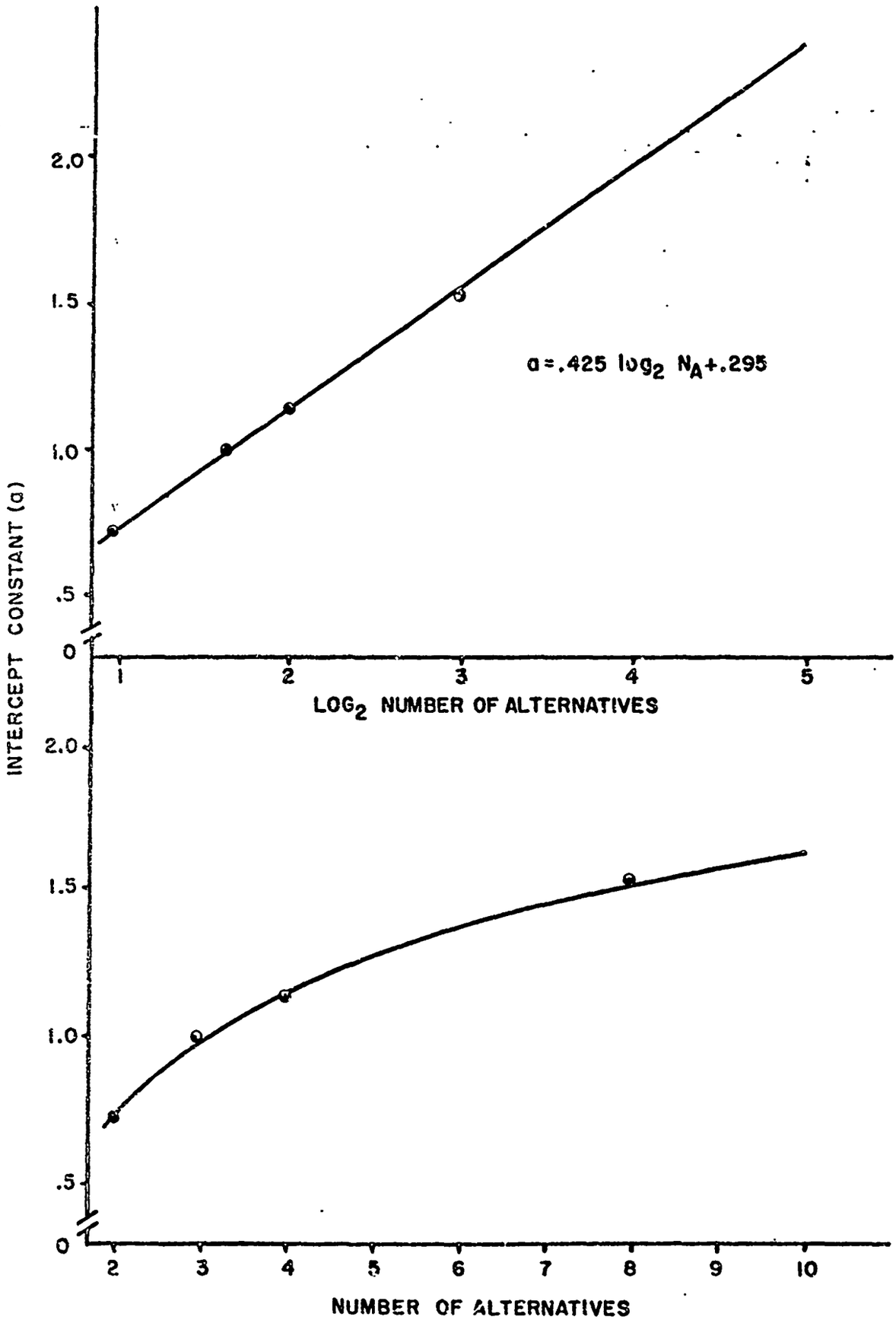

□ = Hale, 1967
■ = Hale, 1967
○ = Hale, 1968
⬡ = Hale, 1969
▽ = Christ, 1970
▼ = Rabbitt, 1967
● = Brainard, et al., 1962
△ = Kulp & Alluisi, 1967
▲ = Bertelson & Boons, 1960
REACTION TIME (Sec.)
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
8
4
3
2
1
2
3
4
5
6
LOG10 NUMBER OF TRIALS

13-F

FIGURE 3

Intercept constants (a) of Equations 3a - 3d as a function of N_A and of $\log_2 N_A$ for the digit-key task.

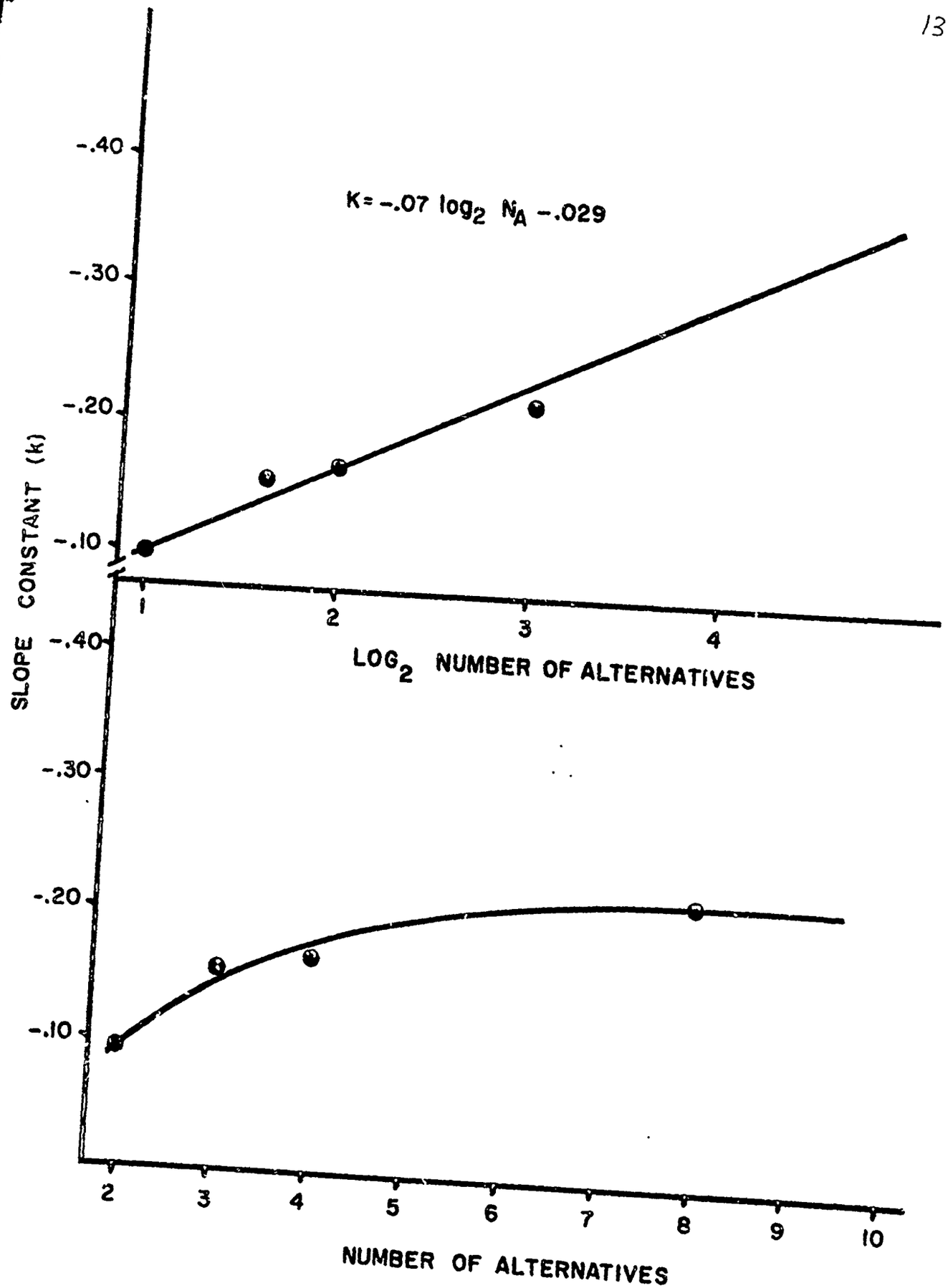
13-G


INTERCEPT CONSTANT (a)
2.0
1.5
1.0
.5
0
a=.425 log2 NA+.295
1
2
3
4
5
LOG2 NUMBER OF ALTERNATIVES
2.0
1.5
1.0
.5
0
2
3
4
5
6
7
8
9
10
NUMBER OF ALTERNATIVES

13-H

FIGURE 4

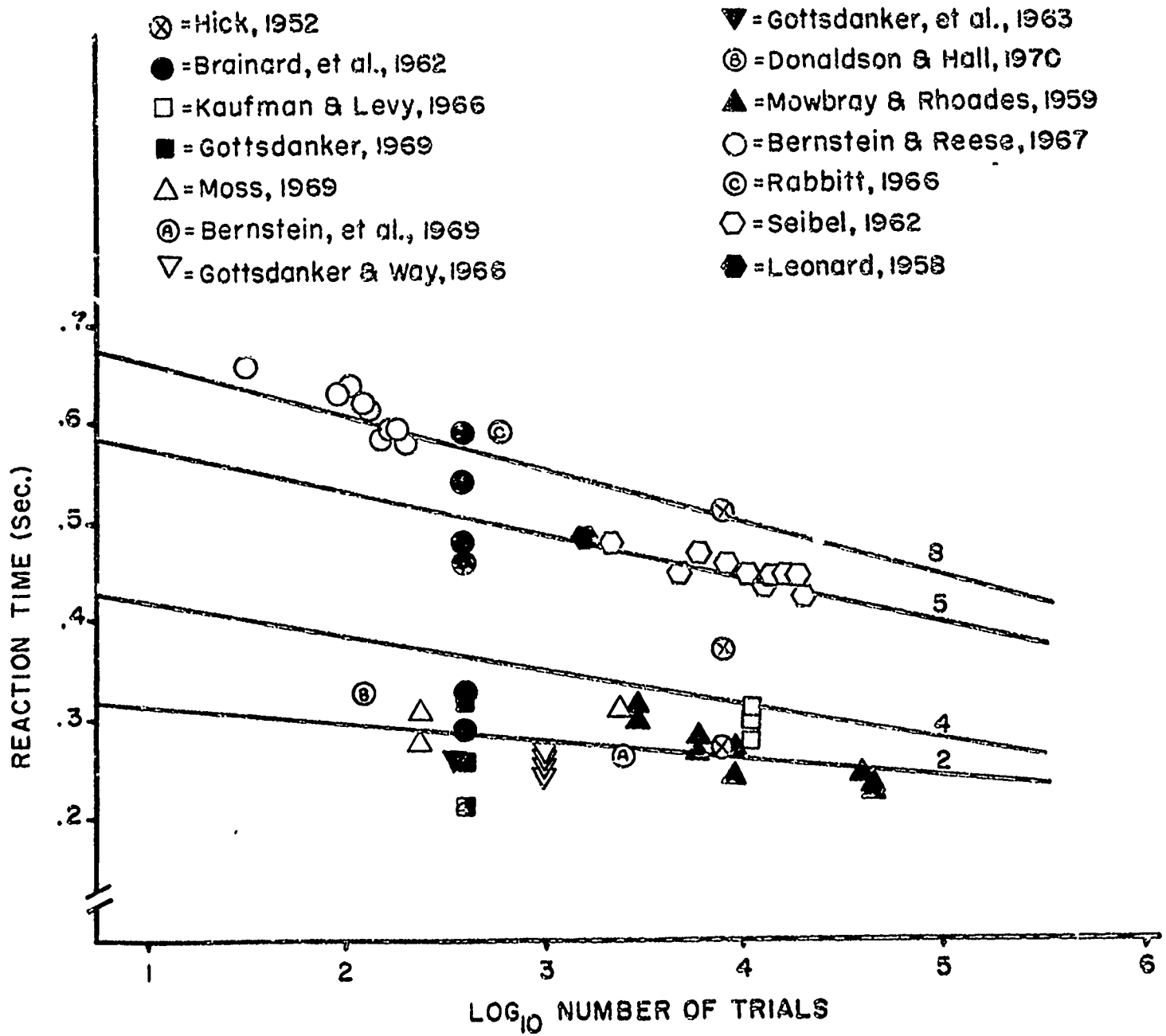
Slope constants (k) of Equations 3a - 3d as a function of N_A and of $\log_2 N_A$ for the digit-key task.


K= -.07 log2 NA -.029
-.40
-.30
-.20
-.10
SLOPE CONSTANT (k)
1
2
3
4
LOG2 NUMBER OF ALTERNATIVES
-.40
-.30
-.20
-.10
2
3
4
5
6
7
8
9
10
NUMBER OF ALTERNATIVES

13-J

FIGURE 5

Choice reaction time as a function of practice for the light-key task. The parameter is the number of equiprobable alternatives.


⊗ = Hick, 1952
● = Brainard, et al., 1962
□ = Kaufman & Levy, 1966
■ = Gottsdanker, 1969
△ = Moss, 1969
Ⓐ = Bernstein, et al., 1969
▽ = Gottsdanker & Way, 1966
▼ = Gottsdanker, et al., 1963
Ⓑ = Donaldson & Hall, 1970
▲ = Mowbray & Rhoades, 1959
○ = Bernstein & Reese, 1967
Ⓒ = Rabbitt, 1966
⬡ = Seibel, 1962
⬢ = Leonard, 1958
REACTION TIME (Sec.)
.7
.6
.5
.4
.3
.2
8
5
4
2
1
2
3
4
5
6
LOG10 NUMBER OF TRIALS

amount provided for a trend which also accounted for the data point from Leonard (1958). Other than this, all other data in this and all other figures are as originally reported.

Comparison of Figure 5 with Figure 2 shows that the slopes of Figure 5 are less steep. This is consistent with the expectation of a lesser practice effect for this combination. On the other hand, although performance is better with the light-key over most of the trials range, extrapolation shows that there will be a reversal of the CRTs of the two combinations before they reach their common limit.

The equations for the light-key lines of Figure 5 are:

$$N_A = 2,\ CRT = -.018 \log_{10} N_T + .335 \quad (3e)$$

$$N_A = 4,\ CRT = -.035 \log_{10} N_T + .460 \quad (3f)$$

$$N_A = 5,\ CRT = -.042 \log_{10} N_T + .620 \quad (3g)$$

$$N_A = 8,\ CRT = -.050 \log_{10} N_T + .720 \quad (3h)$$

Plots of a and of K each vs N_A are presented in Figures 6 and 7. A major difference between these plots and Figures 3 and 4 is that the constant, a, appears to be linear with N_A. The most divergent point is that which is weighted heavily by Seibel's data, however. Duplicating our previous analysis, the equation for the intercept constant is:

$$a = .19 \log_2 N_A + .14 \quad (6)$$

and for the slope constant

$$K = -.017 \log_2 N_A - .001 \quad (7)$$

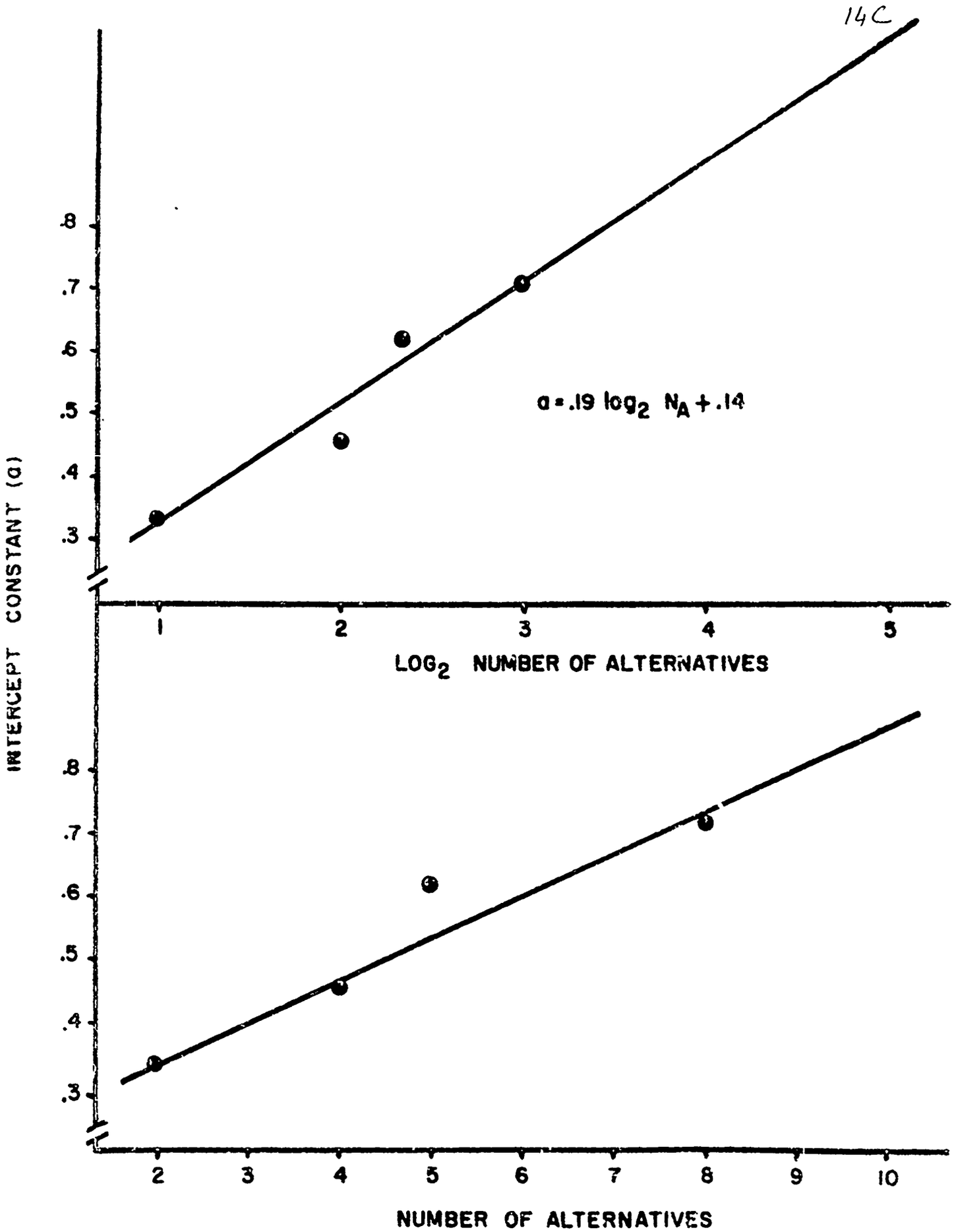
According to Equation 3, when $N_T = 1$, the simple reaction time for this combination is .14 and when $N_T = 100{,}000$, RT =.135. The effect of practice in this case is negligible. Further, .14 second is roughly the minimal possible simple visual reaction time to a light. It is also appreciably lower than that predicted for the digit-key task at lower practice levels. In fact, the simple reaction time would not be expected to be much affected by practice (Teichner, 1954) except, perhaps, in a context in which the signal contained more than sensory attributes in which case the response criterion would be high (Grice, 1968; Teichner and Krebs, 1972).

Figure 8 provides a family of theoretical curves relating CRT for the digit-key combination to N_A with N_T as a parameter. The figure may be derived with the use of Equations 3, 4, and 5 or by reading values from Figure 2. Figure 8 shows, as noted above, that with sufficient practice, CRT should be independent of N_A, at least within the range of N_A used. According to the

FIGURE 6

Intercept constants (a) of Equations 3e - 3h as a function of N_A and $\log_2 N_A$ for the light-key task.

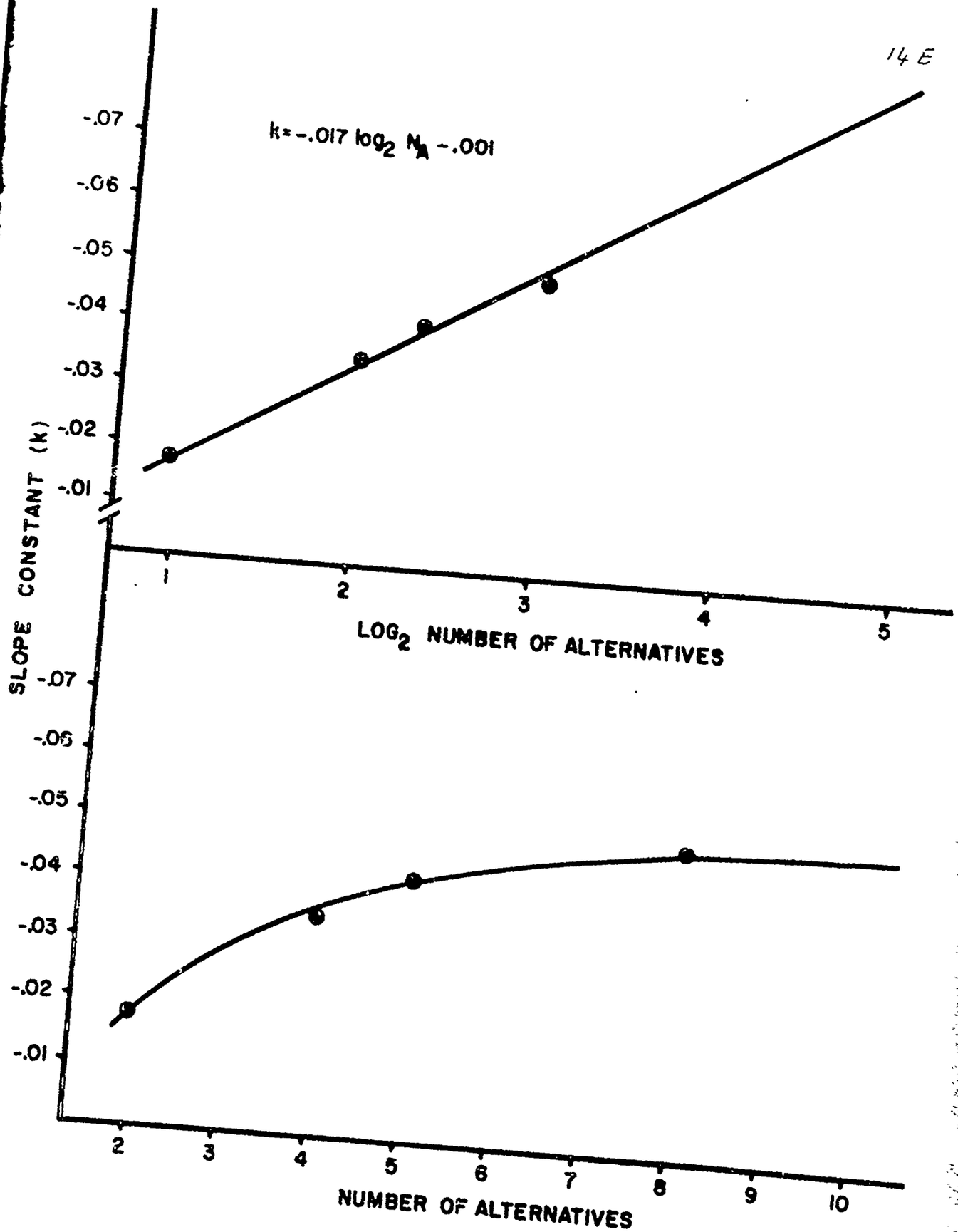
14C


INTERCEPT CONSTANT (a)
.8
.7
.6
.5
.4
.3
a = .19 log2 NA + .14
1
2
3
4
5
LOG2 NUMBER OF ALTERNATIVES
.8
.7
.6
.5
.4
.3
2
3
4
5
6
7
8
9
10
NUMBER OF ALTERNATIVES

14D

FIGURE 7

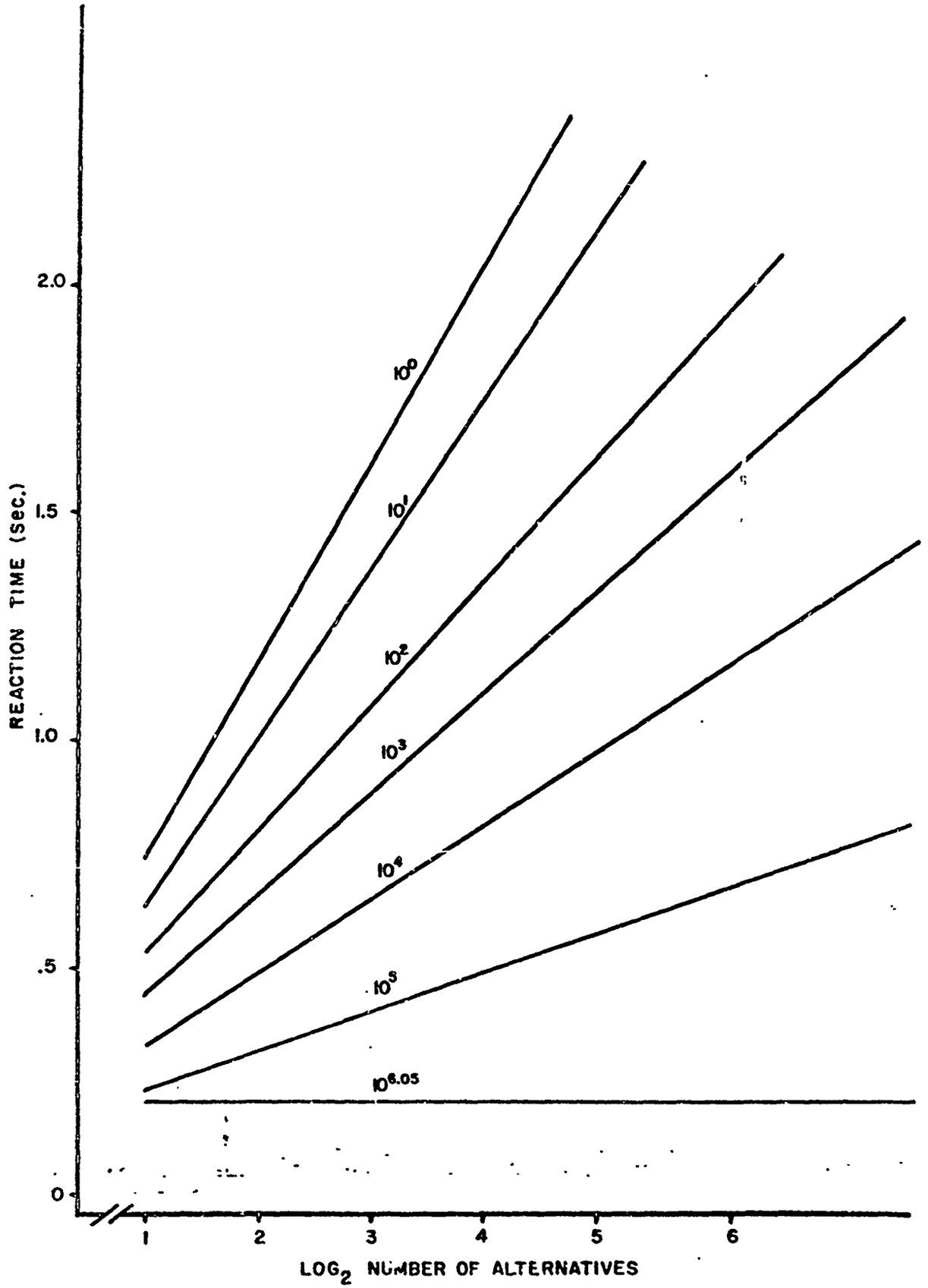
Slope constants (k) of Equations 3e - 3h as a function of N_A and $\log_2 N_A$ for the light-key task.


k = -.017 log2 NA -.001
-.07
-.06
-.05
-.04
-.03
-.02
-.01
SLOPE CONSTANT (k)
1
2
3
4
5
LOG2 NUMBER OF ALTERNATIVES
-.07
-.06
-.05
-.04
-.03
-.02
-.01
2
3
4
5
6
7
8
9
10
NUMBER OF ALTERNATIVES

14F

FIGURE 8

Derived choice reaction time for the digit-key task as a function of the number of equiprobable alternatives with the number of practice trials as a parameter.


REACTION TIME (Sec.)
2.0
1.5
1.0
.5
0
10^0
10^1
10^2
10^3
10^4
10^5
$10^{6.05}$
1
2
3
4
5
6
LOG$_2$ NUMBER OF ALTERNATIVES

figure, for this S-R combination, that point would be reached in over one million trials. While this may seem unreasonable at first, especially since Mowbray and Rhoades (1959) achieved it in 45,000 trials with the light-key combination, it should be borne in mind that the prediction is based upon an arbitrarily-selected limit of .20 second and that a different S-R relationship is involved.

Much of the current theoretical approach to CRT is based upon the early efforts of Hick. Hick (1952) varied N_A using a light-key combination and approximately 8,000 practice trials. Since Hick's (1952) data were not used to develop any of the above formulations, it is appropriate to evaluate the differences between them and his results. This is done in Figure 9, which presents CRT as a function of $\log_2 N_A$. The line in the figure was calculated with Equations 3, 6, and 7 setting $N_T = 8{,}000$. The maximum deviation of any point from the line is .03 second. Considering the possible errors to which the equations are liable, and that Hick's data are from one subject, the result is probably incredibly good luck. On the other hand, it supports and encourages the general approach.

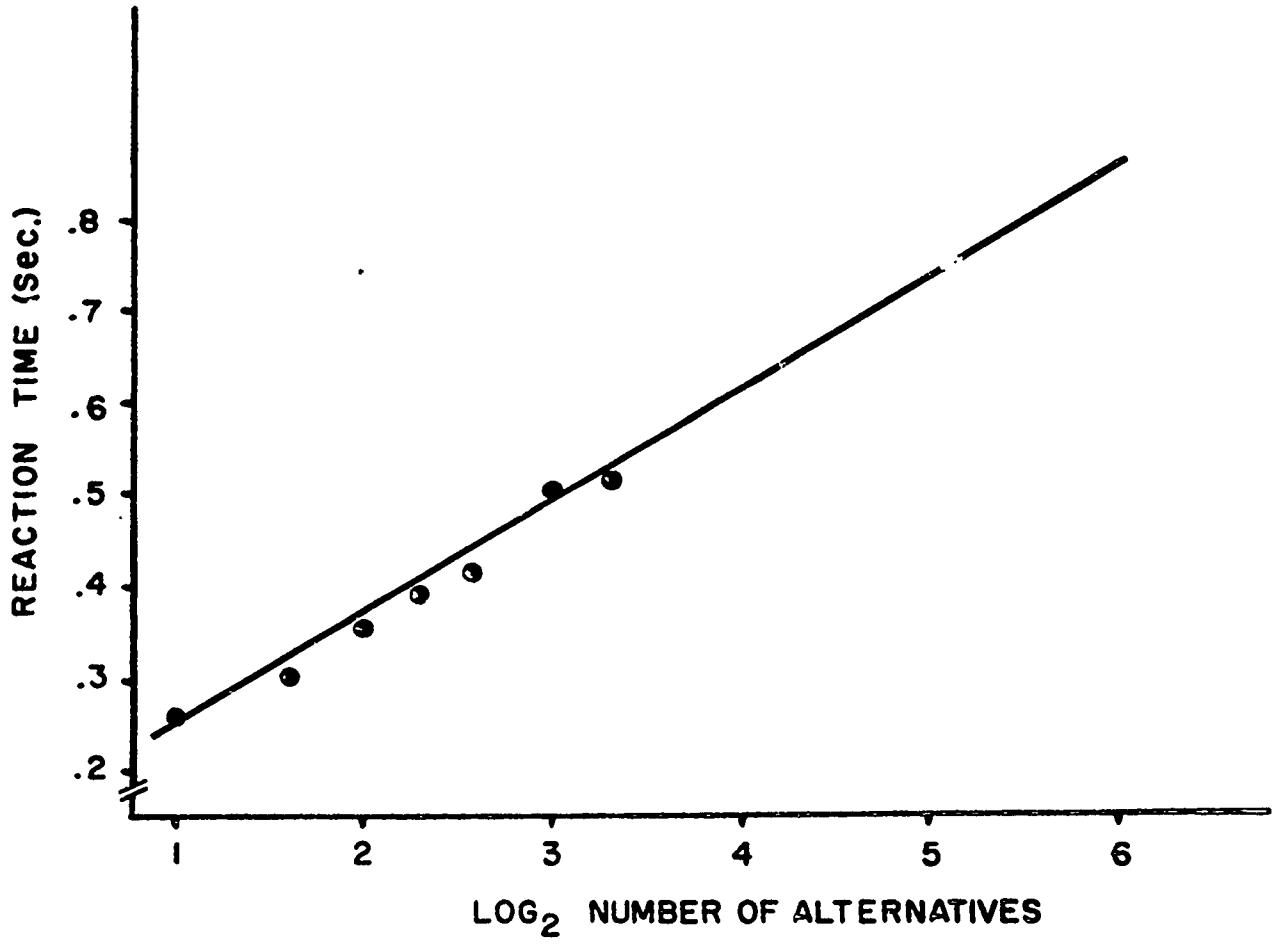
We were able to evaluate the effects of signal probability only for a constant $N_A = 2$, and then only to a limited degree. Figure 10 shows this attempt. As can be seen, the difficulty lies with the large differences in S-R combinations used and the differences in N_T. Primarily the data report again the importance of practice and S-R combination. The smooth lines, drawn by eye, are of significance only in showing that in every study, CRT decreased with increasing stimulus probability. Accordingly, CRT should be a function of amount of information for unequal probability alternatives as well as for equal probability ones as already shown. The results of Hyman (1953), Lamb and Kaufman (1965) and Kaufman, Lamb, and Walter (1970) support that expectation, but due to the confoundings noted in Figure 10, we were not able to test it.

The range of change of CRT within every study of Figure 10 is small, especially as compared to the changes associated with changes in N_A. Thus, even though it may be possible to express the function in uncertainty terms, until more definitive data are available, it would seem wisest to do that only for equiprobable signal sources which differ in N_A. The probability question needs further investigation in this regard, although in general, the signal probability effect looks small.

15B

FIGURE 9

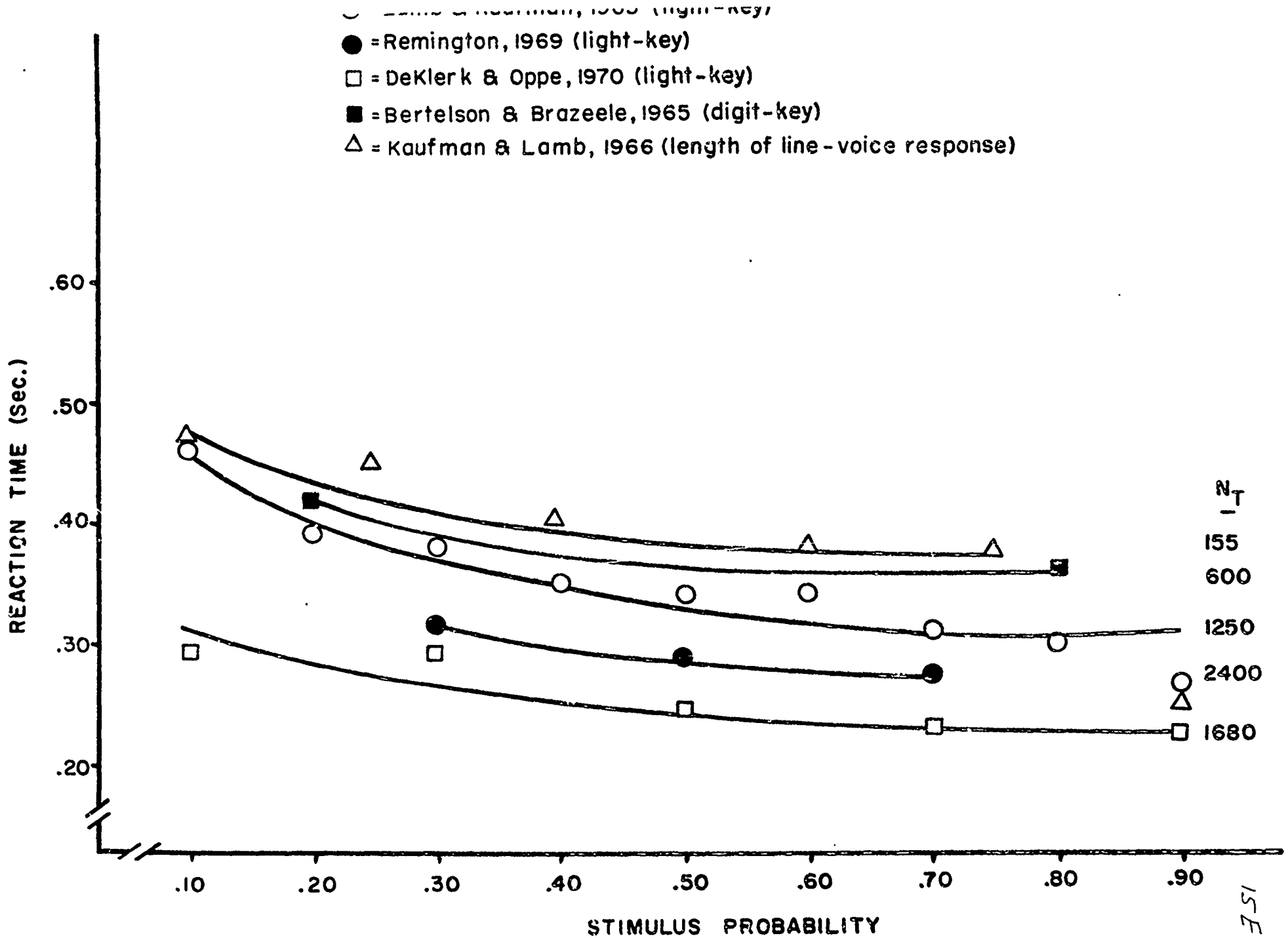
Choice reaction time vs number of equiprobable alternatives for the light-key task after 8000 trials. Data from Hick (1952); line calculated with Equations 3, 6 and 7.


REACTION TIME (Sec.)
.8
.7
.6
.5
.4
.3
.2
1
2
3
4
5
6
LOG2 NUMBER OF ALTERNATIVES

15D

FIGURE 10

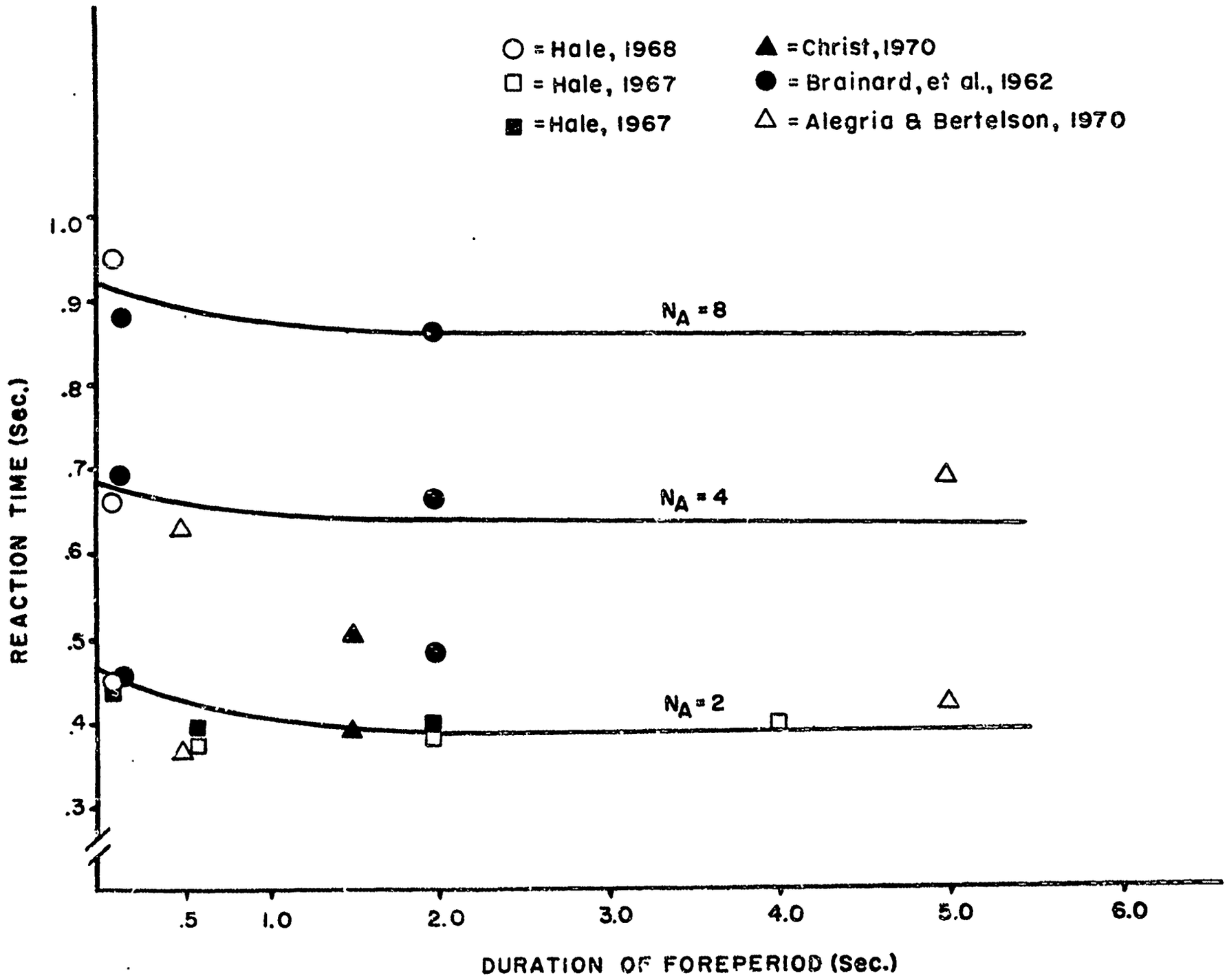
Choice reaction time as a function of stimulus probability for the two-choice case with varying S-R task combinations. The number of trials employed is indicated as N_T.


= Remington, 1969 (light-key)
= DeKlerk & Oppe, 1970 (light-key)
= Bertelson & Brazeele, 1965 (digit-key)
= Kaufman & Lamb, 1966 (length of line-voice response)
REACTION TIME (Sec.)
.60
.50
.40
.30
.20
.10
.20
.30
.40
.50
.60
.70
.80
.90
STIMULUS PROBABILITY
N_T
155
600
1250
2400
1680

15 F

FIGURE 11

Choice reaction time related to foreperiod duration for the digit-key task.


○ = Hale, 1968
□ = Hale, 1967
■ = Hale, 1967
▲ = Christ, 1970
● = Brainard, et al., 1962
△ = Alegria & Bertelson, 1970
$N_A = 8$
$N_A = 4$
$N_A = 2$
REACTION TIME (Sec.)
1.0
.9
.8
.7
.6
.5
.4
.3
.5
1.0
2.0
3.0
4.0
5.0
6.0
DURATION OF FOREPERIOD (Sec.)

So far we have discussed signal uncertainty in relation to N_A and to signal probability. Hick's law (Equation 1) attempts to deal with temporal uncertainty. Such uncertainty is introduced into the CPT experiment via the foreperiod, i.e., the time between a warning signal and the critical stimulus. Figure 11 is a plot of the effects of foreperiod duration at different N_A for the digit-key combination. The data available are not extensive in number, but suggested trends indicate that the effects of foreperiod are very small and complete in less than one second. Figure 12 is a similar plot for the light-key arrangement. Any possible effect is even harder to discern in this case. We conclude that temporal uncertainty is not an important consideration and that the need for Hick's correction is not supported. The model represented by Equations 2 and 3 is to be preferred, therefore, since it allows for an independent determination of the slope and of the simple reaction time. Moreover, without the corrective constant, RT = 0 when N = 1 in Equation 1 and this is clearly untenable.

It will be recalled that the selective reaction type of experiment provides inequality between the number of signals and the number of responses. More recently such studies have been described as many-to-few mapping experiments. In the simpler case, the subject makes only one response and that to just the critical one of various stimuli that are presented. For example, he may respond only when he sees the numeral, 2, in a sequence of different digits. More complex arrangements require the same response(s) to more than one critical event.

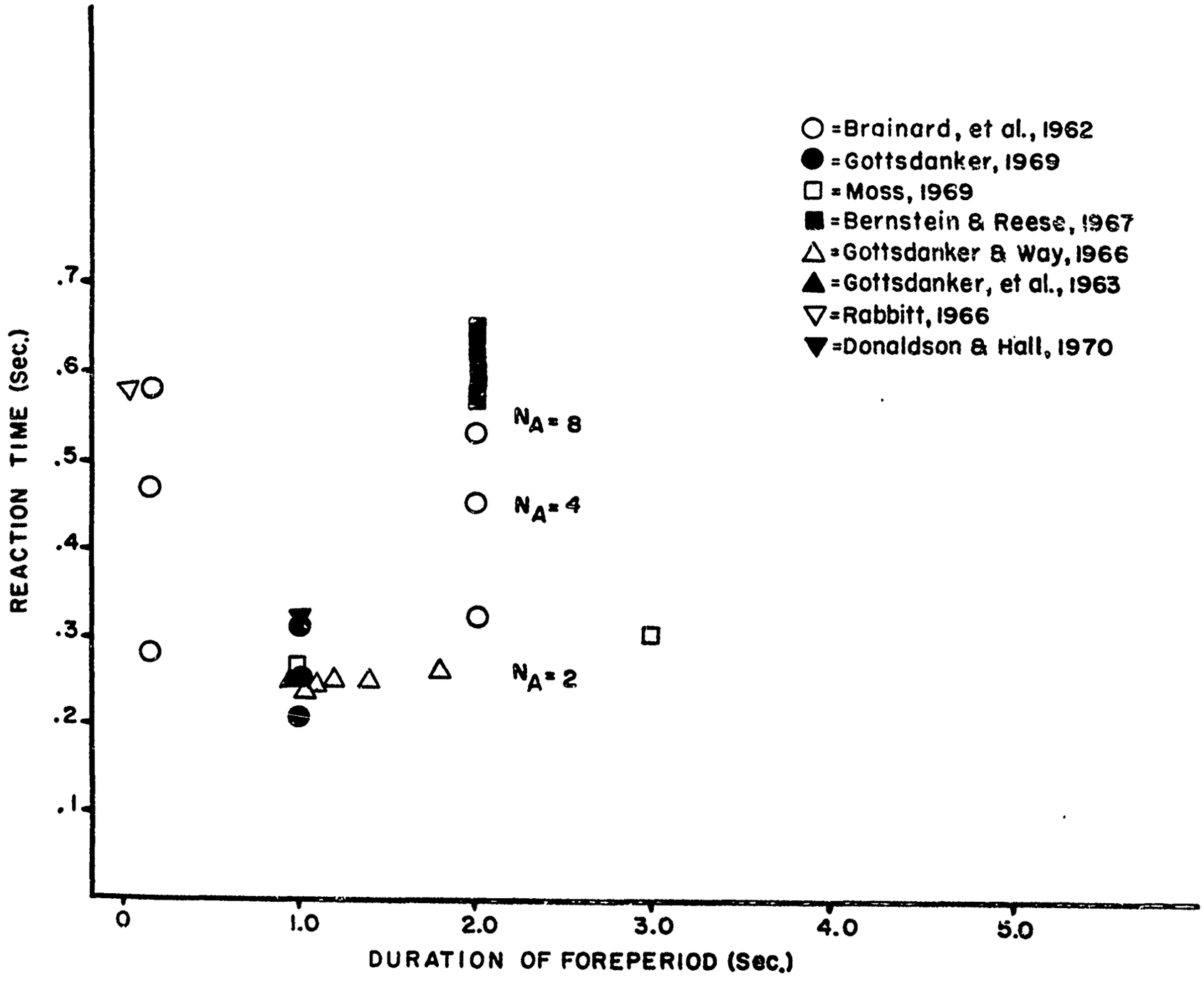
In certain ways this experimental arrangement is also a searching or monitoring task since the subject seeks the arrival of a critical event. It differs from the choice reaction paradigm not only in not having one-to-one mapping, but in that not every stimulus event is associated with a CRT. Thus, sequences of events may contain important experimental variables all of which are hard to define in terms of practice trials. This is particularly true of the many-to-few experiments. Unfortunately, the sequences that have been reported in the literature were too varied for us to put them all into any consistent framework.

We were able to find four studies of the many-to-one type which we could describe as generally similar in practice level and S-R combinations and to relate their data to the probability of the critical signal. That result is shown in Figure 13 where it may be seen that, as with the choice reaction,

16B

FIGURE 12

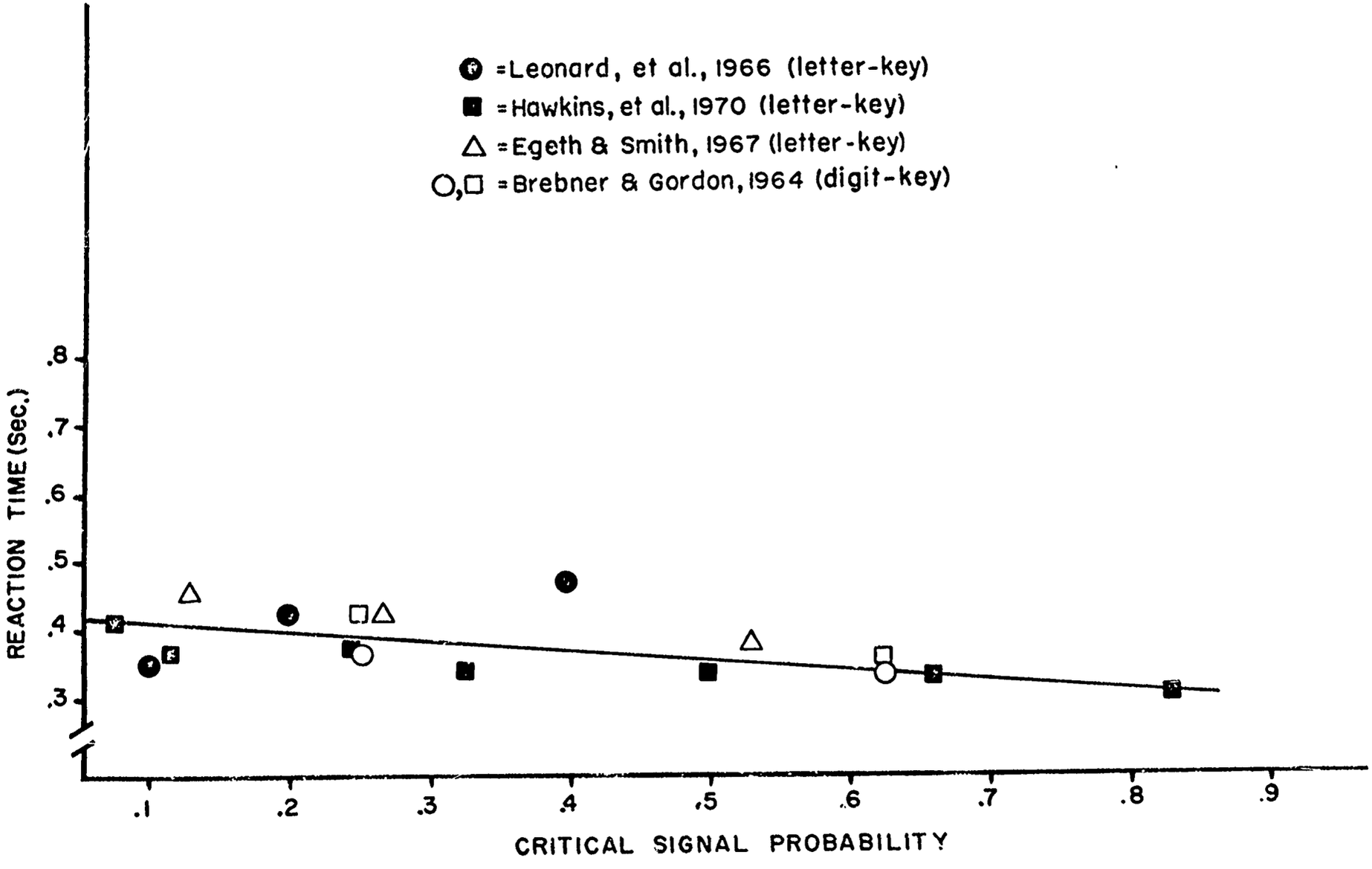
Choice reaction time realted to foreperiod duration for the light-key task.


○ =Brainard, et al., 1962
● =Gottsdanker, 1969
□ =Moss, 1969
■ =Bernstein & Reese, 1967
△ =Gottsdanker & Way, 1966
▲ =Gottsdanker, et al., 1963
▽ =Rabbitt, 1966
▼ =Donaldson & Hall, 1970
$N_A = 8$
$N_A = 4$
$N_A = 2$
REACTION TIME (Sec.)
.7
.6
.5
.4
.3
.2
.1
0
1.0
2.0
3.0
4.0
5.0
DURATION OF FOREPERIOD (Sec.)

16D

FIGURE 13

Choice reaction time for different selective reaction tasks as a function of the probability of the critical signal.


● =Leonard, et al., 1966 (letter-key)
■ =Hawkins, et al., 1970 (letter-key)
△ =Egeth & Smith, 1967 (letter-key)
○,□ =Brebner & Gordon, 1964 (digit-key)
REACTION TIME (Sec.)
.8
.7
.6
.5
.4
.3
.1
.2
.3
.4
.5
.6
.7
.8
.9
CRITICAL SIGNAL PROBABILITY

signal probability has a consistent, but very small effect. The difference in trend may or may not be significant. It should be noted that the figure represents a relatively low practice level. Our impression of the results of individual studies of this sort is that the effects of practice appear much less systematic than those shown above. For this reason we wonder again if this type of experiment belongs in the CRT category or whether it is not more appropriate to think of it as a searching or scanning study. Welford (1968) has also noted the similarity between this experimental paradigm and scanning. It is interesting that if it does belong more properly in that class of study, the relationships involved can be described nicely in information-theoretic terms (Teichner and Krebs, 1972-a).

ON DONDER'S LAW

Donders's law states that

$$CRT = a + b + c \qquad (8)$$

where a is the simple reaction time, a constant

b is the time required for stimulus categorization

c is the time required for response selection

and the order of events is in the sequence indicated. If an S-R translational stage were required, as proposed by Welford (1960), it would be intermediate between the b- and c-components.

Comparing the digit-key and the light-key tasks in these terms, it is apparent for any $N_A \geq 2$ that the two tasks are equal in regard to response selection. Thus, c in Equation 8 is not a variable to take into account in this comparison. What must be invoked to account for different effects of the tasks on CRT are differences in stimulus processing, i.e., stimulus categorizing or coding, and translation. In the digit-key case, the stimuli are presented in a numeric code. They must then be translated to a position code. It is as if the subject sees a stimulus, names it, and then translates the number named to its corresponding response key position. On the other hand, no translational activity appears to be involved in the light-key case since the only possible names that can be given to the lights as stimuli are those for the response position code. Little categorization is involved; nor is there any translation to perform. Presumably, improvements with practice represent improvements in response selection, and only to a very small extent do they represent changes in stimulus processing. Those same response selection improvements must also be present in the digit-key task. It seems, there-

fore, that the digit-key task has a larger CRT because it requires both a stimulus coding and a translational stage, whereas the light-key task requires only stimulus coding.

Donders assumed that no stimulus coding is involved in the a-component, that RT is a constant. Yet, at least a coding of energy levels is implied by recent response criterion models of simple reaction time (Grice, 1968; Teichner and Krebs, 1972). Furthermore, Grice has shown within the context of the model that learning and other factors influence the response criterion and, consequently, RT. It may be, therefore, that the a-component in Donders's law is not constant, and that it includes some of the time required for stimulus coding. If so, the RT portions of CRT should be different for differently-coded stimuli. If they are not different, then Donders's assumption would appear to have been appropriate. To investigate this hypothesis, Equations 3, 4, 5, 6, and 7 were used to obtain estimates of RT, i.e., CRT at $N_A = 1$. Figure 14 presents plots of the two simple reaction times as a function of N_T.

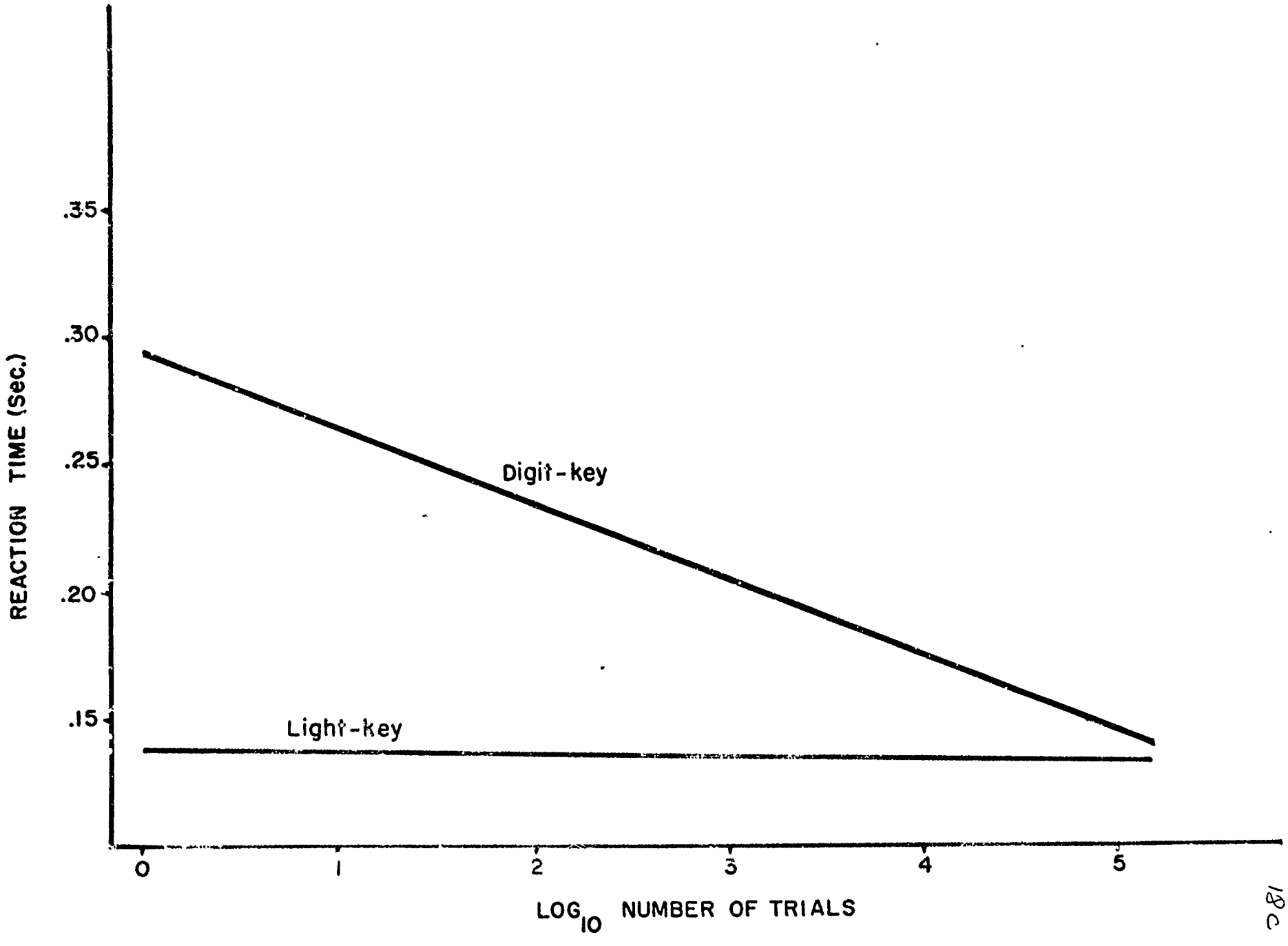
It is clear from Figure 14 that the slopes of the two functions are very different. As pointed out earlier, and shown here, the digit-key task depends importantly on practice, whereas the light-key task shows little or no practice effect. Figure 14 suggests that changes in RT with practice at the digit-key task account for a considerable amount of the CRT practice effect. If RT reflects a stimulus coding process, then Figure 14 also suggests almost no such activity for lights, but a fair amount of such activity with the digits. The implication for Donders's law is that the a-component is not a constant, but that it contains the sum of a constant (transmission lag) and a variable quantity which is the time used to code the stimulus. The coding activity may be part o the simple reaction time even though the subject has no need for it, i.e., even though all he is required to do is to respond to the stimulus as pure energy. Furthermore, the above result suggests that the duration of time required for the coding process depends on the nature of the code and on practice.

Situations are conceivable in which it is necessary to translate from one stimulus code to another. For example, colored lights are used as signals for automobile drivers. The color, itself, may be thought of as a primary code which is processed during the a-component, whereas "stop" associated with red may be thought of as a secondary stimulus code. Or, if

18B

FIGURE 14

Derived simple reaction time as a function of practice.


REACTION TIME (Sec.)
.35
.30
.25
.20
.15
Digit-key
Light-key
0
1
2
3
4
5
LOG10 NUMBER OF TRIALS

the signal is the word, stop, the letters may be thought of as primary and the word as a secondary code. Conceivably, a situation could have a sequence of stimulus codes each but the first of which requires a translation time as well as a coding time. A modification of Donders's law to incorporate this could include the first or primary coding in the a-component and could assign the other stimulus coding activities to the b-component. The translation between stimulus codes would also be expressed, as should be any requirement for a translation between stimulus and response codes, e.g., between numerals and spatial positions in the digit-key task. Finally, similar coding and translational activities may be involved on the response side in addition to response selection. We will not attempt to speculate on them, however.

With those considerations in mind, Donders's law may be re-formulated as follows:

$$CRT = a + b + T_{S-R} + c \qquad (9)$$

Where: $a = a_S + a_K = RT$; a_S is that portion of RT associated with primary stimulus encoding; a_K is a constant portion of RT required for neural transmission at a given stimulus energy level,

$b = b_S + T_{S-S}$; b_S is that time required for the use of stimulus codes which might follow a primary encoding; T_{S-S} is the time required for translations between stimulus codes,

T_{S-R} = time required to translate from the final stimulus code to the response code,

c = total time required for all activities associated with response selection.

If we evaluate the digit-key task in the terms of Equation 9, it would appear that numeral-naming is the only stimulus-coding activity required and the translation from that code to the position code used for response-identification is the only translational activity. Accordingly, if the first or primary stimulus-coding activity is part of the a-component, and if no other stimulus codes are involved, the digit-key task may be described as:

$$CRT = a + T_{S-R} + c \qquad (10)$$

Letting RT = a, and re-arranging,

$$T_{S-R} + c = CRT - RT \qquad (10\text{-a})$$

Consideration of the light-key task in the same terms indicates that the stimulus is coded by position as is the response. If there is a one-to-one relationship between the position codes, as is the case in all of the studies reported here, then there is no S-R translational activity. The only

activities are stimulus-coding and response-selection. Accordingly, for the light-key task,

$$CRT = a + c \tag{11}$$

and

$$c = CRT - RT \tag{11-a}$$

It follows that,

$$T_{S-R} = \text{(Equation 10-a)} - \text{(Equation 11-a)} \tag{12}$$

so that if RT can be estimated, the other components may be derived empirically from a comparison of digit-key and light-key performance as obtained from the choice reaction experiment rather than from the difference between the choice and selective reaction experiments as proposed by Donders.

It should also be noted that the light-key task with one-to-one S-R position coding is a compatible S-R arrangement, whereas the digit-key task has some degree of S-R incompatibility since a translation is required between stimulus and response codes. Consequently, we can define the degree of S-R incompatibility inherent in a task as the proportion of the CRT which is attributable to the S-R translation time, i.e., T_{S-R}/CRT. Thus, a method appears feasible for both the experimental manipulation of stimulus and response coding processes and for the practical evaluation of the degree of S-R incompatibility in a task by using the one-to-one light-key task as a reference situation and applying Equation 12. To achieve that empirically, would require simple RT experiments with which RT estimates may be obtained. Or for RT for single numerals or position-lights, the present formulation provides a theoretical estimate.

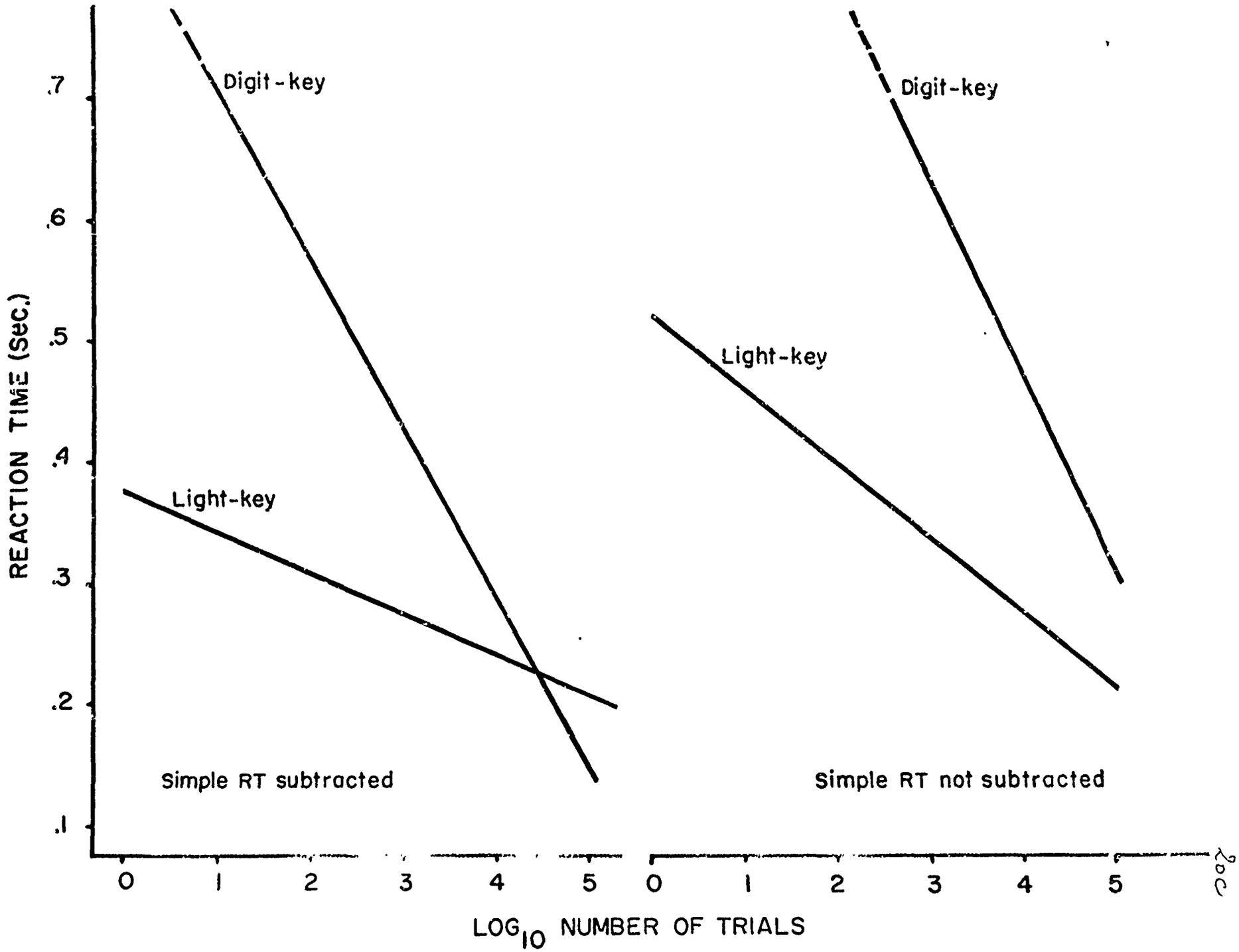
As an illustration, using $N_A = 4$, Equations 10-a and 11-a were developed with Equations 3-7. The results are shown in Figure 15. The left-hand side of the figure shows RT subtracted from CRT for each task: on the right-hand side they are not subtracted. According to Equations 10-a and 11-a, the left side of the figure represents response selection in terms of the light-key line and response selection plus S-R translation time in terms of the digit-key line. Both sides are plotted as a function of practice trials.

Figure 15 shows that with the a-component removed, the two CRTs are closer and, in fact, equal with sufficient practice. We assume a discontinuity after the lines meet, i.e., that all other components of CRT remain constant at that intersection value. The figure also shows that there is a greater gain in the translational speed from practice than in that associated with response selection since on the left side of the figure the initial

20B

FIGURE 15

Derived choice reaction time as a function of practice for $N_A = 4$ with and without substraction of derived simple reaction time.


REACTION TIME (Sec.)
.7
.6
.5
.4
.3
.2
.1
Digit-key
Light-key
Simple RT subtracted
Digit-key
Light-key
Simple RT not subtracted
0
1
2
3
4
5
0
1
2
3
4
5
LOG10 NUMBER OF TRIALS

20c

difference between the two tasks is large and then the digit-key practice curve drops faster.

Figure 16 is a plot of T_{S-R} obtained for $N_A = 4$ by subtracting as indicated in Equation 12. It may be seen that this translational activity represents an important part of CRT and that the time required for it decreases with practice. To evaluate its relative importance and that of the other components, each was determined as a percentage of the total digit-key CRT at different levels of practice. The percentage of the CRT due to translation of the numeric code to the position code (T_{S-P}) was obtained by dividing T_{S-R} as of Equation 12 by the digit-key CRT. The percentage due to the a-component was obtained as RT/CRT for the digit-key task.

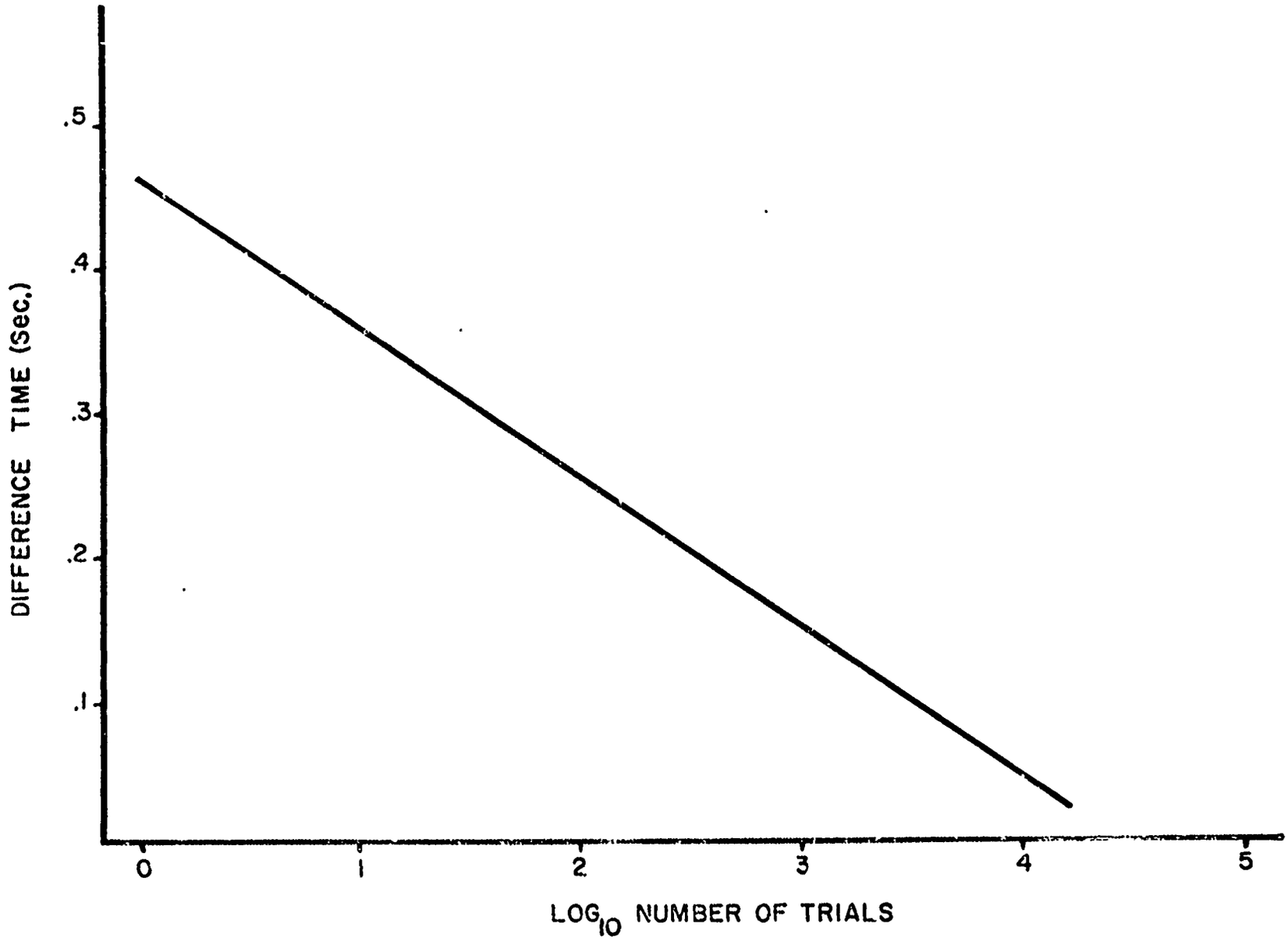
For the illustration we have assumed arbitrarily that $a_K = .1$ second and subtracted that constant from RT to obtain a_S. We were then able to calculate the percentage that each of the variable components is of CRT at different levels of practice. These results are shown along with % RT in Figure 17. The quantity, % a_K, is represented by the difference between the curves for % a-component and % a_S.

Figure 17 shows that the most important of the three isolated variable processes is that due to response selection factors. Except for the initial portion of practice, this component accounts for more of the total CRT than any other and its relative importance increases in a positively accelerated manner as practice continues. At the same time the translational activity starts as the most important component, but loses importance over the trial series so that by about 56,000 trials it is no longer a factor. It can also be seen that the effect of subtracting the constant from RT was to produce an essentially horizontal line. The values of the residual stimulus coding component ranged from 17.0 per cent at $\log_{10} N_T = 0$ to 16.7 per cent at $\log_{10} N_T = 5$. Thus, for the code involved, stimulus coding, as defined, is theoretically the least important factor, without extensive practice, and, although the absolute coding time decreases with practice, as described above, its relative contribution does not change. This seems quite reasonable for digit-naming in the adult population.

We recognize that the results presented rest upon a variety of assumptions. On the other hand, they are derived from the data available and they appear to make sense. Accordingly, we propose that Donders's law be modified in the manner described by Equation 9 and that estimates of stimulus categori-

FIGURE 16

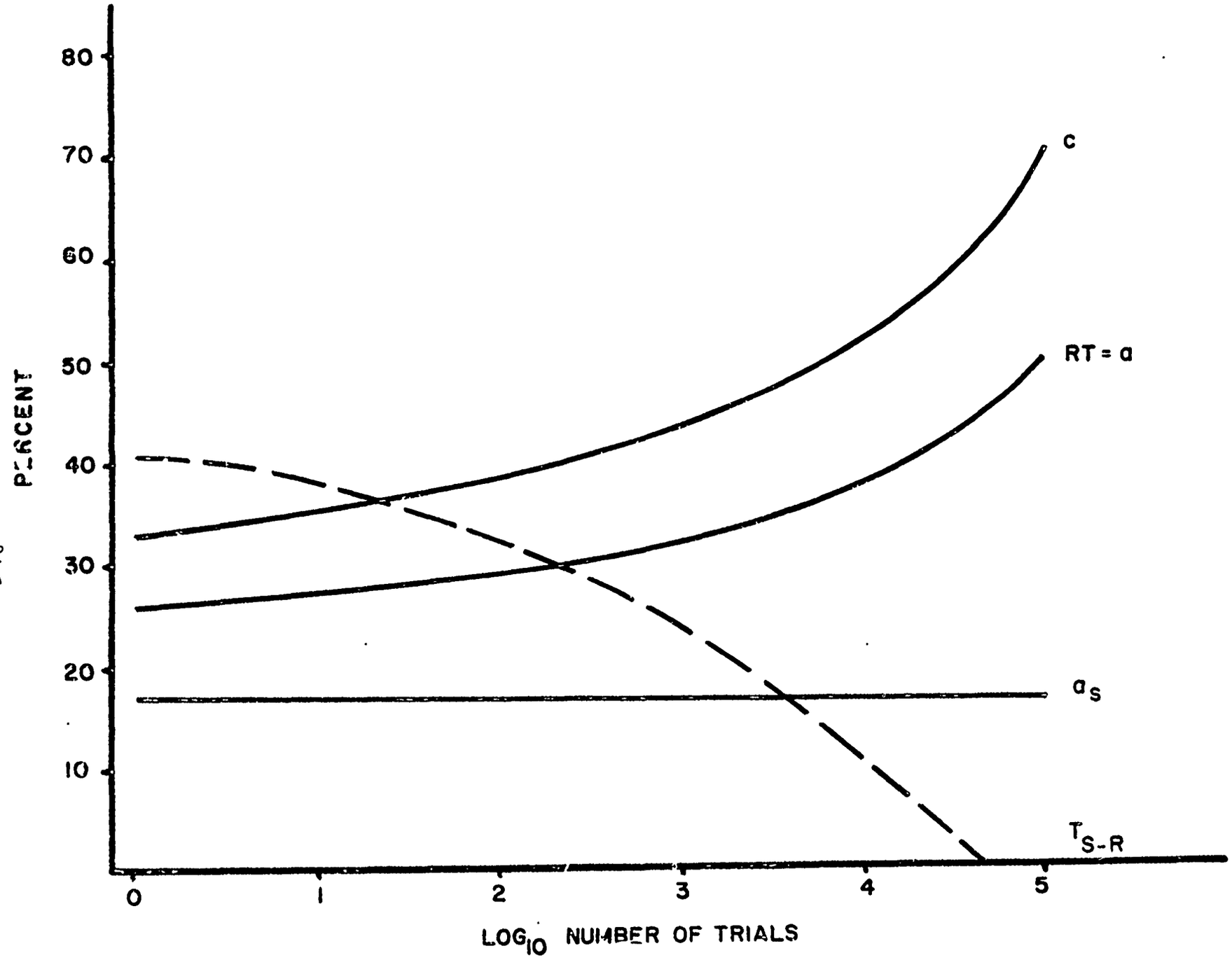
Theoretical S-R translation time for the digit-key task as a function of practice; $N_A = 4$.



21c

FIGURE 17

Theoretical percentage of CRT component times for the digit-key task related to practice; $N_A = 4$.


80
70
60
50
40
30
20
10
PERCENT
c
RT = a
a_S
T_{S-R}
0
1
2
3
4
5
LOG_{10} NUMBER OF TRIALS

zation be obtained from subtractions across experiments having different S-R compatibility arrangements rather than in the manner proposed by Donders. Using the suggested approach appears to provide an experimental method for investigating the stimulus encoding and translational processes. Those processes may often be considerably more important than suggested by the present analysis which was based on highly familiar, simple codes.

SUMMARY DISCUSSION

In terms of their influence on CRT, the three most important variables appear to be: level of practice (N_T), number of different possible S-R pairs (N_A), and the particular S-R combination used. These variables operate jointly. Thus, while practice serves to reduce the slope of the curve relating CRT to N_A, the slope itself is dependent on the S-R code.

It was found that the light-key condition produced faster CRTs at all levels of practice studied and also a smaller slope across N_A as compared to the digit-key combination. The consistent superiority of the light-key task might be attributed to intensive differences between the two stimuli as used experimentally. There is some indication in the literature (Brainard, Irby, Fitts and Alluisi, 1962) that the luminance of the light in the light-key task has been greater than that of the digit in the digit-key task. However, this would not account for the superiority of the digit-voice task over the light-voice task. It seems more reasonable to relate the differences produced by different tasks to differences in coding and translation requirements.

The smaller slope observed for the light-key task has been hypothesized to be the result of a minimal translation process or stage (Fitts, 1964; Welford, 1968). In effect, the response set is a simple extension of the stimulus set since the position code for each is in direct correspondence. It was suggested that such a task might eventually be performed as a multiple series of simple RT tasks carried out in parallel. The digit-key task, on the other hand, requires translation from a numeric code to a position code. While the numeric code may be well-learned through pre-laboratory experience, the translation to an appropriate response is a process which must be learned in the experimental setting. The relationship is not as direct as in the light-key task.

Where, then, does practice exert its major effect on the CRT? In the comparison of the digit-key vs the light-key tasks, our analysis suggests

that the most important effect of practice is on the S-R translation stage since that process appears to be the one which shows a decreasing importance to the CRT with increasing practice. This is not to say that stimulus coding and response selection are not importantly affected by practice, because we have shown that they are, but that the relatively greatest practice effect is on the translation stage. In fact, as a consequence, it is response selection which becomes relatively the most inportant process determining CRT after practice. This gain in importance is initiated in about 25 trials in the digit-key task. From that point it continues to increase as the subject attains further performance experience. This is a particularly interesting result in light of the relatively small amount of research attention that has been given to the process of response selection as compared to that of stimulus information processing. On the other hand, stimulus processing may have a much greater significance in more complex situations than those considered here. If so, the level, and perhaps the slope, of the a-component of Figure 17 might be different, and the number of trials to an intersection of T_{S-R} and c in Figure 17 might be considerably greater. Nevertheless, the results suggest that ultimately the factors of greatest relative importance in a decision-making situation will be those which determine which response is selected and not those associated with coding and translational activities.

If our treatment of Donders's law, and our proposed comparisons between tasks having different stimulus codes and translational activities are acceptable, an experimental method is implied for the study of the stimulus encoding process. That is, a systematic comparison of different S-R task combinations in the CRT experiment may provide a methodological approach to the problem.

The results also suggest that Hick's law holds to the extent that CRT is a linear function of the amount of stimulus information for equiprobable alternatives. The law holds without Hick's corrective factor, and in the form proposed by Hyman and others. The law holds, however, only up to some limited amount of practice after which CRT is independent of N_A, at least for $N_A \leq 10$.

Finally, the results suggest that stimulus categorization or coding takes place during the a-component, or simple RT, portion of CRT. This is accountable in terms of a response criterion model. It is not consistent with Donders's law as originally proposed, and as used since. As a result we have proposed revisions of the law.

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