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INFORMATION CAPACITY OF DISCRETE MOTOR RESPONSES¹

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The effects of response amplitude and terminal accuracy on 2-choice reaction time (RT) and on movement time (MT) were studied. Both the required amplitude (A) of a movement, and the width (W) of the target that S was required to hit, had a large and systematic effect on MT, whereas they had a relatively small effect on RT. Defining an index of movement difficulty as $ID = \log_2 2A/W$, the correlation between ID and MT was found to be above .99 over the ID range from 2.6 to 7.6 bits per response. Thus the times for discrete movements follow the same type of law as was found earlier to hold for serial responses. The relative independence of RT and MT is interpreted as pointing to the serial and independent nature of perceptual and motor processes.

The relation of response variability and response magnitude has long been one of the major topics of interest in psychophysics. Recently the effects of these two variables plus that of response duration have received renewed emphasis in connection with studies of the information capacity of the human motor system.

For physical communication systems having limited bandwidth (W) and signal power (S), and perturbed by white Gaussian noise of average power (N), Shannon (1948, Theorem

17) showed that channel capacity (C) is equal to

$$C = W \log_2 \frac{S + N}{N}$$

bits per second [1]

Arguing by analogy, Fitts (1954) reasoned that the average amplitude (A) of a human movement is equivalent to average signal plus noise amplitude, and that half the range of movement variability is equivalent to peak noise amplitude (n), and proposed that an index of task difficulty (ID) be defined as

$$ID = \log_2 \frac{A}{n} \quad [2]$$

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In an experiment in which the per-

missible plus-and-minus range of terminal movement error is specified as a target band of width (W), and S is induced to keep the proportion of his responses exceeding this limit small, it can be assumed further that $n = W/2$ and therefore ID can be evaluated as

$$ID = \log_2 \frac{2A}{W} \quad [3]$$

On these grounds it was conjectured that average movement time (MT) should remain constant for different values of A and W , within limits, as long as the ID ratio remains constant, i.e.,

$$\frac{ID}{MT} = C \quad [4]$$

where C may be interpreted as analogous to man's capacity for executing a particular class of motor responses in bits per second.³ Extending the analogy to the case where ID takes on different values, then if motor processes follow the same type of law as do perceptual-motor processes, it would be expected that, within limits,

$$MT = a + b ID \quad [5]$$

Fitts (1954) obtained results in agreement with these predictions, using three different self-paced, cyclical tasks. Performance was maximum for a midrange of values of A , W , and ID and fell off gradually outside these values (optimum performance being obtained in the vicinity of $A = 8$ in. and $ID = 4-8$ bits, depending on the particular task). Subsequent investigators (Annett, Golby, & Kay, 1958; Crossman, 1960; Welford, 1958) have, with minor exceptions,

³ The analogy with Shannon's Theorem 17 is not exact, since the ID ratio involves an amplitude rather than a power ratio, and since the range of variability is used in estimating noise amplitude.

reported findings that provide general confirmation of the theory. The times required for different components of a movement sequence appear to follow somewhat different rules, however, and a more complex relation between A and W has been found in certain tasks (Andriessen, 1960; Vredenburg, 1959). Welford (1960, 1961) has also proposed the adoption of a modified ID ratio. However, all of these results have been obtained in repetitive self-paced tasks, where the only uncertainty confronting S in regard to the requirements of the next response in a series has been the uncertainty resulting from his own amplitude variability in executing the previous response. It therefore was decided to conduct further studies of the generality of the theory when applied to discrete movements. Separate measures of reaction time (RT) and movement time (MT) were taken, and variations introduced in the degree of uncertainty as to what response would be required by the next stimulus.

The experiments were planned to provide answers to the following specific questions: (a) Does a single index of performance apply equally well to both discrete and serial tasks? (b) Are RT and MT affected in the same way by variations in task conditions?

METHOD

Apparatus and task.—The S s held a light-weight metal stylus on a small metal starting plate (see Fig. 1), fixated a point midway between two signal lights, and when one of the lights came on attempted to hit the appropriate one of two alternative targets as quickly as possible. Target widths were varied (all were 4 in. long); targets could be located at any desired distance to right or left of the starting point.

An electrical current, sufficient in amount to activate an electronic relay, but below the threshold for detection, passed through S 's body whenever the stylus was in contact

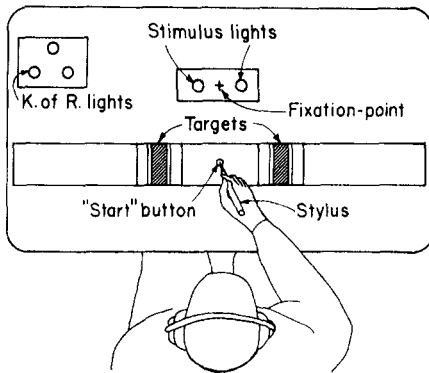


FIG. 1. Plan view of the apparatus.

either with the starting button, the target plate, or overshoot and undershoot plates on either side of the target. Three time clocks were used to measure RT, MT, and total time to the nearest .01 sec. Lights for knowledge of results provided immediate information regarding hits, overshoot errors, and undershoot errors.

Subjects.—Six paid male Ss, 18–25 yr. of age, were used.

Conditions of A and W.—Twelve combinations of movement amplitude (A) and target width (W) were provided by using 3-, 6-, and 12-in. values for A , the distances between the starting button and the midline of the target, in combinations with .125-, .25-, .5-, and 1-in. values for W (see Table 1).

Procedure.—A series of five studies was carried out (see Table 2). The conditions, including target or stimulus probabilities, were explained fully to Ss. The Ss were instructed to make quick movements aimed at hitting one of two alternative targets as soon as one of the two stimulus lights appeared. Five trials were given per minute, and about 1 min. was required to change targets within blocks of trials. The order of target conditions within experiments was randomized and different for each S. The same six Ss served in all five experiments following a training session.

The basic condition was that used in the Practice Session and in Exp. II (see Table 2). Two identical targets were located to the right and left of the starting button, and the right and left stimulus lights were turned on with equal frequency in random order. This task is thus a standard two-choice B reaction. In Exp. I one of each pair of targets, sometimes the right and sometimes the left one, was designated in advance but S was told

TABLE 1
TARGET CHARACTERISTICS EMPLOYED IN
THE SERIES OF EXPERIMENTS

Target	Movement Amplitude (A , in.)	Target Width (W , in.)	Index of Difficulty (ID, Bits)
A	3	1.0	2.58
B	3	0.5	3.58
C	3	0.25	4.58
D	3	0.125	5.58
E	6	1.0	3.58
F	6	0.5	4.58
G	6	0.25	5.58
H	6	0.125	6.58
I	12	1.0	4.58
J	12	0.5	5.58
K	12	0.25	6.58
L	12	0.125	7.58

that the stimulus indicating he should initiate a movement to that target would follow the ready signal only 50% of the time, and that no stimulus would occur on the other half of the trials. This is similar to an A reaction with 50% "catch" trials; the stimulus is known but there is 1 bit of uncertainty as to whether or not it will occur. In the absence of a better designation this will be referred to as an A reaction. The B reaction was used in Exp. III but unequal probabilities were introduced. In the two remaining experiments, pairs of equally probable but asymmetrical targets were used.

The Ss wore headphones and listened to white masking noise of about 70 db. loudness. A momentary interruption of this noise served as the ready signal, with a stimulus light (when it occurred) appearing exactly 2 sec. later.

The time between the onset of the stimulus light and the breaking of contact between the stylus and the starting button (RT) was recorded, as well as the time between the initiation of the movement and initial contact of the stylus with a target or error plate (MT). The Ss were told their average (RT + MT) time and number of errors after each block of trials. They were not aware of the analysis of response times into RT and MT.

RESULTS

Results for the Practice Session and for all experiments except Exp. III were highly consistent and will there-

TABLE 2
EXPERIMENTAL CONDITIONS FOR THE DIFFERENT EXPERIMENTS

	Target Pairs	Summary of Procedures
Practice Session	12 pairs of identical targets, on opposite sides of the starting button.	24 successive trials per target pair. Each target designated randomly and equally often on successive trials. Order of pairs randomized.
Exp. I	12 pairs of identical targets, on opposite sides of the starting button.	40 successive trials per target pair. One target designated preceding each trial, but the signal to respond given on only half the trials. Order of pairs randomized.
Exp. II	12 pairs of identical targets, on opposite sides of the starting button.	Same procedure followed as used for the Practice Session.
Exp. III	6 pairs of identical targets (C, D, H, I, J, K), on opposite sides of the starting button.	Same procedure followed as for the Practice Session and Exp. II except that one target of each pair designated on the average 50%, 75%, or 92% of the time over blocks of 24 trials.
Exp. IV	3 pairs of heterogeneous targets (C and I, D and J, H and K), each pair of equal difficulty but differing in <i>A</i> and <i>W</i> ; both targets on the same side of the starting button.	24 successive trials per target pair. Tests made with both targets to the right and also with both to the left of the starting button.
Exp. V	3 pairs of heterogeneous targets (C and I, D and J, H and K), each pair of equal difficulty but differing in <i>A</i> and <i>W</i> ; targets on opposite sides of the starting button.	24 successive trials per target pair. Tests made with each target of a pair alternately to the right and to the left of the starting button on successive blocks of trials.

fore be discussed together. The standard *B* reaction (Practice and Exp. II) will serve as the prototype.

Reaction times.—In all instances where pairs of identical targets were used RT data were very similar for the right and left targets. Accordingly, the data were combined for all identical pairs of targets.

The correlation between mean RT and ID value for the 12 movement conditions of Exp. II was found to be .79, which is statistically significant. RT increased slightly as movement amplitude (*A*) was increased, and as target width (*W*) was decreased, although only the former effects were

significant ($p < .05$). However, the slope of the linear function relating the two variables was only 5.4 msec. per 1-bit change in ID (see Fig. 2). Results for Exp. I, IV, and V were also consistent in indicating that changes in ID values have a consistent but very small effect on RT.

Reaction times were slightly but significantly faster ($p < .01$) for Exp. I (*A* reaction with 50% stimulus uncertainty) than for Exp. II (two-alternative *B* reaction). The mean difference, over all 12 target conditions, was only 15 msec. Practice effects alone should have produced a difference in the opposite direction,

however, so that the true RT difference between time and event uncertainty may be larger than 15 msec.

The only variable which had an appreciable effect on RT was the relative probability of the two alternative targets (degree of redundancy of a response sequence). These effects (from Exp. III) will be discussed later.

Movement times.—Changes in required movement characteristics had large as well as highly reliable effects on MT, in sharp contrast to their small effects on RT. The MT data from the Practice Session, and from Exp. I and II (see Fig. 2), permit a direct comparison with the earlier data from self-paced cyclical tasks (Fitts, 1954). It appears that the index of task difficulty (ID) provides equally as good a prediction of movement times for discrete responses as has been shown previously to hold for serial responses. As long as the level of stimulus uncertainty is held constant, the source of uncertainty (*A* reaction vs. *B* reaction) does not change the nature of the function. However, the slope of the function is less steep for discrete than for serial responses. Although individual differences were large, the effects of changes in target distances and widths were highly consistent within Ss.

The movement times were of similar magnitude in Exp. I and II. Five of the six Ss made faster movements under the *A* reaction condition while one S showed a very small (2 msec.) difference favoring the *B* reaction. Although the mean difference is statistically significant ($p < .05$), the effect is quite small relative to other experimental effects. Within each experiment about 99% of the variance in mean MT was accounted for by the ID ratio, the correlations between ID and MT for these two experiments being .995 and .994, respectively.

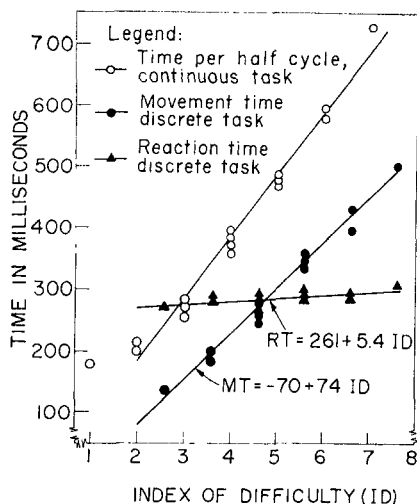


FIG. 2. Relation of reaction time and movement time to the index of task difficulty. (The solid data points show the relation of RT and MT data obtained in Exp. II, to $ID = \log_2 2A/W$. The open circles show mean times per movement in performing a serial tapping task in which target amplitudes and widths were varied in the same manner as in the present experiments; see Fitts, 1954.)

Furthermore, the regression equations for predicting MT on the basis of a knowledge of required movement amplitude and accuracy are very similar for the two experiments as well as for the Practice Session. These three equations are:

$$MT = 74 ID - 42 \text{ msec.}$$

(Practice Session) [6]

$$MT = 70 ID - 63 \text{ msec.}$$

(Exp. I) [7]

$$MT = 74 ID - 70 \text{ msec.}$$

(Exp. II) [8]

Examination of the constants of Equation 6 vs. 8, for comparable data taken at different stages of practice, suggests that practice resulted in a displacement of the function downward without a change in slope. Thus easy and difficult movements became

TABLE 3
MEAN REACTION AND MOVEMENT TIMES FOR COMPARABLE
TARGET PAIRS IN EXP. II, IV, AND V

Target Pair	ID	Exp. II		Exp. IV		Exp. V	
		RT	MT	RT	MT	RT	MT
C and I	4.58	28	27	29	25	30	25
D and J	5.58	29	35	30	31	30	32
H and K	6.58	29	41	28	38	30	40

Note.—Data are for all Ss and for right and left targets combined; times are shown to the nearest .01 sec.

slightly faster by similar absolute amounts.

The results of the analyses of movement durations for experiments in which pairs of dissimilar targets were used (Exp. IV and V) are summarized in Table 3. It can be seen that variations in target pairings had a very small effect on RTs. The actual times were very comparable to those found in Exp. II in which identical targets were placed at equal distances on opposite sides of the starting point. However, again it was found that MT increased progressively and by large amounts as a linear function of ID. Movement durations were similar in absolute magnitude to those found for homogeneous pairs of targets in Exp. II, the times for different movements varying over a range of about 150 msec.

MTs in Exp. IV and V were 33 and 23 msec. faster, respectively, than for comparable target conditions in Exp. II. Most or all of this increase could easily have been due to a continuing practice effect, however. Movements to the target on the side of the preferred hand were 20 and 11 msec. faster, respectively, than to the alternative side, whereas movements to the nearer and farther targets of a pair on the same side, equated for ID, differed by only 4 and 6 msec., respectively.

Errors.—Error data for the Practice Session and for Exp. I and II are summarized in Table 4. The Ss failed to hit the target on approximately 10% of their responses, overshoot and undershoot errors being very nearly equal. Error frequencies were found to be essentially independent of movement amplitudes, but were more frequent for the two smaller than for the two larger targets. *A* responses, where *S* knew in advance which target he should try to hit, were no more accurate than *B* responses. (In fact, errors were slightly more frequent for the former.) The percentage of errors in Exp. IV and V were comparable, being 9.5% and 8.2%, respectively, and overshoot and undershoot errors were again almost exactly equal.

Redundant sequences.—The results from Exp. III, in which response series of three levels of redundancy were employed, differed from those obtained in other experiments in the series (see Table 5). As redundancy was increased as a consequence of one target of an identical pair being designated more frequently than the other, on the average, both RTs and MTs became slightly faster, for those responses that were made to the more probable target. Accuracy also became somewhat greater for the more probable target.

The differences between the RTs

TABLE 4
PERCENTAGE OF UNDERSHOOT (U) AND OVERSHOOT (O) ERRORS
FOR THE PRACTICE SESSION AND FOR EXP. I AND II

Target	Practice		Exp. I		Exp. II	
	U	O	U	O	U	O
A	4.2	0.7	1.7	4.2	5.6	5.6
B	3.5	2.1	2.5	5.8	2.8	5.6
C	6.2	4.9	10.0	6.7	5.6	3.5
D	4.2	4.9	7.5	7.5	10.4	6.9
E	4.9	3.5	2.5	4.2	2.8	2.1
F	2.8	3.5	7.5	8.3	3.5	4.2
G	7.6	5.6	4.2	8.3	2.8	4.2
H	8.3	6.9	7.5	10.8	9.0	10.4
I	1.4	1.4	2.5	4.2	5.6	2.1
J	4.2	5.6	8.3	5.8	2.8	4.2
K	6.2	4.9	8.3	10.8	2.8	9.7
L	6.2	5.6	8.3	9.2	6.9	7.6
M	5.0	4.1	5.9	7.2	5.0	5.5

Note.—The Practice Session and Exp. II involved 1,728 trials each; Exp. I involved 1,440 actual and 1,440 "false" trials. In Exp. I, three additional errors occurred as Ss lifted the stylus when a stimulus was not given.

to the alternative targets in each pair increased approximately linearly with redundancy, as has recently been reported by Fitts, Peterson, and Wolpe (1963) for two other tasks, and so did movement times. Although relatively small in magnitude, these effects were consistent for all Ss and for all target pairs. Since time and errors are usually negatively correlated, the MT differences should have been even greater had Ss achieved equal accuracy for the less

frequent movements. Gains in speed and accuracy for the more frequent target of each pair, weighted for frequency, just about compensated for losses in speed and accuracy for the less frequent target.

DISCUSSION

Independence of reaction time and movement time.—The present results indicate that RT and MT can be influenced quite independently by (a) the degree of uncertainty regarding the stimulus to a

TABLE 5
SUMMARY OF REACTION TIME, MOVEMENT TIME, AND ERROR DATA
FOR MOVEMENTS IN TWO DIRECTIONS IN EXP. III

Percent Redundancy	Reaction Time (Msec.)				Movement Time (Msec.)				Percentage of Movements Missing Target			
	N	P	Diff.	Wtd. Aver.	N	P	Diff.	Wtd. Aver.	N	P	Diff.	Overall % Misses
0.0	293	279	14	286	342	339	3	340	10.0	8.3	1.7	9.1
18.9	315	282	33	290	354	341	13	344	12.0	9.7	2.3	10.3
58.7	326	268	58	271	366	343	23	344	22.2	8.2	14.0	9.4

Note.—P indicates a movement to the target on the side of the preferred hand and N a movement to the non-preferred side; the target on the preferred side was made the most frequent target under conditions of 18.9% and 58.7% redundancy.

movement, and (b) the degree of uncertainty permitted in executing the movement. This finding supports the view that perceptual processes and motor response processes are relatively independent (see Broadbent, 1958; Welford, 1960), and that human information processing proceeds by a series of essentially independent steps.

Welford's (1958) conclusion that RT and not MT shows the major effect of aging offers strong parallel evidence for the separate nature of perceptual and motor information handling processes, as do results from related experiments of Leonard (1952), Singleton (1954), and Szafran (1951).

Apparently RT reflects the time required for perceptual or cognitive processes, and is determined in part by the preparations which *S* makes prior to a stimulus, such as those resulting from his knowledge of stimulus probabilities. Movement time, in contrast, appears to reflect the duration of motor system processes that are necessary for the control of the timing and patterning of a movement, and which begin after the decision is made to execute a movement. Advanced preparation for two-alternative movement processes does not appear to lengthen the time required to execute one of the movements, as compared to the situation where *S* is prepared in advance for only one response which has a 50% probability of being designated.

Several suggestions can be offered regarding processes which might utilize increased time to gain greater accuracy in the control of an output. As an illustration, if neural timing should involve feedback loops or reverberating circuits, then the relative effects of random biological noise in such loops should decrease as the timing interval increases.

Effects of redundancy and of time vs. event uncertainty.—The effects of differences in relative stimulus frequencies on RT, although small in absolute magnitude, are similar to those recently reported by Fitts, Peterson, and Wolpe (1963), and offer further support for a

stimulus sampling theory of choice behavior. The close similarity of RT and error data for the *A* and *B* reactions, where 50% probability obtained in both instances, suggests that the effects of time uncertainty and of event uncertainty are closely equivalent.

The index of task difficulty.—Crossman (1960) and Welford (1960) have suggested that instead of actual target width, a corrected estimate of *W*, adjusted for errors, should be used in computing ID values. Applying such an empirical correction (so that $W = \pm 2SD$), the equation fitted to the data for Exp. I becomes

$$RT = 74 ID - 57 \text{ msec.} \quad [9]$$

This indicates a slightly less efficient rate of processing information than does Equation 7. However, the correction has no appreciable effect on the correlation between ID and RT (changing it from .995 to .993). The main point for emphasis is an *S*'s remarkable ability for maintaining error rate relatively constant across a wide variety of task conditions, while varying the speed of his movements.

Welford has also suggested that an improved index of task difficulty might be

$$ID' = \log_2 \frac{A + .5W}{W} \quad [10]$$

This suggestion is based in part on the observation that this definition reduces the numerical value of the first constant, *a*, in Equation 5, giving theoretical predictions of MT near zero for an ID' of zero. Accordingly, Equation 5 was re-evaluated for the data of Exp. I, using ID' in place of ID. This expression was found to be

$$MT = 72 ID' + 6 \text{ msec.} \quad [11]$$

Near zero MT is now predicted for values of ID = 0 (in place of near zero MT for ID = 1), and the correlation between these modified predictions and actual MTs was found to be .997. These results therefore support Welford's arguments.

It is obvious, however, that neither RT nor MT can ever approach zero in any real task. It also appears reasonable to expect that empirical determinations of human motor performance may indicate that capacity varies over the range of possible response amplitudes and tolerances. Since neither index has been derived formally from a theory, choice between them should rest on heuristic considerations. Some implications of the original index (Equation 3) are indicated below.

Human channel capacities.—Accepting Equation 3 as the definition of ID, and Equation 8 as providing a generalized empirical estimate of discrete movement times, the estimates of human performance capacity, as specified in Equation 4, would vary from about 22 bits per second for a value of $ID = 2.5$ (the least difficult movement studied), to just over 14 bits per second for $ID = 7.5$ (the most difficult movement studied). Thus it might appear that the motor system is relatively more efficient in producing low-information than high-information responses. Such estimates cannot be extended directly to self-paced cyclical motor tasks, however, since some additional uncertainty is introduced by the requirement that Ss process feedback data in repetitive tasks.

Earlier results (Fitts, 1954) indicate that actual performance rates in self-paced repetitive tasks vary from about 9.5 to 11.5 bits per second for ID values comparable to those studied here, and that maximum performance is attained for intermediate values of A , W , and ID . It is interesting to note that a linear combination of the equations for RT and MT would predict better performance for more difficult tasks as long as the effect of RT was weighted sufficiently to give a positive value for the intercept constant, a . Approximately a 4 to 1 weight for MT relative to RT would give a predicted zero intercept, or equivalent information rates at all difficulty levels.

The view that performance in self-paced cyclical tasks is a combined

function of RT plus MT is, of course, an old one and, as mentioned earlier, agrees with the approach taken by Welford (1958) in analyzing age changes in perceptual-motor performance. It is significant that the average total time per response in the self-paced serial task (see Fig. 2) exceeded the present movement times by only about .1–.2 sec., and not by an amount as great as the present reaction times. This suggests that the processing of feedback data can to some extent overlap the processes involved in the control of subsequent movements, or else, as Woodworth (1899) and others have suggested, that a sequence of two or more movements may be programed in advance and executed independently of feedback. Such a finding is also consistent with Licklider's (1960) observation that S's lag in a continuous tracking task is often less than reaction time data might suggest, and with the data from studies bearing on psychological refractory period delays (Welford, 1952) where the increase in RT to the second of two stimuli presented in rapid succession usually is less than a simple reaction time.

In summary, it appears that the processing of feedback data in serial or continuous tasks introduces some small delay relative to simple open-loop movements, but less delay than would be expected if every response involved a separate reaction time.

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