Journal of Applied Psychology
1961, Vol. 45, No. 5, 303–308

OPERATOR PERFORMANCE ON A CHORD KEYBOARD

H. C. RATZ
University of Saskatchewan

AND

D. K. RITCHIE[1]
Ferranti-Packard Limited, Toronto

The man-machine link has received considerable attention both in simple feedback systems (Hick, 1952) and as a data processing unit. In a computer system, the human operator may be employed because of his ability to translate between plain language and machine language, while in a control system his ability to recognize complex patterns in performance data is exploited (Elkind & Forgie, 1959).

The performance of an operator in choice and sorting problems has been treated by several investigators (Crossman, 1953). They have found the "choice reaction time" to be proportional to the stimulus complexity as measured by the logarithm of the number of alternatives. Experimental variations have included frequency unbalance among the alternative stimuli (Hyman, 1953), and the addition of extraneous information not relevant to the required choice (Archer, 1954; Gregg, 1954). Fitts (1953) has pointed out that an operator's data processing capability is subject to the fixed constraints of his motor system. These constraints are implicit in the form of the response code and determine his effective capacity. For example, a telegraph operator produces time sequences with one hand, while the teletypist uses 10 fingers one at a time. The fact that motor constraints have a considerable influence in the latter case is known from the improvements that can be achieved through keyboard and language studies (Dvorak, Merric, Dealey, & Ford, 1936). The type of keyboard studied in this paper is more akin to that used by the stenotypist who employs several fingers simultaneously. At present, the typewriter remains the most effective man-computer communication link (Licklider, 1960) although other aspects of computer systems such as displays and programing language have advanced considerably. The multiple finger or "chord" keyboard may be a useful alternative in some special purpose data processing systems.

The relative difficulty of the various chords can be measured in terms of the reaction time in responding on the keyboard to a visual presentation of the chord pattern. Since lights, fingers, and keys are in direct correspondence, the stimulus-response codes are highly compatible; that is, mental recoding of the information is avoided. Thus we obtain an experimental assessment of the performance of an operator using this chosen set of response motor tasks. Using these data and the principles of optimum coding, the more frequently used message units can be assigned to the easier response tasks. This optimum distribution of message units will minimize the average time per message and maximize the rate of information processing (Blachman, 1954).

Method

Apparatus

A block diagram of the experimental apparatus is shown in Figure 1. A paper tape reader provided sequences of patterns for the lamp display. The operator responded to each pattern in turn by depressing the corresponding keys of the keyboard. A complete temporal record of both the display and response activity was obtained from a 20-pen recorder. Ten of the pens recorded the motions of the keyboard responses, while the other 10 recorded the timing of the lights. Thus reaction time, errors, latency, etc., could all be obtained from the paper strip record.

The keyboard contained 10 keys mounted on a horizontal surface and placed at the positions occupied by the fingertips with the fingers slightly curled and the wrists straight. The keys operated snap action switches through a lever which required about three-eighths inch travel at the key, and quite low pressure. These switches drove the recording pens and, when all keys were released, signaled the tape reader to present the next stimulus pattern. The lights used in the stimulus display were placed in two groups of five on a horizontal line above and beyond the keyboard. They were mounted on a surface tilted so as to be roughly perpendicular to the line of sight.

[1] The authors gratefully acknowledge the assistance and guidance of John Ogilvie and M. Humphries in the formulation of these experiments and in the analysis of the data. The valuable comments on the manuscript by George A. McMurray are also appreciated.

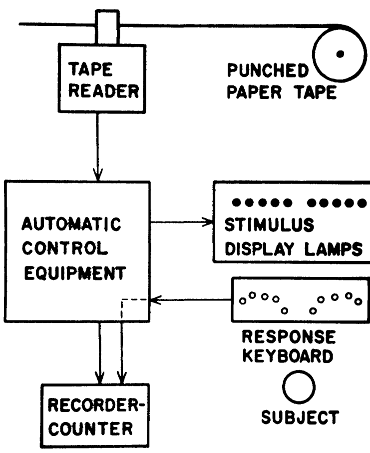

FIG. 1. Block diagram of the experimental apparatus. (The flow of stimulus and response information is indicated. Control signals are omitted.)

In a typical experiment, the operator depressed the keys on the keyboard which corresponded to the combination of illuminated lights presented to him. That is, the operator transcribed light "chords" into key "chords." When all keys were released by the operator, a new combination of lights would appear whether or not the correct chord had been struck.

The function of the control apparatus was to automatically step on the tape reader and to transfer the combinations punched on the tape to the lamps. The method of operation as described above is one in which the operator paces himself; that is, the new stimulus was automatically presented after the keys were released from the previous response. Although not used in these experiments, forced pacing at various speeds, and with a choice of ratio of "on time" (stimulus presented) to "off time" (dead time between stimuli), could be programed with the same control apparatus.

Stimuli

The tape reader was a standard type used with computers and employed five-hole tape. For experiments using chords in only one hand, successive characters on the tape provided the stimulus combinations. By using a pair of characters from the tape for each presentation, a full 10-light pattern was achieved. This choice of program could be preset at the control apparatus. Thus when both hands were used the reader passed two characters of the tape at a time.

Since the sequence of light patterns depended only on the characters of the punched tape, many experiments with various sets of chords could be easily programed. For example, one tape employed all the 31 different possible combinations with equal frequency but in random order; another employed only those 15 different chords per hand which are possible using either one or two fingers.

Subjects

Six operators were used in the experiments. Three of these used both hands throughout, while the other three used only the hand of preference, which was the right hand. Each operator practiced 10 minutes a day on random sequences of the 31 chords. The performance was completely recorded for the first and last 100 seconds of each 10-minute interval.

Although the task required in these experiments is a simple motor reaction, there is an initial short learning period. By checking the average reaction time of a few of the chords, it was observed that little improvement took place after the second day. Asymptotic behavior was reached rather quickly because the order of the presentations was random. The absence of any systematic intersymbol influence between successive chords precluded any longer term improvement through learned predictability since, in this case, each of the possible stimuli was equally likely to occur at any point in the sequence. In other terms, the stimuli signals contained no redundancy, so the gross data rate and the net rate of informational entropy were equivalent. Finally, because self-pacing was used, the number of erroneous responses made was negligible.

Procedure

In order to rank the chords according to increasing reaction times, a stimulus tape using all 31 different chords at random was used to generate patterns. The daily test periods and recording intervals were the same as during training. From the total of 2,660 measured reaction times, each chord was assigned a rank number according to its position in a list of increasing reaction times. The reaction time was measured between the appearance of the lamp stimulus pattern and the complete selection of the corresponding chord. The data for each chord was totaled for the complete duration of the experiment since an operator's behavior might vary 10% from day to day.

In the second part of the experiment, information rates were measured using selected groups of stimulus chords. Four groups were defined which used a maximum of one, two, three, or all five fingers per hand. They appeared in random sequence with equal frequency. The appropriate information measure is the logarithm of the number of possible choices, which is the average entropy per pattern of the source, i.e.:

$$H = \log_2 \text{(number of choices)}$$

The information rate (bits per second) is obtained from the product of H and the average number of responses per second. The latter was measured by counting the total number of responses in 3-minute tests for the cases involving only one hand, and in

RANK	CHORD	RANK	CHORD
1	– – – – O	17	O – O – –
2	O – – – –	18	O – – O –
3	– – O – –	19	– – O O O
4	– – – O –	20	O – – O O
5	– O – – –	21	O O – – O
6	O O – – –	22	O – O – O
7	O – – – O	23	– O – – O
8	– O O – –	24	O – O O O
9	O O O – –	25	– – O – O
10	– O O O –	26	O – O O –
11	– – O O –	27	O O – O –
12	– – – O O	28	O O O – O
13	O O O O O	29	O O – O O
14	– O O O O	30	– O O – O
15	O O O O –	31	– O – O O
16	– O – O –		

FIG. 2 Chord rank chart. (The fingers used in the right hand are indicated.)

6-minute tests for the cases with two hands. The six different experiments are listed in Table 1.

RESULTS AND DISCUSSION

Chord Ranking

The average ranking of chords by increasing reaction times is shown in Figure 2, where the fingers used in each chord are indicated for the right hand. The average correlation coefficient among operators for all 31 chords is .91, hence, the agreement on the overall ranking is excellent. However, there is no significant agreement among operators concerning the rank of any chord relative to those immediately adjacent on the list. For example, if we confine our attention to the first five on the list, the correlation in the ranking by different operators is not significant; but if eight or more chords are taken the agreement is good. This is clear from the maxima and minima for the different subjects in Figure 3.

The main features of the chord rank chart are not unexpected, thus, the top five on the list involve only one finger each. The chords requiring the longest response times all contain patterns requiring one or two fingers to be held off while their neighbors on each side are used. In between (ranks 8 to 15) lie those chords consisting of a consecutive group of fingers.

Distribution of Response Times

If each chord is assigned a "cost" proportional to its associated reaction time, then the distribution of Figure 3 is obtained. These response times include a 0.1-second delay in the presentation of the stimulus pattern. In passing, it was observed that about 65% of the total time required to complete the chord response could be assigned to latency, where latency is taken as the time between stimulus presentation and the first indications of response. Figures 2 and 3 give the relative ranking of chords by response time and show quantitatively how the cost in reaction time is distributed over the different chords.

The quantitative difference in performance using various subgroups of chords can be predicted from Figure 3. If it is assumed that the cost distribution of Figure 3 represents the motor response times of each chord and that the effect of choice when there are different numbers of possible alternatives is negligible, then the expected response time would be the average cost (in seconds of reaction time) determined from the distribution for the given subgroup of stimulus patterns. The "predicted response time" of Table 1 is the average of the costs of those chords used in a particular group of stimulus patterns plus the 0.1-second dead time between presentations. To extend

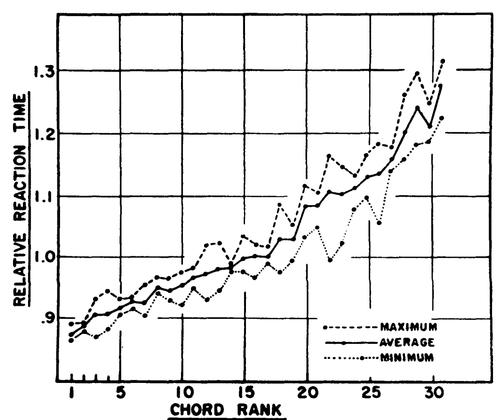

FIG. 3. Distribution of reaction times. (Chords are ranked according to Figure 2 and reaction times are expressed relative to the median of 1.16 seconds.)

TABLE 1

COMPARISON OF THE OBSERVED DATA RATE FOR SUBGROUPS OF CHORDS WITH THAT PREDICTED BY THE CHORD RANKING EXPERIMENT

Experiment	Stimulus Chords	Patterns H (bits/stimulus)	Observed Response Time T seconds/ response)	Observed Data Rate H/T (bits/sec.)	Predicted Response Time C (seconds/ response)	Predicted Data Rate H/C (bits/sec.)
One Hand						
A	1-finger chords	2.32	.94	2.4	1.05	2.2
B	1-, 2-finger chords	3.91	1.07	3.7	1.13	3.5
C	1-, 2-, 3-finger chords	4.64	1.15	4.1	1.18	3.9
D	All chords	4.95	1.20	4.1	1.20	4.1
Two Hands						
E	1 finger per hand	4.64	2.08	2.3	(2.1)	(2.2)
F	All chords	9.91	2.63	3.8	(4.1)	(4.1)

this to two hands, the distribution for all 961 allowable 10-finger patterns would be required. Lacking these data, the figures entered in parenthesis in the table are merely double the expected reaction times for one hand.

Table 1 shows the results of experiments using only selected groups of chords and measuring the average response time for the group in each case. The "Observed Data Rate" is obtained by dividing the H for the group by the observed average response time T. Since H measures the stimulus information in binary units, the result is an information flow rate expressed in bits per second which neglects the possibility of errors. As is usual in this type of human operator experiment, the higher information rates correspond to the stimuli giving the greater choice and having higher values of H. While this conclusion is valid here for the cases involving one handed operation, note that it does not necessarily extend to the use of two hands. Comparing Experiment A with E, and D with F, it is seen that an operator using only one hand may perform at somewhat better than twice the speed of one using both, and therefore having a greater resulting information handling capacity. Thus the increase in choice derived from using both hands on 10 keys was more than offset by the slower response of the operator.

Information Rates

The agreement between the observed response time T and the expected average cost C indicates that the reaction time for a given subgroup of chords is very nearly the average of the reaction times for its individual members. Thus the assumption made in computing C is substantially supported, namely, that the reaction times are highly characteristic of the individual chords and relatively independent of the number and remaining members of the set. However, there is a tendency for the response times to be shorter (and the information rate higher) than that predicted when the amount of choice in the set becomes smaller; that is, the effect of the amount of choice on the overall response time may be present but is secondary to the average motor reaction time. Since the basis of all predictions was reaction time measurements using all 31 chords, the agreement in Experiment D is an arithmetic check.

In Table 1, the highest data rate is obtained using all chords on one hand. However, this assumes that the 31 different stimuli patterns are used with equal frequency, a method which is not optimum in view of the nonuniform cost distribution function. Obviously, the more difficult chords should be used less often than the easier ones. The frequency distribution required for optimum performance can be determined from coding theory.

Application of Coding Theory

The problem of communication with unequally weighted vocabularies has been examined as a game of strategy by Mandelbrot (1954). By interpreting the average response time to each of the chords as its cost, the code can be specified which will transmit a given amount of information in minimum time. Under the assumption that the response time to a chord is independent of its predecessors or the amount of choice, the encoding which minimizes the cost can be essentially specified by the relative frequencies of use of the chords (Blachman, 1954). Since Table 1 shows this assumption to be approximately true, the maximum information rate will be achieved by assigning the easier chords to the more frequent messages.

Suppose the chords are given a rank $R = 1, 2, \ldots, 31$ as shown in Figure 2 with an associated cost (C_R) from the experimental results of Figure 3. The problem is to find the relative frequency of use for each chord—its probability p_R—that will maximize the net information rate H/C. Here H is the weighted average entropy per chord:

$$H = -\Sigma p_R \log_2(p_R)$$

and C the average cost:

$$C = \Sigma p_R C_R$$

The probabilities are normalized so that:

$$\Sigma p_R = 1$$

The solution of this variational problem is in terms of the "partition functions" of statistical mechanics (Jaynes, 1959); the distribution is of the form:

$$p_R = 2^{-kC_R}$$

where k, the maximum information rate, is the solution of the equation:

$$\Sigma 2^{-kC_R} = 1$$

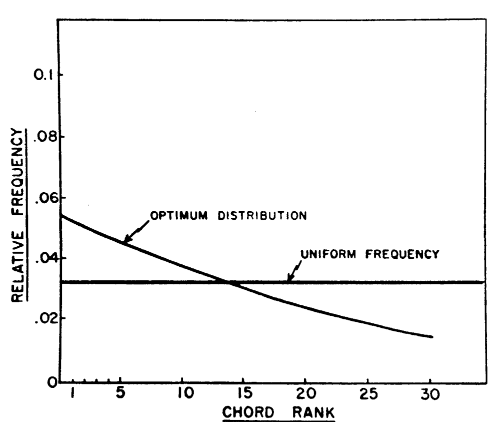

FIG. 4 Comparison of uniform with optimum frequency distribution.

Using Figure 3 as the description of C_R, the information rate obtained with optimum frequency distribution of the chords is:

$$k = 4.33 \text{ bits/second}$$

The resulting distribution is compared in Figure 4 with the uniform frequency method of Experiment D. Note that the frequency of occurrence of the most used chords ($R = 1$) is about 3.7 times that of the least used ($R = 31$), with the unbalance in favor of the easier chords. The improvement to be expected over the results of Experiment D is of the order of 5% in the net information rate, if the frequency of use is optimum as shown in Figure 4.

SUMMARY

The 31 chords have been ranked according to their difficulty or "cost" as measured by the reaction times, and a quantitative measure obtained for the distribution. Assuming that the motor system predominates over choice reaction time, these results are used to predict the expected average response times and information rates using subgroups of the chords that involve less choice; for example, a group may include only a few of the easier chords with the shorter response times. The agreement with experiment indicates that the results were determined primarily by the reaction times of the particular chords in the group, and that the effect of the amount of choice was secondary. On this basis, coding theory can be used to deduce the distribution of the frequency of occurrence of chords with the measured cost function that gives the maximum information rate through the man-machine link.

For one hand the information rate increases with the complexity of choice of patterns, but this does not remain valid for two hands where the loss in response speed overbalances the increased choice of stimuli. It should be noted that these keyboard experiments were conducted using a highly compatible display, and that other forms of presentation might introduce effects of stimulus-response coding that would reduce the importance of the motor reaction time. With this qualification, the results show that motor system constraints are predominant over choice reaction time in determining speed on a chord keyboard.

REFERENCES

ARCHER, E. J. Identification of visual patterns as a function of information load. *J. exp. Psychol.,* 1954, **48**, 313–317.

BLACHMAN, N. M. Minimum-cost encoding of information. *IRE Trans.,* 1954, **IT-3**, 139–149.

CROSSMAN, E. R. F. W. Entropy and choice time: The effect of frequency unbalance on choice response. *Quart. J. exp. Psychol.,* 1953, **5**, 41–51.

DVORAK, A., MERRIC, N. I., DEALEY, W. L., & FORD, G. C. *Typewriting behavior.* New York: American Book, 1936.

ELKIND, J. I., & FORGIE, C. D. Characteristics of the human operator in simple manual control systems. *IRE Trans.,* 1959, **AC-4**, 44–55.

FITTS, P. M. The influence of response coding on performance in motor tasks. In, *Current trends in information theory.* Pittsburgh: Univer. Pittsburgh Press, 1953. Pp. 47–75.

GREGG, L. W. The effect of stimulus complexity on discrimination responses. *J. exp. Psychol.,* 1954, **48**, 289–297.

HICK, W. E. On the rate of gain of information. *Quart. J. exp. Psychol.,* 1952, **4**, 11–26.

HYMAN, R. Stimulus information as a determinant of reaction time. *J. exp. Psychol.,* 1953, **45**, 188–196.

JAYNES, E. T. A note on unique decipherability. *IRE Trans.,* 1959, **IT-5**, 98–102.

LICKLIDER, J. C. R. Man-computer symbiosis. *IRE Trans.,* 1960, **HFE-1**, 4–11.

MANDELBROT, B. Simple games of strategy occurring in communication through natural languages. *IRE Trans.,* 1954, **IT-3**, 124–137.

(Received September 14, 1960)