A STUDY OF EFFECT OF ANGLE AND DISTANCE ON THE SPEED AND ACCURACY OF SINGLE HAND AND TWO HAND SIMULTANEOUS MOTIONS IN THE HORIZONTAL PLANE

by

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A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1968

Approved by:

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INTRODUCTION

Management and industrial engineers are continuously confronted with the problem of determining the best possible working conditions for their employees. While many operations can be and are being converted to automatic tooling and controls, many tasks are still relegated to human performance. Particularly in recent decades self-controlled machines and self-controlled industrial processes have evolved rapidly, but still there are many tasks and control operations which require the application of human information and control. There exists neither the technology nor the hardware to replace that control system with an artificial one and, if such hardware existed, it would be very expensive.

Industrial engineers in their role of designing work systems have a responsibility to the management and their profession to apply scientifically proven principles. To design the most effective methods, equipment, and control system to suit the operation, it is essential to have a detailed knowledge of the capacities and capabilities of the human operators. Such designs require the application of certain rules and principles of motion economy, which affect the manual activity of the operation.

Frank B. Gilbreth (1911) made valuable attempts to formulate some rules of motion economy and efficiency on the basis of general observations. These rules of motion economy were further revised by Barnes (1940) who collected the fragments of early works; these principles of motion economy had been developed on the basis of experience, intuition and common sense but were not verified by controlled experiments.

Although recently efforts have been made by various experimenters (Briggs, 1955; Nichols, 1958; Jeans, 1966) to verify some of the principles of motion economy by controlled experiments using different criteria, yet much is to be done to evaluate and confirm these principles.

In view of the limited research in this field, the purpose of this study was to investigate the effect of angle and distance on the accuracy and speed of single hand and two hand simultaneous motions and thus to evaluate the following principle of motion economy as established by Barnes (1940).

"Motions of the hands should be made in opposite and symmetrical directions and should be made simultaneously."

LITERATURE REVIEW

(1) Single hand motions and two hand simultaneous motions.

Frank B. Gilbreth (1911) was the pioneer of motion study and his concepts of time and motion study included the procedures which are now classified as motion economy. He studied brick laying work and concluded that "when work is done with two hands simultaneously, it can be done quickest and with least mental effort, particularly if the work is done by both hands in a similar manner, that is to say when one hand makes the same motions to the right as the other does to the left." He formulated the rules of motion economy mainly on the basis of experience and did not verify them by controlled experiments.

Barnes and Mundel (1939) investigated the effect of simultaneous symmetrical motions of hands upon the efficiency of the work. After completion of their study, they made the following conclusions:

(1) The 90 degrees position was the best for both the hands, when hands were directed by the vision while performing the task. (0° was referred to as three o'clock position)

(2) In absence of visual direction, 60 and 120 degree angles were the best for the right and left hand respectively.

Barnes (1940) revised the rules of motion economy formulated by Gilbreth (1911) and developed his own principles of motion economy by collecting the fragments of early works. His principles of motion economy are generally being used throughout the industries of U.S.A. In one of his principles he has stated that "Motion of the hands should be made in opposite and symmetrical directions and should be made simultaneously." He further stated that the symmetrical movements of the arms tend to balance each other reducing the shock and jar on the body and thus enabling the worker to perform the task with less mental and physical effort. The above principle was demonstrated by the task of Bolts and Washers assembly. In the improved method, the bins containing the washers were arranged in duplicate, so that both hands could move simultaneously, assembling washers for two bolts at the same time. By changing the arrangements of bins as above, which required the simultaneous and symmetrical motions of hand, (old method involved one hand motions at a time) the output of the work was increased by 53%. He concluded from this example that the simultaneous and symmetrical motions of hands are better than non-simultaneous motions of hands.

Fitts (1947) studied the blind positioning movements of the right hand in free space. Accuracy of reaching with a stylus to an array of targets arranged around the subject at various heights was recorded; the subject was allowed to move his hand freely in all three dimensions. The targets located directly in front of the subject were marked with considerably greater accuracy than any other targets. He also concluded that the accuracy was better for the target on the right side than on the left side.

Corrigan and Brogden (1948) found the following trigonometric relationship between precision and angle.

$$y = a - b \cos 2x + c \sin 2x$$

where y = precision of right arm movement in terms of group mean frequency of stylus contact

x = angle from the body at which movement is made.

a, b and c are constants.

As stated in words, the precision of constant velocity movements of right hand is a function of angle from the body at which the movement is made. They incremented the angles by 30 degrees and divided the study into three experiments each having a set of different angles. Subjects moved the metal tipped stylus on a 0.4 cm. wide glass track positioned at different angles and the number of stylus contacts made on the side of the track were recorded at each angle by means of an electronic counter.

Brown, Knauft and Rosenbaum (1948) studied the positioning in total darkness of the right hand and arm. The subjects moved a slider tied on an endless string, from a point of rest to a terminal position located at either 0.6, 2.5, 10 or 40 cms. distant. The movements were made either parallel or perpendicular to the frontal plane of the subject. The errors in location were recorded. They concluded that the positioning reactions made by moving away from the body are more accurate at comparable distances from their starting point then the positioning reactions made by moving towards the body. The percentage of error is maximum for short distances and it decreases with each increment in distance. Movement away from the body exhibits a smaller percentage of errors in positioning than do movements towards the body; they suggested that this probably was because the motions towards the body are closer to the body at the end of the move. Accuracy was used as the criterion while the speed of movement was kept constant.

Corrigan and Brogden (1949) made a study to test the validity of the trigonometric relationship between precision and angle that they had investigated in their previous experiment (1948). In general, the experimental task was the same as the previous one, except that the direction of the track incremented at intervals of 15 degrees around the circle instead of having three different groups of angles. The number of contacts of the stylus with the track sides was recorded for each of the angles. Maximum errors were observed at 135 degrees and 315 degrees, and minimum number of errors were observed at 45 degrees and 225 degrees. They concluded that the trigonometric relationship holds good between the precision of pursuit movements and the angle.

Brown and Slater-Hammel (1949) studied the speed and accuracy of discrete movements of the hand-arm in the horizontal plane. The subjects moved a slider either from center to the right or from the center to the left in the horizontal line running parallel to the frontal plane of their body. The movements were made by the subjects in both directions at three fixed distances (2.5, 10 and 40 cms.). The movements were made by the right hand and accuracy was used as the criterion. At each of the three distances it took less time to move from center to left than center to right; the percentages at 1, 4 and 10 inches are 90, 87 and 95 respectively. Although they could not find any consistent difference related to direction of movement, there was a slight indication that the movements from right to left are faster than the movements from left to right.

Brogden (1953) conducted a study to find out the effect of amount of practice on the trigonometric relationship of precision and angle of linear pursuit movement of the right hand. The task of the experiments was the same as used in his previous studies (1948, 1949). In order to obtain the effect of practice upon the relationship between the angle and precision of movement without contamination of transfer effect between angles, the subjects were divided into eight groups of five subjects each and different groups of subjects were given practice on different angles, with only one angle for a given group. After constructing the learning curves, it was found that the practice has a differential effect for angles. No learning was obtained at the angles of 90 degrees and 120 degrees and there were considerable differences in the amount of learning and the terminal level of performance for the other angles.

Briggs (1955), at Purdue, studied the effect of distance, angle and the target size on linear hand-arm movements in the horizontal plane. The subjects moved a light stylus between targets of various sizes and the distance of movement was kept as 14 inches. The movements were made at angles of 0°, 30°, 60° and 90° to the subject's right and the size of the target was varied from 1/4" to 1" diameter in 1/4" increments. The criterion of his study combined accuracy and speed; it was the hits in a 20 second trial. He concluded that when the movements are made towards the body, there are less number of hits than when the motion was outward. The angle at which most hits were made was 30 degrees for both inward and outward motions. By fitted curves, the best angles for outward and inward motions were found as 27 degrees and 37 degrees, respectively. In another experiment, Briggs studied the effect of angle and distance on inward movements using nine angles and seven distances. The target size was held constant at 1" diameter while the direction of movement was varied from 120° towards left to 120° towards right in 30° increments and the distance of the target was varied from 7" to 35" in 7" increments. These movements were made by the right hand. The best angle for such movements was found as 30 degrees and the worst was 180 degrees. He also concluded that for right hand movements an angle of 210 degrees was better than 180 degrees. By fitting curves he concluded that an angle of 19 degrees was best for distances up to 14 inches, 7 degrees was best for 21 inches movements and 336 degrees for 28 inches movements.

Nichols (1958), at Purdue, made a study on the physiological evaluation of selected principles of motion economy using the criterion of minimum increase in heart rate. For evaluating the motion economy principle involving simultaneous and symmetrical use of hands, four motion patterns were employed. The subjects moved weights of 0.5 lbs., 2.5 lbs. and 4.5 lbs. (holding the same weight in each hand) under four experimental conditions. The four conditions studied were (1) single hand motions (2) simultaneous and symmetrical motions (3) non-simultaneous and symmetrical motions and (4) simultaneous and non-symmetrical motions. He concluded that (1) for an equal amount of work performed, one-handed operations resulted in a significantly smaller increase in heart rate than did two-handed symmetrical non-simultaneous motions, (2) for an equal amount of work performed, two handed simultaneous and symmetrical motions resulted in a significantly smaller increase in heart rate than did two handed simultaneous and non-symmetrical motions.

Schmidtke (1958), at the Max-Plank Institute in Germany, studied the influence of motion speed on motion accuracy. The task was performed by six subjects and the motion speed was varied between 10 cms/sec. and 100 cms/sec. The mean distance from the target point to the starting point was kept as 40 cms. and the motion rhythm was controlled by a metronome. The subjects struck the target with the stylus by moving the hand at various speeds between the target point and the starting point. The error (the deviation from the target center) in millimeters was registered. The minimum errors were registered for the speed between 20 and 25 cms/sec. For the speeds less than 20 and greater than 25 cms/sec., there was an increasing tendency in the amount of errors.

Schmidtke and Stier (1961) conducted a number of experiments concerning the various types of hand-arm movements. In one of the experiments, they investigated the effect of direction of movement on the linear hand motions. The subjects were asked to move the stylus forward and backward, always touching the contact surfaces fixed at various angles. The contact surfaces were fixed on the circumference of a 25 cms. dia. circle at increments of 45 degrees. They concluded that the motion time decreases to a minimum near 45 degrees and from there onwards, it increases to a maximum near 135 degrees. By fitting curves, the maximum and minimum times were obtained at 145 degrees and 55 degrees respectively.

Konz (1967) reported that Bouisset, Henon, Monod and Laville (1962, 1964) of France investigated two handed symmetrical motions at (1) 90° and 15 cms. (2) 90° and 30 cms. and (3) 30° and 30 cms. The subjects moved a 200 gram weight in each hand, while cardiac frequency was measured. Using Muller's method of contrasting the sum of the excess pulsations in relation to level at rest, they found that there was a significant difference between condition one and three and condition two, but not between one and three; a reduction in distance may compensate for the effect of angle.

Wu (1965), at Kansas State University, investigated the effect of angle and work table height on the efficiency of work. He studied the movements of the right hand at the angles of 0°, 45°, 90°, 135° and 180°. The subjects moved a two pound weight between the center point and the point situated on the periphery of a circle having a radius of 15 inches. The speed of the movement was kept constant by the help of a metronome while the apparatus used for measuring the physiological cost was a force platform. He concluded that there is a difference in the amount of work required in inward and outward motions of the arms. He further concluded that the movement of the hand was most efficient at an angle of 0° for both inward and outward motions.

Peterson (1965) conducted an experiment to determine whether or not response compatability effects were present in a simple perceptual motor task, where simultaneous two hand pointing responses were required. In this experiment, subjects moved their hands to four different targets made of 1/2 inch dia. metal discs in a diamond pattern around a homebutton fixed at the center. The centers of the targets were 4 inches from the center of the home-button. The arrangements of the targets were separate for both hands. He found that, in one hand tasks, the lateral movements were the fastest and the proximal movements were the slowest. The movements away from the subject's frontal plane was called distal, movement towards the frontal plane was called proximal, movement away from the medial plane was called lateral and the movement towards the medial plane was called medial. He concluded that the direction of movement had an effect on one hand and two hand tasks. In two hand simultaneous motions, there was a tendency for proximal movements to be slower than lateral, medial or distal. The highest frequency of errors was for the conditions of movements of left hand to distal and right hand to lateral position for simultaneous motions.

Maria Wyke (1965) analyzed the differences in accuracy of pointing to a target by moving right and left arms, using the "kinesthetic memory for the target" technique. The experimental task consisted of a semicircular arrangement of 57 pegs mounted on the board. The angular separation between each pair of pegs at the vertical axis of subject's body was 3.2 degrees and all pegs were at a constant distance of 45.5 cms. The subjects' eyes were masked and they were asked to touch with their forefinger one of the pegs. She concluded that pointing with the right arm is significantly better than with the left and accuracy of pointing is greater for targets located directly in front of the body than when the target lies to either left or right.

Jeans (1966), at Kansas State University, studied the physiological cost of simultaneous and symmetrical motions using the output of a force platform as a criterion. The subjects were 18 female students, who moved a two pound weight in each hand between the specified points 18" apart under three experimental task conditions. The three conditions studied were (1) simultaneous and symmetrical motions at an angle of 53° and 127° (0° was defined as 3 o'clock position) (2) simultaneous motions and assymmetrical motions at 53° and 143° and (3) non-simultaneous and symmetrical motions at an angle of 53° and 127°. It was concluded that for the particular conditions studied (1) simultaneous and non-symmetrical motions require lower physiological cost than the simultaneous and symmetrical motions, (2) simultaneous motions require lower physiological cost than non-simultaneous or sequential motions, (3) outward motions of the arm require more force than inward motions, and (4) the left hand exerts more force than the right hand when both hands are working at equal tasks.

Lincoln and Konz (1966) studied the speed and accuracy of operating a switch and they concluded that the movements of hand at an angle of 45° were better than the movements made at an angle of 135°.

(2) INFORMATION THEORY IN MOTOR PERFORMANCES:

During the period from 1947 to 1949, several investigations were made on sensory motor performances and a series of important publications were produced relating the above subject. The important papers published by Craik (1947, 1948) and by Hick (1948) discussing the theory of human operators of control mechanisms are the valuable contributions in this field. The theoretical points discussed in the above papers were further developed by Vince (1948, 1949) by conducting a series of experiments. This subject has also been enlightened in the books written by Fitts (1947) and by Chapanis et. al. (1949). In these books, the authors have given the abstracts of many series of experiments indicating the ways in which the design of equipments could influence the speed and accuracy of an operator's performance.

The studies conducted by Vince (1948, 1950) and Welford (1952, 1959) have proved that when one signal occurs very shortly after another, the time taken to respond to the second signal may be longer than normal and as such the signals may therefore have to queue. If they arrive during or shortly after the movement of the hand in response to a previous signal, they may clash with kinaesthetic or other sensory feedback. Hence it was interpreted by them (Vince, 1948; Welford, 1952) that the central mechanism behaves as if it contained, at some point, a single channel dealing with only one set of co-ordinated signals at a time.

The relation between amplitude, accuracy and the time taken to make hand movements had been a subject of discussion for some years before Fitts (1954) suggested a formulation in information theory which connected all the three factors together:

$$\text{Movement time} = a + b \log \frac{A}{w/2}$$

where w is the width of the target within which the movement is required to end, measured parallel to the direction of movement.

A is the amplitude of the movement measured from its starting point to the center of the target and a,b are constants.

The essential point in this formulation is that it makes the movement time constant for any given ratio between amplitude and target width. Fitts calculated an index of difficulty and rate of performance from the positioning tolerance and amplitude of movement to specify the minimum average amount of information to produce the movement.

Thus $I_d = \log \frac{A}{w/2}$ bits/response

and $I_p = 1/t \log \frac{A}{w/2}$ bits/second

where I_d and I_p are the index of difficulty and the index (rate) of performance and t is the average movement time per response.

Fitts verified his formulation with four sets of experimental data. In one experiment, the subjects tapped alternately on two six inches long metal strips, using a metal tipped stylus about the size of a pencil and weighing one ounce. The long axes of the strips were perpendicular to the line of movement between them. The strips were mounted on a board placed in such a position that the subject's movements were from side to side in front of him. Four widths of target strips were used (0.5, 1.0, 2.0, and 2.5 inches) at each of four distances between centers (2, 4, 8, and 16 inches). By plotting the average time/movement versus $\log \frac{A}{w/2}$, it was found that Fitts' formulation was valid.

As the straight line obtained by plotting the points according to the Fitts formula cuts the zero line below the origin thereby making the constant 'a' in the equation a negative quantity, Crossman (1960) suggested the following modification in the Fitts formula:

$$\text{Movement Time} = a + b \log A/w$$

Crossman's results, although obtained independently of Fitts, are in striking agreement with them. He has further shown that the length of target strip as well as its width affect movement time, although to a smaller extent.

It has been further found in another similar experiment by Welford (1958) that the results are on the whole more uniform in their fit to the equations of Fitts, if the times on the target and between targets are added together than if the later measure only is taken.

Similar close results were again obtained by Fitts (1954) in a similar dotting task but using a stylus weighing 1 pound instead of 1 ounce. Fitts noted that this similarity clearly supports the view that the movement time is determined more by central processes controlling and monitoring movements than by any factors of muscular effort involved.

In a third experiment by Fitts (1954), the subjects transferred washers from a vertical pin to another pin a given distance to the left. Four distances between pin centers were used with each of four sizes of holes. The target widths were taken as the difference between the diameters of pins and holes. He found that the rate of performance was approximately constant over a considerable range of amplitude.

In the fourth task of Fitts (1954), the subjects transferred metal pins from one set of holes to another a given distance away. Four diameters of pins were used with five distances. The holes were in each case twice the diameter of the pins. The target width was again taken as the tolerance between pins and holes. The rate of performance was found constant for all the conditions of task.

Annett, et. al. (1958) employed a similar task to one used by Fitts (1954) and found that to obtain the proper measure of index of performance, it is necessary to use only the time for that portion of the motion which is related to the difficulty in question. Another very important point that can be ascertained from their experiment is that the information is the same for a given experiment when either the total forward movement is concerned or this motion is broken down in therbligs.

Rosenstein (1955) has discussed the possible applications of the information theory in the industrial field. He stated that, because of mathematical structure, information theory should prove the tool to resolve the industrial engineering problems of capacity, production rate, system noise and error (quality control). He further stated that Fitts' work has already added another dimension to time and motion study and in the near future the information communication theory should become the mathematics of Industrial Engineering.

Ross (1960) made a wide study of information theory and he said information theory can be extended to provide a powerful aid in the evaluation, measurement and synthesis of human work. He has further stated that information theory can be used to analyze a number of sensory motor tasks.

Further investigations by Fitts and Peterson (1964) and Fitts and Radford (1966) have proved that the information capacity of the motor system in discrete tasks is rather higher than serial tasks and the same was found to vary from about

22 bits/secs. for a value of I_d = 2.5 bits to 14 bits/secs. for I_d = 7.5 bits.

Thus the review of literature revealed that the principles of motion economy, as established by Barnes (1940) have been investigated under the criteria of physiological cost, the least time or accuracy only. But under the criteria of speed and accuracy both, no study has been conducted in regards to simultaneous motions of hands.

However Briggs (1955) studied the movements of hands under the criterion of accuracy and speed both, but this study was restricted to single hand motions only. It was therefore decided to undertake the study of simultaneous motions of hands using the criterion of both accuracy and speed.

HYPOTHESES:

(1) The accuracy and speed of linear hand motions varies with the direction of the path of movement.

(2) The accuracy and speed of the linear hand-arm motions is affected by the length of the movements.

(3) The angle or the combination of angles of maximum response does not remain the same for different lengths of movements.

(4) There is a considerable difference between the response of the left hand and the right hand. The performance of right hand is superior to the left hand.

(5) There is an interaction effect between the two hands, when moving simultaneously.

(6) Simultaneous and symmetrical motions of hands in opposite directions are faster and more accurate than the simultaneous and assymetrical motions in the horizontal plane.

TASK AND APPARATUS

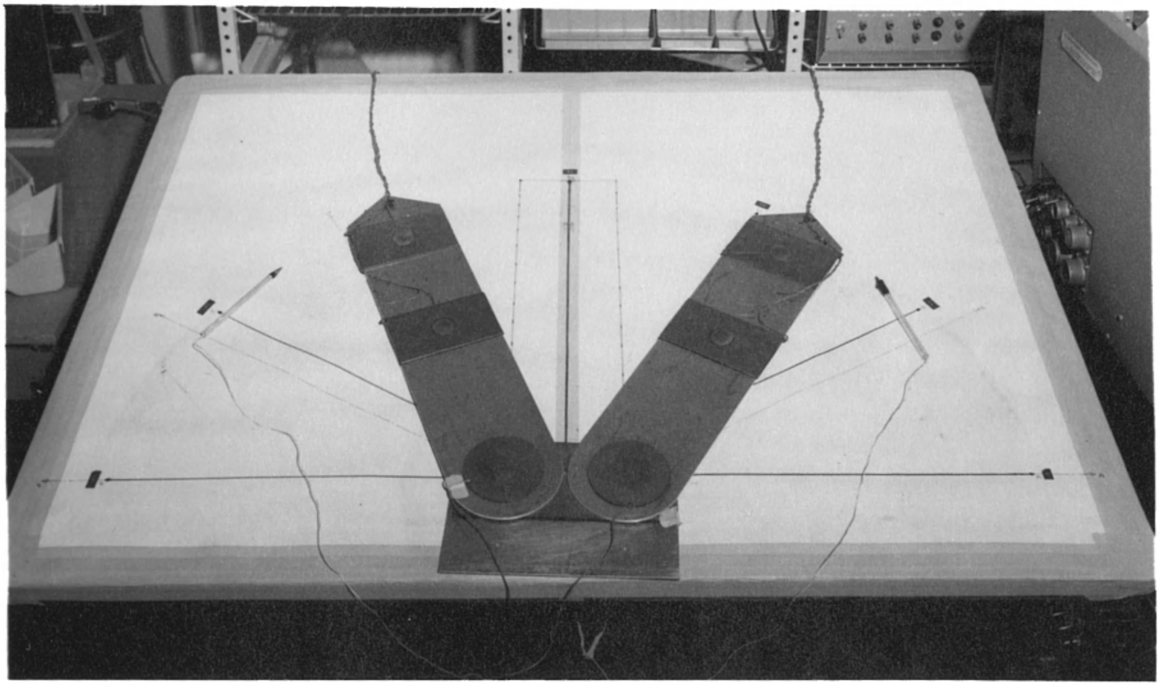
(1) Working table with adjustable heights: (Plate 1)

The table used for this study was 26 inches in depth and 52 inches wide with a mechanism attached to it for adjusting its height from the floor. The table top was covered by a white drawing sheet, on which the direction of movements were clearly marked by drawing the radii of the circle. The centers of two fixed circular plates (3-1/2" diameter) were marked at a distance of 5 inches from the front edge of the table and 2-3/4 inches on either sides of the central vertical line dividing the table top into two equal parts. From these two centers, two quarter circles were drawn on either side of the vertical reference line. The radii were drawn from the centers of the above quarter circles to their circumference at angles of 0°, 30°, 60°, 90°, 120°, 150° and 180° (0° is defined as "3 o'clock" position). These angles were marked as A, B, C, D, E, F and G respectively for reference purposes. (Plate 1).

(2) Target Assembly Plate:

The brass inner targets (3-1/2" diameter) and the brass outer targets (1 inch diameter) were mounted on an aluminum plate 22 inches long, 5 inches wide and 1/8 inch thick as shown in Plate 1. The brass circular outer targets were surrounded by a steel rectangular error surface plate 3 inches x 5 inches. The two outer targets along with their error surface plates were fixed on the aluminum plates at 9 and 16 inches from the center of the inner targets. These assembly plates were fixed on the table

Plate 1. Experimental Apparatus



in such a manner that they were free to rotate at the center of their inner target. The inner targets, outer targets and error plates were insulated from each other and each plate was electrically connected to separate mechanical counters (Plate 1).

(3) Stylus:

Each metal tipped stylus was 5-1/2 inches long and 5/16 inches in diameter fitted with a sharp conical tip of brass. The weight of the stylus was one ounce and its shape was just like an ordinary ball point pen. The brass tip was electrically connected to the circuit of the counter through a 8 volt DC supply source, so as to record the number of hits. There was one stylus for each hand (Plate 1).

(4) Mechanical Counters:

The counters were used for recording the number of hits made by the stylus on the inner targets, outer targets and error plates. All these plates were electrically connected to the different counters in such a manner that as soon as the contact of the electrical circuit of the corresponding counter was closed by the contact of stylus with one of the plates, the respective counter incremented one digit. Each plate was connected separately to each different counter and, in all, ten counters were utilized.

(5) Battery Eliminator and Charger:

This apparatus was used as a 8 volt D.C. supply source for the counters.

(6) Measuring Tape:

A measuring tape in 1/2 inch increments was used for measuring the elbow height, upper arm length, lower arm length of the subject and also to adjust the height of the work table.

(7) Stop Watch:

A decimal minute stop watch was used to time trial periods and the rest periods.

SUBJECTS

Eight right-handed female students were paid by the hour. Table 1. Their ages varied from 17 years to 22 years; their heights from 62 inches to 68 inches and their elbow heights ranged from 38 inches to 43 inches.

Table 1

Personal data for subjects

Subject Number	Name	Major	Age	Height	Lower Arm Length	Upper Arm Length	Elbow Height	Experience in Assembly Task
1	S.M	High School Senior	17 yrs.	64"	12"	12"	39"	No
2	J.T	High School Senior	17 yrs.	64"	11"	12"	39"	No
3	V.B	Home Economics	22 yrs.	68"	12"	13"	42"	No
4	S.K	High School Senior	17 yrs.	$65\frac{1}{2}$"	11"	12"	$40\frac{1}{2}$"	No
5	D.M	English	21 yrs.	66"	12"	13"	$41\frac{1}{2}$"	No
6	P.B	High School Senior	17 yrs.	63"	12"	12"	39"	No
7	P.G	Political Science	21 yrs.	62"	$11\frac{1}{2}$"	12"	38"	No

EXPERIMENTAL DESIGN

The subjects were required to make repetitive motions between the outer and inner targets at their maximum accuracy and speed (Plate 2). The criterion used in this study was the hits on the outer target within the 18 second trial interval.

The task had the following features:

(1) The task was comprised of basic motions found in most industrial situations.

(2) The basic method of performing the task was constant for all the subjects at all paces.

(3) The task was simple enough to minimize the effect of learning and fatigue.

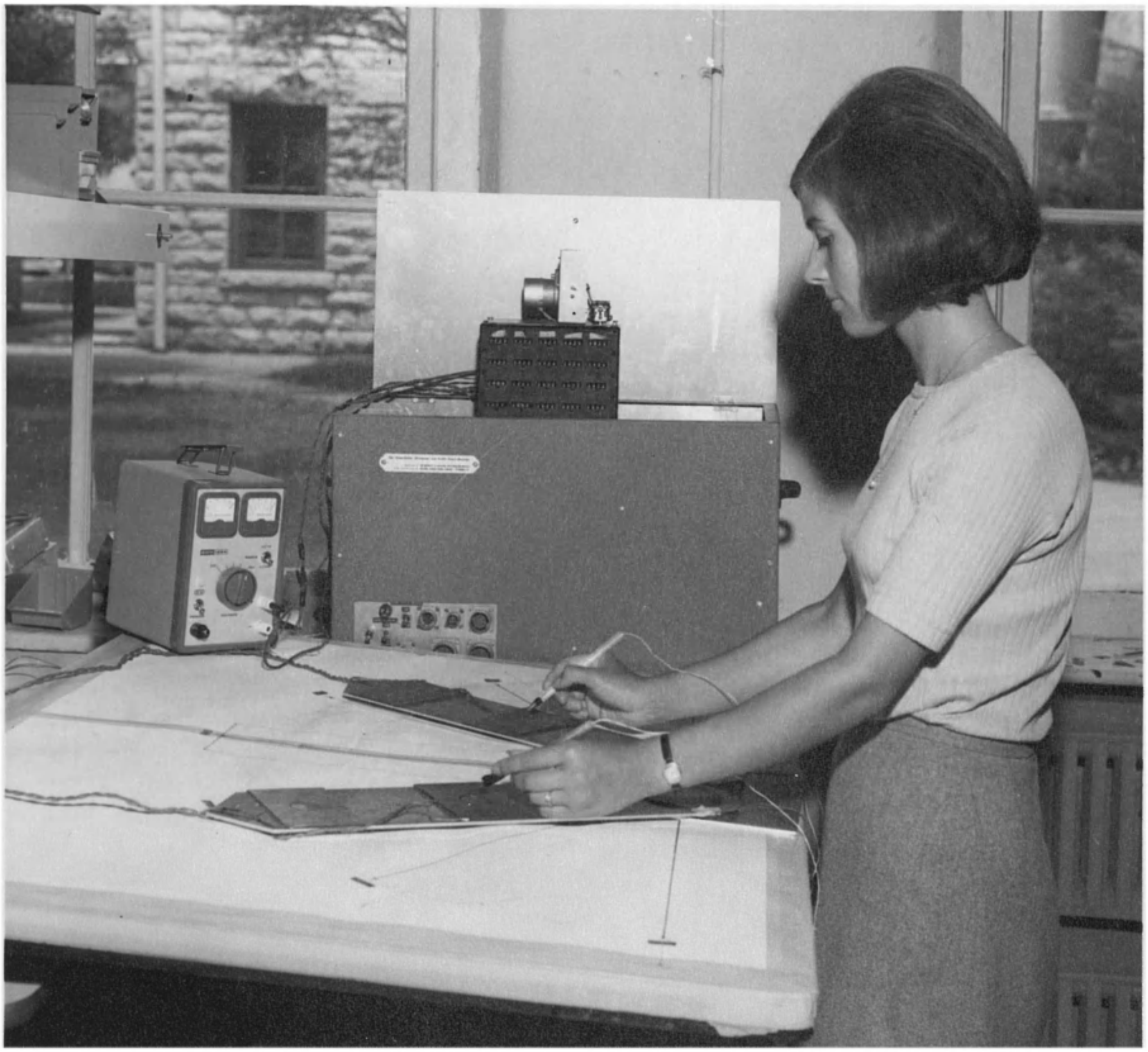
(4) The speed of performing the task could be controlled by the subjects.

In order to make comparisons with the results of previous experiments, the angles were chosen as 0°, 30°, 60°, 90°, 120°, 150° and 180°, where 0° was referred to as 3 o'clock position (Plate 2). The study was restricted to the investigation of the movement variable, when the subject was standing before the table (Plate 3).

The second consideration was to compensate for or to minimize the individual differences among the subjects. Some of the physiological differences such as the heights, arm reach etc. were compensated by designing the apparatus so that it was adjustable. Konz (1967) stated:

Plate 2. Simultaneous Motions of Hand

Plate 3. Simultaneous Motions of Hand



"It has been shown that experimental evidence for working height is scarce, but the results of experiments 1, 2, 3 and 4 along with the literature, indicates that the best height for a standing operator is about one inch below the elbow although the working height can vary several inches up or down without much effect on performance."

Therefore, the height of the work table was kept as one inch below the subject's elbow.

Barnes (1940) recommended that the place where the object being worked upon was located should be three inches to seven inches in front of the subject on the table; therefore the centers of the inner targets were kept five inches from the front edge of the work table.

In order to minimize the cumulative physiological and psychological effects, it was felt necessary to use a different sequence for each operator and each replication. Tables 2 and 3. Since sequence of conditions might influence the accuracy and speed of hand-arm movements at a condition, a random sequence design was used to balance the effect of sequence.

For the study of simultaneous motions of hands, the angle between the hands ranged from 0 to 180 degrees in seven steps (0, 30, 69, 90, 120, 150 and 180 degrees of spread). Each spread had a different number of conditions. In all there were 28 conditions for the two hand simultaneous motions. The conditions for simultaneous motions of hands were designed by using two letter codes, the first letter indicating the direction of movement of the left hand and the second letter the right hand. The groups of angles thus formed were not randomized but the angles within each spread were randomized. In each case, the sequence

Table 2

Sequence of experimental conditions
for simultaneous motions of hands

Subject	Repetition	Conditions (Angles) and Distance													
1.	(i)	X-1	Y-2	Y-3	X-4	X-5	Y-6	Y-7	X-7	X-6	Y-5	Y-4	X-3	X-2	Y-1
	(ii)	Y-1	X-2	X-3	Y-4	Y-5	X-6	X-7	Y-7	Y-6	X-5	X-4	Y-3	Y-2	X-1
2.	(i)	Y-2	X-3	X-4	Y-5	Y-6	X-7	X-1	Y-1	Y-7	X-6	X-5	Y-4	Y-3	X-2
	(ii)	X-2	Y-3	Y-4	X-5	X-6	Y-7	Y-1	X-1	X-7	Y-6	Y-5	X-4	X-3	Y-2
3.	(i)	X-3	Y-4	Y-5	X-6	X-7	Y-1	Y-2	X-2	X-1	Y-7	Y-6	X-5	X-4	Y-3
	(ii)	Y-3	X-4	X-5	Y-6	Y-7	X-1	X-2	Y-2	Y-1	X-7	X-6	Y-5	Y-4	X-3
4.	(i)	Y-4	X-5	X-6	Y-7	Y-1	X-2	X-3	Y-3	Y-2	X-1	X-7	Y-6	Y-5	X-4
	(ii)	X-4	Y-5	Y-6	X-7	X-1	Y-2	Y-3	X-3	X-2	Y-1	Y-7	X-6	X-5	Y-4
5.	(i)	X-5	Y-6	Y-7	X-1	X-2	Y-3	Y-4	X-4	X-3	Y-2	Y-1	X-7	X-6	Y-5
	(ii)	Y-5	X-6	X-7	Y-1	Y-2	X-3	X-4	Y-4	Y-3	X-2	X-1	Y-7	Y-6	X-5
6.	(i)	Y-6	X-7	X-1	Y-2	Y-3	X-4	X-5	Y-5	Y-4	X-3	X-2	Y-1	Y-7	X-6
	(ii)	X-6	Y-7	Y-1	X-2	X-3	Y-4	Y-5	X-5	X-4	Y-3	Y-2	X-1	X-7	Y-6
7.	(i)	X-7	Y-1	Y-2	X-3	X-4	Y-5	Y-6	X-6	X-5	Y-4	Y-3	X-2	X-1	Y-7
	(ii)	Y-7	X-1	X-2	Y-3	Y-4	X-5	X-6	Y-6	Y-5	X-4	X-3	Y-2	Y-1	X-7

Where -

1- 0° Spread - AA, BB, CC, DD, EE, FF, GG.

2- 30° Spread - AB, BC, CD, DE, EF, FG.

3- 60° Spread - AC, BD, CE, DF, EG.

4- 90° Spread - AD, BE, CF, DG.

5-120° Spread - AE, BF, CG.

6-150° Spread - AF, BG.

7-180° Spread - AG.

X- Distance- 9 inches.

Y- Distance-16 inches.

Table 3

Sequence of experimental conditions
for single hand motions

Subject	Repetition	Conditions (Angles) and Distances													
1.	(i)	X-A	Y-B	Y-C	X-D	X-E	Y-F	Y-G	X-G	X-F	Y-E	Y-D	X-C	X-B	Y-A
	(ii)	Y-A	X-B	X-C	Y-D	Y-E	X-F	X-G	Y-G	Y-F	X-E	X-D	Y-C	Y-B	X-A
2.	(i)	Y-B	X-C	X-D	Y-E	Y-F	X-G	X-A	Y-A	Y-G	X-F	X-E	Y-D	Y-C	X-B
	(ii)	X-B	Y-C	Y-D	X-E	X-F	Y-G	Y-A	X-A	X-G	Y-F	Y-E	X-D	X-C	Y-B
3.	(i)	X-C	Y-D	Y-E	X-F	X-G	Y-A	Y-B	X-B	X-A	Y-G	Y-F	X-E	X-D	Y-C
	(ii)	Y-C	X-D	X-E	Y-F	Y-G	X-A	X-B	Y-B	Y-A	X-G	X-F	Y-E	Y-D	X-C
4.	(i)	Y-D	X-E	X-F	Y-G	Y-A	X-B	X-C	Y-C	Y-B	X-A	X-G	Y-F	Y-E	X-D
	(ii)	X-D	Y-E	Y-F	X-G	X-A	Y-B	Y-C	X-C	X-B	Y-A	Y-G	X-F	X-E	Y-D
5.	(i)	X-E	Y-F	Y-G	X-A	X-B	Y-C	Y-D	X-D	X-C	Y-B	Y-A	X-G	X-F	Y-E
	(ii)	Y-E	X-F	X-G	Y-A	Y-B	X-C	X-D	Y-D	Y-C	X-B	X-A	Y-G	Y-F	X-E
6.	(i)	Y-F	X-G	X-A	Y-B	Y-C	X-D	X-E	Y-E	Y-D	X-C	X-B	Y-A	Y-G	X-F
	(ii)	X-F	Y-G	Y-A	X-B	X-C	Y-D	Y-E	X-E	X-D	Y-C	Y-B	X-A	X-G	Y-F
7.	(i)	X-G	Y-A	Y-B	X-C	X-D	Y-E	Y-F	X-F	X-E	Y-D	Y-C	X-B	X-A	Y-G
	(ii)	Y-G	X-A	X-B	Y-C	Y-D	X-E	X-F	Y-F	Y-E	X-D	X-C	Y-B	Y-A	X-G

Where -

A - 0°	D - 90°	G - 180°
B - 30°	E - 120°	X - 9 inches
C - 60°	F - 150°	Y - 16 inches

of spreads was represented by rows in Table 2 and 3 with each row having 14 groups of angles. In the first row, the sequence started from group number one (0° spread) and it ended with the same group, as the groups of angles in the last seven cells of the first row reversed the sequence of the conditions in the first seven cells. This was done in order to balance the effect of practice and fatigue between two replications. In order to study the effect of distance on the simple hand arm movements, the distances chosen for this study were 9" and 16". In the second row the angles were given in the same sequence as in row one but the nine and sixteen inch distances were reversed. This procedure was continued until a 14 x 14 table for simultaneous motions of the two hands and 14 x 14 table for single hand motions of each hand separately was constructed. The pairs of rows were assigned randomly to the subjects.

To summarize, seven angles and two distances were varied and the number of correct hits made on the target were recorded with an electronic counter. The main variables involved in this study were (1) Angle, (2) Distance and (3) Hands.

The controlled conditions designed in this experiment were as follows:

(1) Subjects were selected on a random basis from among the volunteers.

(2) All the subjects performed identical tasks and each subject served in each condition.

(3) The individual trials were assigned randomly.

(4) A formal set of introductory instructions was given to the subjects.

(5) The complete objective of the experiment was not explained to the subjects to reduce the possibility of bias.

(6) The subjects performed their task in standing position.

(7) The height of the work table was kept one inch below the subject's elbow joint throughout the experiment.

(8) A practice session was given for one set of trials before beginning each part of the experiment to each subject.

(9) The subjects were provided with the knowledge of their performance i.e. response scores and errors, after completion of each trial during the practice session. The purpose of this feed-back was to provide continuous motivation of the operator to perform at her best and to enable her to adjust her hand movements for the maximum accuracy and speed.

(10) The amount of rest between the set of trials in each part of the experiment was kept constant at 5 minutes.

(11) The subjects were not allowed to study the task during the rest periods.

A pilot study for the complete task consisting of 168 trials excluding practice trials was conducted on a subject to check the equipment, to provide experience for the experimenter, to know the approximate duration of the experiment and to verify the applicability of the experimental task; this data is not included in the analysis.

The statistical model was a four-factor, twice replicated, completely randomised, mixed factorial design. The model was as follows:

$$Y_{ijklm} = \mu + S_i + A_j + D_k + H_l + SA_{ij} + AD_{jk} + DH_{kl} + HS_{li} + HA_{ij} + SD_{ik} + SDH_{ikl} + SAD_{ijk} + ADH_{jkl} + SAH_{ijl} + SADH_{ijkl} + e_{ijklm} .$$

where Y denotes the response score.

μ denotes the true response of the over-all mean.

S denotes the effect due to subjects.

A denotes the effect due to angles.

D denotes the effect due to distances.

H denotes the effect due to hands.

i denotes the number of levels of subjects.

j denotes the number of levels of angles.

k denotes the number of levels of distances.

l denotes the number of levels of hands.

m denotes the number of replications.

e denotes the effect due to experimental error.

This is a mixed model as the main effect of subject was random and the main effects of distances, angles and hands were fixed.

EXPERIMENTAL PROCEDURE

Each subject was brought into the experimental room, where the following anthopometric measurements were taken:

(1) Height (2) Upper arm length (3) Lower arm length and

(4) Elbow height.

Her personal data such as name, age and major course of study also recorded. Table 1. She was also asked whether she had done any assembly work before. The measurement of length of her upper arm was taken from the tip of the elbow to the top of the shoulder. While taking the above measurement, the subject was asked to keep her upper arm in a vertical position adjacent to her body with her lower arm at right angles to the upper arm. Elbow height was then measured from the floor.

After taking the elbow height, the height of the work table was adjusted to a height one inch below the subject's elbow.

The subject was then directed to stand in front of the task as close to the work table as was comfortable to her (Plate 2). The readings of the counters were cleared to zero.

The subject was given the instruction sheet containing the appropriate instructions for the task and the same was read by the experimentor. The reading was accompanied at appropriate places by careful demonstrations of the desired task/movements.

The text was:

"In this experiment, you will be required to perform a series of simple motor tasks involving one hand and two hand motions. The purpose of this experiment is to determine the speed and accuracy with which you would hit the target with the stylus. The task consists of moving the stylus, held in one hand or in both hands from the circular plates in front of you to the targets fixed at the other end of the target assembly plate. Your task is to hit the target with the stylus as fast and accurately as you can. Your efficiency will be judged on the basis of number of correct hits made on the target. If you go very fast, you will make more errors and if you go very slow, you will make few errors, but less number of correct hits. During the practice trial, you would be able to estimate your optimum speed for the highest response scores.

You will start your task by touching the circular plates in front of you and then moving the hand/hands to hit the respective targets and return. Thus every time you strike the target, you will make one 'in' and one 'out' motion. The position of the targets will vary from trial to trial. Before starting the actual experiment you will be given a practice session, so as to enable you to estimate your optimum speed for the maximum response scores. You will be given eighteen seconds for completion of each trial and a rest of five minutes will be given after each set of trials.

You are now about to start the experiment. Stand erect close to the edge of the work table, so that the center of your body touches the center of the front edge of the table. Grasp the stylus with your thumb, fore-finger and middle finger and try to hold it in a vertical position all the time.

The experimenter will say 'Set' and then 'Go'. As soon as you get the signal 'Go', touch the fixed circular plates in front of you and move your hand/hands simultaneously to hit the respective targets and return to the starting position. Continue repeating this operation as rapidly and accurately as you can, till you get the signal 'Stop'. Always remember to return your hands to the starting position immediately after striking the targets each time. Be careful not to shift your body to any new position after you have begun to tap the targets.

In single hand motions, your task will remain the same as above, except that you will be required to move only one hand at a time, while the other hand will remain idle.

Do you have any questions?"

Any questions by the subjects were answered immediately during the course of reading.

Before starting the task of two hand simultaneous motions, the subject was given a practice session of 56 trials (one trial for each condition); 14 practice trials were given before the single hand motions. After completion of each performance trial, the subject was told her correct response scores and number of errors, so as to enable her to adjust her speed and to improve her scores in the subsequent trials.

After the subject had completed her practice session, the angles of the target-assembly plates were adjusted to that which occurred first in the sequence to which she was assigned and the experiment was begun.

The number of trials performed and the rests given to each subject were as follows:

(i) Two hand simultaneous motions -

Practice Session - 56 trials (One trial at each distance and angle)
3 minutes rest after every 14 trials
5 minutes rest after completion of practice session

Experimental Session - 112 trials (Two trials at each distance and angle)
3 minutes rest after every 14 trials
5 minutes rest after 56 trials
15 minutes rest after completion of 112 trials

(ii) Single hand motions

Practice Session - (a) Right Hand
14 trials (One trial at each distance and angle)
5 minutes rest

Experimental Session - 28 trials (two trials at each distance and angle)

3 minutes rest after every 14 trials

5 minutes rest after completion of 28 trials

Practice Session - (b) Left hand

14 trials (one trial at each distance and and angle)

5 minutes rest

Experimental Session - 28 trials (two trials at each distance and angle)

3 minutes rest after every 14 trials

5 minutes rest after completion of 28 trials

Each trial consisted of a 18 seconds work interval followed by a rest period of about 15 seconds (the time required to record the scores, to clear the counter readings to zero and to change the angle of the target-assembly plate). Every subject was given two trials at each distance and angle. The duration of experimental session was approximately four hours.

Whenever the subject failed to hit the inner target in any of the trials, the condition was repeated. The task was performed by the subjects as shown in Plate 2, Plate 3, Plate 4 and Plate 5.

Plate 4. Single Hand Motions (Left Hand)

Plate 5. Single Hand Motions (Right Hand)

RESULTS

(1) Simultaneous motions of hands:

A four-way analysis of variance was used for analyzing simultaneous motions of hands.

An analysis of variance applied to the complete data of the simultaneous motions of both hands showed that the main effects of subjects, angles, distances and hands were all significant at the one percent level of probability and the subject x distance, the subject x hands and the angle x hands interactions were also significant ($p < .01$). (Table 4)

Duncan's New Multiple Range Test ($\alpha = 0.05$) was employed to determine the significant statistical differences among the different combinations of angles. Mean response scores of both the hands summed over two distances for each condition were used. Table 5.

The mean response scores of DD, EE, and CC were found significantly better than all the remaining 25 combinations of angles (Table 5) but there was not any statistical difference among these three conditions. BB and FF are second best and CD and AA are third. These results are in complete agreement with the results obtained by Barnes and Mundel (1939). They concluded that the 90° position was the best for both the hands when the hands were directed by vision, and in absence of visual direction, 60° for the right hand and 120° for the left hand was best.

From the mean scores in Table 6, 7 and Fig. 1, it appears that as the spread of the angle between the direction of move-

Table 4

Analysis of variance for simultaneous motions of hands

Source	d.f	M.S.	F
Subjects (S)	6	438.66	58.84 **
Angles (A)	27	326.74	24.42 **
Distance (D)	1	21352.00	218.61 **
Hands (H)	1	1502.00	16.94 **
S X A	162	13.38	1.63
S X D	6	97.67	11.88 **
S X H	6	88.67	10.79 **
A X D	27	14.74	1.35
A X H	27	73.26	4.19 **
D X H	1	38.00	0.58
S X D X H	6	65.83	8.01 **
S X A X D	162	10.88	1.32 **
S X A X H	162	17.46	2.12 **
A X D X H	27	12.55	1.48
S X A X D X H	162	8.50	1.03
Residual (Error)	784	8.22	
Total	1567		

** $p < .01$

Table 5

Mean score for simultaneous motions at each combination of angles. Those scores underlined by the same line are not significantly (α = .05) different.

Rank	1	2	3	4	5	6	7	8	9	10	11	12	13
Angles	D D	E E	C C	B B	F F	C D	A A	D E	G G	B C	E F	A B	C E
Mean Score	98.78	97.78	96.00	92.57	90.14	86.86	85.21	82.14	81.93	81.78	81.78	79.28	77.57

Rank	14	15	16	17	18	19	20	21	22	23	24	25	26
Angles	B D	F G	A C	E G	D F	B F	C F	B E	A D	C G	D G	A F	A E
Mean Score	76.14	75.42	75.21	74.50	74.21	73.57	72.93	72.50	70.28	70.28	69.50	68.86	67.93

Rank	27	28
Angles	A G	B G
Mean Score	65.86	64.57

Key: A = 0°, B = 30°, C = 60°, D = 90°, E = 120°, F = 150°, G = 180°

Table 6

Mean response score, mean error score, average speed and index of performance for simultaneous motions of hands for a distance of movement of nine inches.

Spread of Angle	Angles in Spread	Mean Score LH	Mean Score RH	Mean Score LH+RH	Mean Error LH	Mean Error RH	Mean Error LH+RH	Average Speed, cm/sec.	Index of Perform- ance, bits
	E E	27.86	27.93	55.79	3.85	3.79	7.64	80.60	14.72
	D D	28.64	27.28	55.92	2.43	3.79	6.22	79.00	14.42
	B B	28.36	25.86	54.22	2.21	4.71	6.92	77.75	14.20
0°	C C	28.43	26.07	54.50	2.21	3.93	6.14	77.00	14.05
	E F	24.71	25.93	50.64	5.21	4.00	9.21	77.00	14.05
	A A	26.21	23.21	49.42	2.79	5.78	8.57	72.50	13.82
	G G	22.14	24.36	46.50	6.28	4.15	10.43	72.20	13.50
	C D	26.21	25.50	51.71	5.15	5.85	11.00	79.75	14.58
	B C	26.14	22.71	48.85	4.07	7.50	11.57	76.75	14.00
	E F	24.36	24.28	48.64	5.65	5.71	11.36	76.30	13.92
30°	D E	24.64	24.07	48.71	5.21	5.65	10.86	75.60	13.80
	A B	26.14	21.57	47.71	3.28	7.85	11.13	75.00	13.68
	F G	22.71	22.71	45.42	6.15	6.07	12.22	73.40	13.39
	C E	24.57	22.21	46.78	5.35	7.71	13.06	76.10	13.90
	D F	24.14	21.71	45.85	5.35	8.07	13.42	75.40	13.88
60°	B D	25.00	21.57	46.57	4.57	8.00	12.57	75.20	13.72
	A C	25.07	21.14	46.21	4.43	8.35	12.78	75.00	13.68
	E G	23.43	22.71	46.14	5.57	6.28	11.85	73.65	13.45
	A D	24.93	17.36	42.29	4.35	11.85	16.20	75.20	13.72
90°	B E	24.21	19.78	43.99	5.21	9.65	14.86	74.70	13.63
	C F	24.50	20.71	45.21	4.78	8.57	13.35	74.40	13.58
	D G	20.43	21.78	42.21	7.65	7.00	14.65	72.30	13.20
	B F	23.36	20.86	44.22	4.93	7.43	12.36	71.90	13.12
120°	C G	20.21	21.71	41.92	7.71	6.21	13.92	70.60	12.96
	A E	23.50	17.50	41.00	4.28	10.28	14.56	70.00	12.00
150°	A F	23.00	18.78	41.78	5.58	9.85	15.43	72.60	13.28
	B G	21.71	15.64	37.35	6.28	12.35	18.63	71.15	13.00
180°	A G	20.93	18.28	39.21	7.56	10.21	17.77	72.40	13.20

Table 7

Mean response score, mean error score, average speed and index of performance for simultaneous motions of hands for a distance of movement of sixteen inches.

Spread of Angle	Angles in Spread	Mean Score LH	Mean Score RH	Mean Score LH+RH	Mean Error LH	Mean Error RH	Mean Error LH+RH	Average Speed, cm/sec.	Index of Perform-ance, bits
	E E	21.50	20.50	42.00	3.21	4.00	7.21	111.20	13.66
	D D	22.21	20.64	42.85	2.35	3.93	6.28	111.00	13.65
	C C	21.86	19.64	41.50	2.57	4.79	7.36	110.20	13.55
0°	F F	19.86	19.64	39.50	4.35	4.50	8.85	109.10	13.42
	G G	17.00	18.43	35.43	6.35	4.93	11.28	105.30	12.95
	B B	20.00	18.36	38.36	2.85	4.50	7.35	103.00	12.68
	A A	19.43	17.07	36.50	3.15	4.93	8.08	100.80	12.40
	E F	16.57	16.57	33.14	8.07	7.35	15.42	109.80	13.50
	C D	18.86	16.28	35.14	5.15	7.71	12.86	108.30	13.35
30°	B C	18.50	14.43	32.93	5.07	9.15	14.22	106.40	13.10
	D E	18.78	16.64	35.42	6.21	6.35	12.56	103.60	12.75
	A B	18.28	13.28	31.56	4.50	9.50	14.00	102.80	12.65
	F G	13.64	16.36	30.00	8.28	5.57	13.85	99.00	12.19
	C E	16.28	14.50	30.78	7.15	8.93	16.08	105.90	13.00
	B D	17.21	12.36	29.57	5.65	10.50	16.15	103.00	12.68
60°	D F	14.14	14.21	28.35	8.43	8.35	16.78	101.80	12.52
	A C	17.43	11.57	29.00	5.21	10.93	16.14	101.80	12.52
	E G	12.78	15.57	28.35	9.15	6.35	15.50	99.00	12.18
	B E	16.71	11.78	28.49	6.15	10.65	16.80	102.20	12.58
	C F	14.50	13.21	27.71	7.00	8.93	15.93	98.50	12.12
90°	A D	16.93	11.07	28.00	4.85	10.15	15.00	97.10	11.95
	D G	12.93	14.36	27.29	8.21	6.93	15.14	95.75	11.78
	B F	15.57	13.78	29.35	8.35	10.15	18.50	108.00	13.30
120°	A E	16.57	10.36	26.93	6.43	12.57	19.00	103.50	12.74
	C G	14.57	13.78	28.35	8.43	9.21	17.64	103.40	12.74
	A F	14.28	12.78	27.06	8.71	10.21	18.92	103.50	12.74
150°	B G	13.64	13.57	27.21	8.43	8.50	16.93	99.60	12.25
180°	A G	13.43	13.21	26.64	8.21	8.93	17.14	100.00	12.28

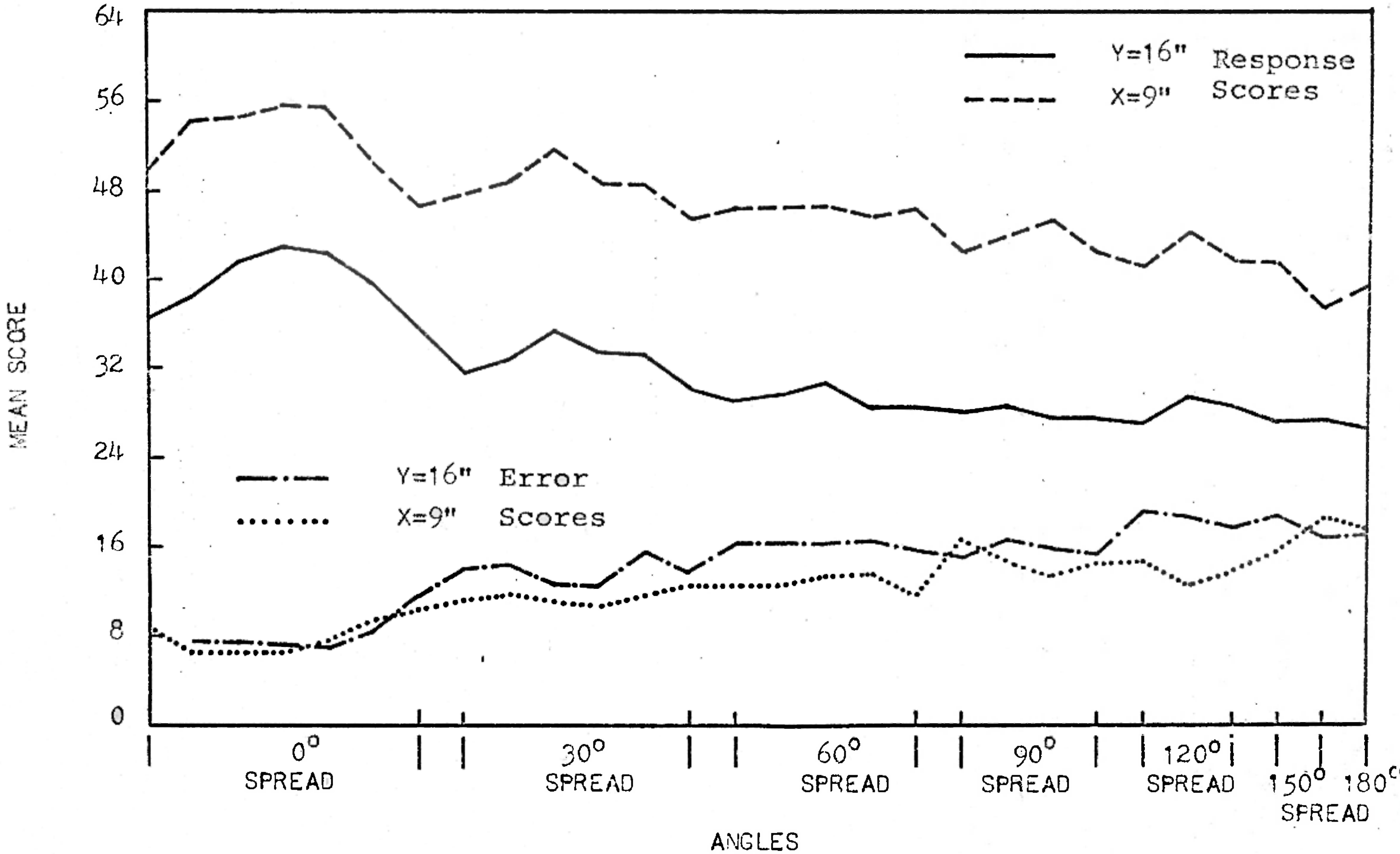


Figure 1

Simultaneous Motions of Hands

ment of the right and left hand increases, the mean response scores decreases. According to the results, the response scores of the combination of angles for 0° spread were found maximum, whereas the response scores for 180° were minimum. These results clearly show that the main factor affecting the speed and accuracy of simultaneous motions of hand is the spread of the angle between the direction of movement of right hand and left hand. Therefore it can be concluded that, in simultaneous motions of hands, the spread of angle is more important than simply the angles.

The response scores were further analysed by grouping them according to the spread of the angle (Table 8). The result is summarised as follows:

Spread	0°	30°	60°	90°	120°	150°	180°
Best Condition	CC,EE,DD	CD	CE	BE,CF	BF	AF	AG

From the above analysis it was found that the majority of the best conditions in various spread of angles fall into the category of symmetrical motions and considering the correct response scores, simultaneous and symmetrical motions are 6.38% better than simultaneous and assymmetrical motions. This was calculated by taking the overall average of correct response scores at various angles of symmetrical and non-symmetrical motions separately.

Table 8

Mean score for simultaneous motions at each combination of angle when arranged by amount of spread. Those scores underlined by the same line are not significantly (α=.05) different. Scores for 9 and 16 inches combined.

(1) 0° Spread -

Rank	9	7	5	4	3	2	1
Angles	G G	A A	F F	B B	C C	E E	D D
Scores	81.93	85.21	90.14	92.57	96.00	97.78	98.78

(2) 30° Spread -

Rank	15	12	11	10	8	6
Angles	F G	A B	E F	B C	D E	C D
Scores	75.42	79.28	81.78	81.78	82.14	86.86

(3) 60° Spread -

Rank	18	17	16	14	13
Angles	D F	E G	A C	B D	C E
Scores	74.21	74.50	75.21	76.14	77.57

(4) 90° Spread -

Rank	24	22	21	20
Angles	D G	A D	B E	C F
Scores	69.50	70.28	72.50	72.93

(5) 120° Spread -

Rank	26	23	19
Angles	A E	C G	B F
Scores	67.93	70.28	73.57

(6) 150° Spread -

Rank	28	25
Angles	B G	A F
Scores	64.57	68.86

(7) 180° Spread -

Rank	27
Angles	A G
Scores	65.86

Distance ov movement was found significant at the one percent level of probability in Table 4.

From the mean scores plotted in Fig. 1, in appears that as the length of movement increases, the response scores decrease, but by plotting the number of errors made at each angle for each distance, it was found that as the distance of movements increases, the number of errors also increases simultaneously.

As a result of the increase in distance of movement from 9 inches to 16 inches, the number of errors increased by 11% whereas the number of total hits and the number of correct hits were reduced by 22% and 31% respectively. Therefore it can be concluded that the simultaneous movements of hand are less accurate for longer distances than for smaller distances.

From the experimental data, the estimate of the average speed of movement for a condition under each spread was obtained by calculating an average speed of movement for each individual from the mean length of the primary movements and their duration. This was done separately for each combination of angle and for each distance (Table 6 and 7).

The term average speed is used because the method of calculation yielded the average speed during an interval between the start of a movement and its termination, rather than the instantaneous speed at any point. From Tables 6, 7 and Fig. 2, it is apparent that an increase in the length of a movement is accompanied by an increase in the mean average speed.

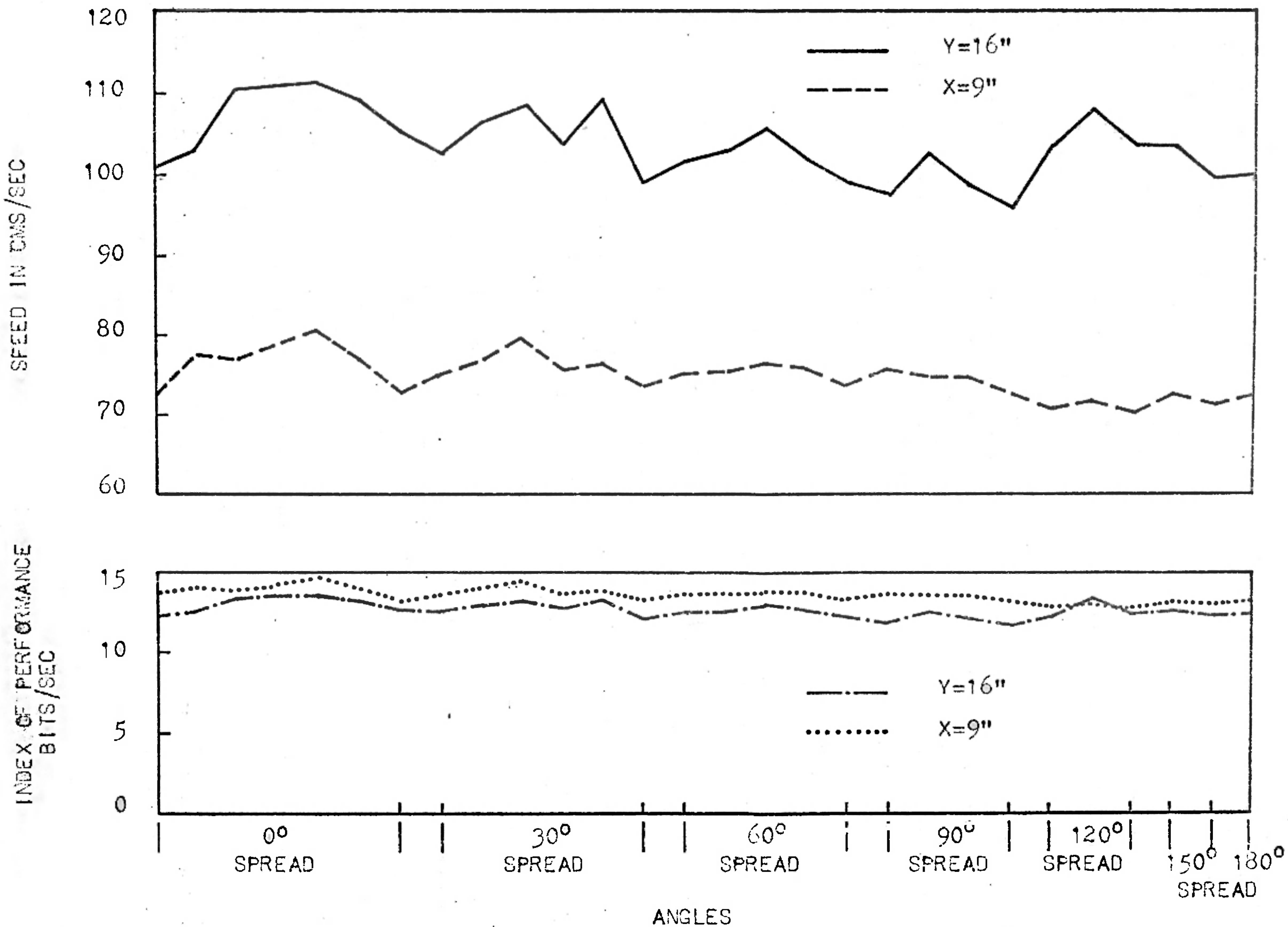


Figure 2

Simultaneous Motions of Hands

In Tables 6 and 7, data are presented showing the mean speeds obtained at various directions and for each distance. For a distance of 9 inches (Table 6), the speed of hand movements varied from 70 cms/sec. at CG to 80 cms/sec. at EE. The speed of hand movements at DD and EE were found almost the same. For a distance of 16 inches (Table 7), the speed of hand movements varied from 95.75 cms/sec. at angles DG to 111.20 cms/sec. at angles EE. The speeds of hand movements at angles CC, DD, and EE were almost the same and it was maximum. This further confirms that the simultaneous hand movements at 0° spread within the zone from 60° to 120° are the most accurate and fast.

From the error scores, it was found that as the spread of the angle increases, the number of errors also increases simultaneously (Fig. 1 and Tables 6 and 7).

The index of difficulty as calculated from Fitts' formula, was 4.2 bits per response for 9 inch movements and 5 bits per response for 16 inch movements.

The index of performance varied from 12.90 bits/sec. to 14.7 bits/sec. at 9 inches and from 11.8 to 13.7 bits/second at 16 inches.

The experimental data was further analyzed for the response score of the left and right hand separately; the analyses of variance are shown in Tables 9 and 10.

Subjects, distance, angles and the interaction of subjects with distance were found significant at the one percent level of probability. In the case of the right hand, the interaction

Table 9

Analysis of variance for left hand in simultaneous motions

Source	d.f	M.S.	F
Subject (S)	6	678.33	37.29 **
Angles (A)	27	330.15	15.22 **
Distance (D)	1	22920.00	97.53 **
S X A	162	21.69	1.19
S X D	6	235.00	12.92 **
A X D	27	24.67	1.36
Residual (Error)	162	18.19	
Total	391		

**p < .01

Table 10

Analysis of variance for right hand in simultaneous motions

Source	d.f.	M.S.	F
Subjects (S)	6	464.66	22.54 **
Angle (A)	27	470.44	11.76 **
Distance (D)	1	19858.00	213.91 **
S X A	162	39.99	1.94 **
S X D	6	92.83	4.50 **
A X D	27	29.18	1.42
Residual (Error)	162	20.61	
Total	391		

$^{**}p < .01$

of subject with angle was also found significant at one percent level of probability but the angle x distance interaction was not significant for either hand.

The significant effect due to subjects and its interaction with distance shows that some subjects had maximum scores at one distance and some at the other distance. For example, subject five's maximum score might have been at 9 inches while subject two's maximum score might have been at 16 inches.

Although the analysis of combined scores of both the hands in Table 4 showed non-significant interaction between the subject and angle, the same interaction was found significant for the right hand movements in simultaneous motions. It can be concluded that the performance of the right hand in simultaneous motions differs with angle from subject to subject, whereas the performance of the left hand does not differ with angle for the right handed subjects.

By analysing the data of left hand and right hand separately for each distance, the mean response score of left hand was found to be more than the mean response score of the right hand for both the distances (Table 11). This shows that the left hand makes movements more accurately and faster than the right hand, when both hands are involved in simultaneous motions.

On analysing the data of simultaneous motions of hands separately for each distance (Tables 12 and 13), the overall results were found the same and the angle of maximum response was found as DD for both the distances. Hence it can be con-

Table 11

Overall mean response scores of left hand and right hand

Distance of Movement, Inches	Simultaneous Motions		Single Hand Motions	
	Left Hand	Right Hand	Left Hand	Right Hand
9	24.50 (72%)	22.25 (65%)	29.30 (86%)	34.05 (100%)
16	16.85 (65%)	15.12 (58%)	22.85 (88%)	26.00 (100%)

Table 12

Mean score for 9 inch distance for simultaneous motions at each combination of angle when arranged by amount of spread. Those scores underlined by the same line are not significantly (α = .05) different.

(1) 0° Spread -

Rank	14	7	6	4	3	2	1
Angles	G G	A A	F F	B B	C C	E E	D D
Scores	46.50	49.43	50.64	54.21	54.50	55.78	55.90

(2) 30° Spread -

Rank	18	11	10	9	8	5
Angles	F G	A B	E F	D E	B C	C D
Scores	45.43	47.71	48.64	48.71	48.85	51.71

(3) 60° Spread -

Rank	17	16	15	13	12
Angles	D F	E G	A C	B D	C E
Scores	45.85	46.14	46.21	46.57	46.78

(4) 90° Spread -

Rank	23	22	21	19
Angles	D G	A D	B E	C F
Scores	42.21	42.28	44.00	45.14

(5) 120° Spread -

Rank	26	24	20
Angles	A E	C G	B F
Scores	41.00	41.93	44.21

(6) 150° Spread -

Rank	28	25
Angles	B G	A F
Scores	37.35	41.78

(7) 180° Spread

Rank	27
Angles	A G
Scores	39.21

Table 13

Mean score for 16 inch distance for simultaneous motions at each combination of angle when arranged by amount of spread. Those scores underlined by the same line are not significantly (α = .05) different.

(1) 0° Spread -

Rank	7	6	5	4	3	2	1
Angles	G G	A A	B B	F F	C C	E E	D D
Scores	35.43	36.50	38.35	39.50	41.50	42.00	42.85

(2) 30° Spread -

Rank	14	12	11	10	9	8
Angles	F G	A B	B C	E F	D E	C D
Scores	30.00	31.57	32.92	33.14	33.44	35.14

(3) 60° Spread -

Rank	20	19	17	15	13
Angles	D F	E G	A C	B D	C E
Scores	28.35	28.35	29.00	29.57	30.78

(4) 90° Spread -

Rank	24	23	22	18
Angles	D G	C F	A D	B E
Scores	27.28	27.71	28.00	28.50

(5) 120° Spread -

Rank	27	21	16
Angles	A E	C G	B F
Scores	27.00	28.35	29.35

(6) 150° Spread -

Rank	26	25
Angles	A F	B G
Scores	27.07	27.21

(7) 180° Spread -

Rank	28
Angles	A G
Scores	26.64

cluded that for short distances of movement within a range of 9 to 16 inches, the performance of the simultaneous motions of hands does not change and the angle of maximum response is the same.

From the analysis of variance of combined response score of both hands (Table 4), the interaction effects of Subject X Angle, Angle X Distance and Distance X Hand were found non-significant. On the basis of these non-significant interactions, the following conclusions can be made:

The angle of maximum response score is the same for all individuals.

The angle of maximum response does not vary with the distance of movement.

The relative performance of the left and right hand does not vary with the distance.

Similarly the significant interaction effects of Subject X Hands, Hands X Angle and Subjects X Distance can be interpreted as follows:

The performance of hands vary with the individual.

The angle of maximum response for one hand was not the same for the other hand.

The performance of each individual varies from distance to distance, that is, a distance favorable to one subject may not be favorable to the other.

(2) Single Hand Motions:

(i) Left hand:

The results of analysis of variance for the response scores of the left hand showed that subjects, angles and distances were significant at the one percent level of probability (Table 14). None of the interactions were found significant. Therefore D.N.M.R.T. test was applied to the experimental data to determine statistically the significant differences among the angles (Table 15).

(a) For distance X = 9 inches:

Although the mean response score at angle D was maximum, statistically it was not possible to declare the angle D better than C, G, E or F although it was better than A and B. (Table 15).

The average speed of movement was computed for each individual from the distance of primary movement (bits plus errors) and its mean duration; it varied from 77.50 cms/sec. to 86.50 cms/sec. (Table 16 and Fig. 3). The maximum speed was found at angle D (90°). From the mean response score and the speed, it can be concluded that probably the left hand movements are fastest and most accurate at angle D.

The index of difficulty as calculated from Fitts formula was 4.17 bits/response so the index of performance varied from 14.15 to 15.80 bits/sec. depending on the angle. (Table 16 and Fig. 3).

(b) For distance Y = 16 inches:

The results of Duncan's New Multiple Range Test as applied to the mean response scores at various angles of movement are

Table 14

Analysis of variance for left hand in single hand motions

Source	d.f.	M.S.	F
Subjects (S)	6	83.83	11.53 **
Angles (A)	6	47.50	7.31 **
Distance (D)	1	2029.00	196.42 **
S X A	36	6.5	0.89
S X D	6	10.33	1.42
A X D	6	2.33	0.32
A X D X S	36	7.24	0.99
Residual (Error)	98	7.27	
Total	195		

** $p < .01$

Table 15

Results of D.N.M.R.T. test as applied on mean response scores of single hand motions for left hand

(1) For Distance 9 inches -

Rank	7	6	5	4	3	2	1
Angles	B	A	C	G	E	F	D
Scores	27.50	28.21	28.93	29.21	30.15	30.21	31.00

(2) For Distance 16 inches -

Rank	7	6	5	4	3	2	1
Angles	A	B	C	G	F	D	E
Scores	20.85	21.21	22.65	22.93	23.64	24.28	24.50

Table 16

Mean response scores, mean error scores, average speed, and index of performance of left hand in single hand motions

Criterion	Distance in inches	Angles						
		A(0°)	B(30°)	C(60°)	D(90°)	E(120°)	F(150°)	G(180°)
Mean response scores	9	28.21	27.50	28.93	31.00	30.15	30.21	29.21
	16	20.85	21.21	22.65	24.28	24.50	23.64	22.93
Mean Error scores	9	3.21	3.00	2.79	3.07	2.57	2.93	3.57
	16	2.79	2.85	2.15	2.78	3.15	4.50	3.85
Index of performance, bits/sec.	9	14.60	14.15	14.70	15.80	15.18	15.38	15.20
	16	19.50	19.80	20.43	22.30	22.80	23.20	22.05
Average speed, cm/sec.	9	79.65	77.50	80.50	86.50	83.00	84.00	83.20
	16	106.80	108.80	112.00	112.20	124.80	127.00	121.00

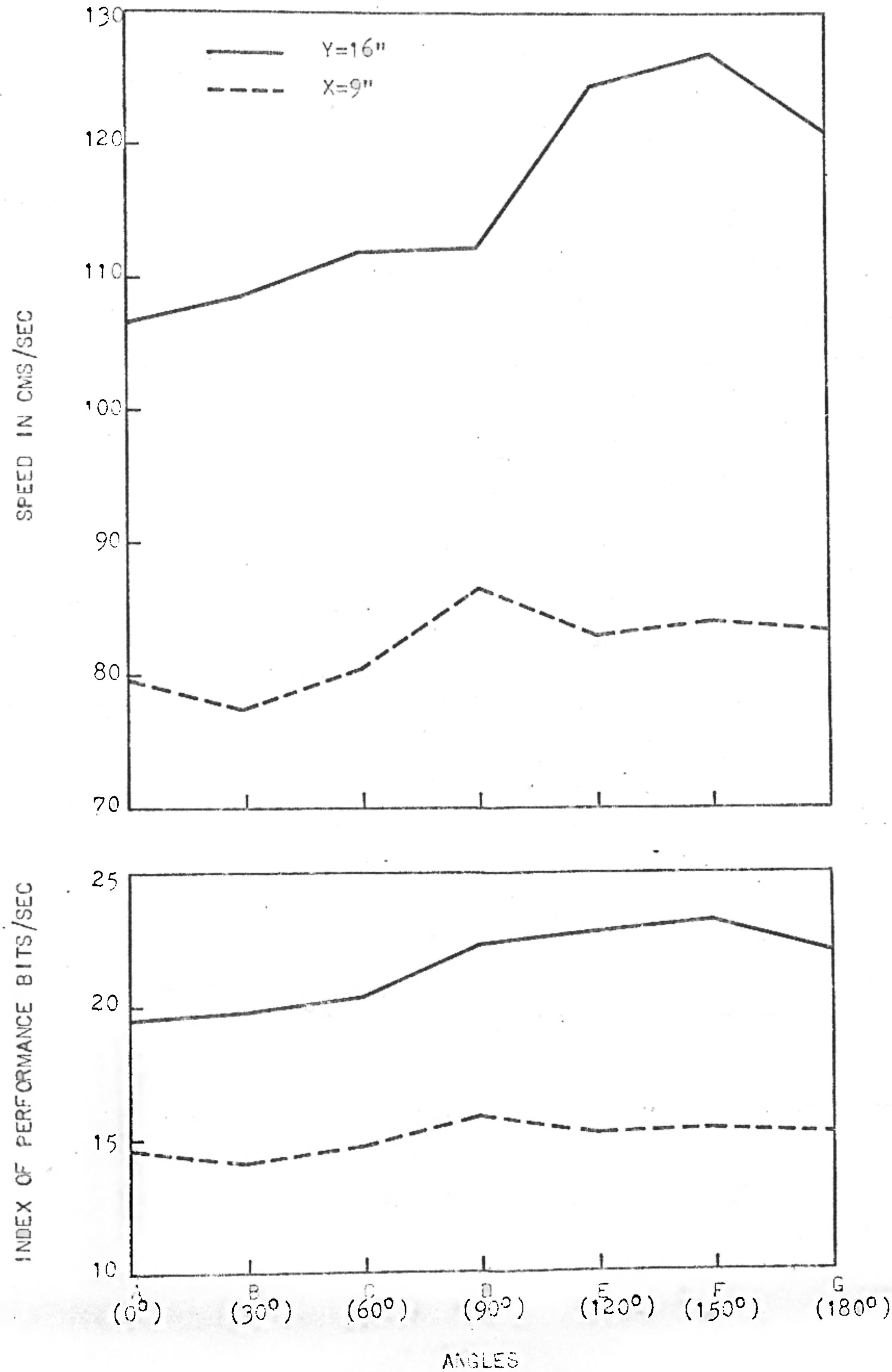


Figure 3
Single Hand Motions - Left Hand

shown in Table 15. Although the mean response score at angle E (120°) was found maximum, statistically there was no difference among the angles G, F, D and E. Therefore, it was not possible to declare any one angle as the best angle.

The average speed of movement varied from 106.80 cms/sec. to 127 cms/sec. The maximum speed was found at the angle F (150°) and the angle for the next highest speed was E (120°) (Table 16 and Fig. 3).

Although statistically no concrete conclusion can be made, it seems that as the distance of movement increases the angle of maximum response and speed shifts towards the left. In this particular study, the angle of maximum score shifted from 90° to 120° (Fig. 4).

The index of difficulty, as calculated from Fitts' formula, was 5 bits/response so the index of performance varied from 19.50 bits/sec. to 23.20 bits/sec. (Table 16 and Fig. 3).

<u>Single hand motions: Right hand</u>:

The results of analysis of variance applied to the data of right hand movements (Table 17) showed that the main effects of subjects, angles and distances were significant ($p < .01$). The interaction of subjects with distance was also significant ($p < .01$), which shows that the distance of best response was not the same for all subjects.

(i) <u>For distance X = 9 inches</u>:

In order to determine the significant differences among the various angles, D.N.M.R.T. test ($\alpha = 0.05$) was applied to

Table 17

Analysis of variance for right hand in single hand motions

Subjects (S)	6	49.33	4.19 **
Angle (A)	6	67.17	6.26 **
Distance (D)	1	3220.00	75.76 **
S X A	36	10.72	0.91
S X D	6	42.50	3.61 **
A X D	6	11.83	1.00
A X D X S	36	5.93	0.50
Residual (Error)	98	11.76	
Total	195		

** $p < .01$

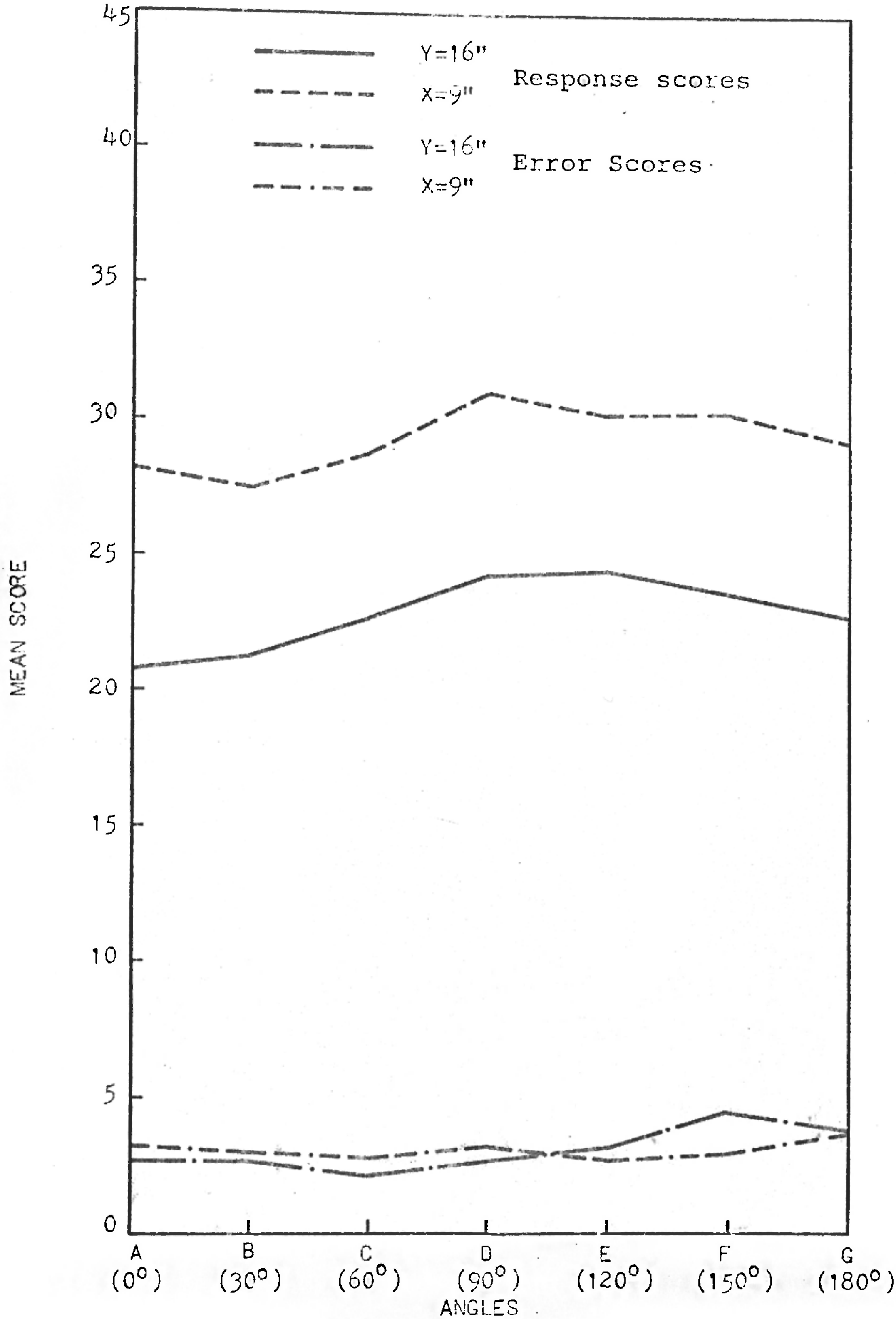


Figure 4

Single Hand Motions - Left Hand

the response scores of the right hand (Table 18). The score was maximum at angle B, but there was no significant difference among the angles A, E, C, D and B.

The average speed of the right hand at various angles varied from 81.65 cms/sec. to 97.75 cms/sec. with the maximum speed at angle D (90°). Considering the speed and the response scores, it was concluded that the angle of best response was B (60°) (Table 19 and Fig. 5).

The index of performance, as calculated from Fitts' formula, varied by angle from 10.06 to 12.02 bits/sec. (Table 19 and Fig. 5).

(ii) For distance Y = 16 inches:

The D.N.M.R.T. test ($\alpha = 0.05$), when applied on the experimental data (Table 18), indicated no significant difference among the angles B, D, and C although C had the maximum score.

The average speed of the right hand varied from 118.30 cms/sec. to 138.80 cms/sec. Considering the speed and the response scores, it was concluded that the angle of best response was C (60°). (Table 19 and Fig. 5).

There is a slight indication that, as the distance of movement increases, the angle of best response shifts counter-clockwise (Fig. 6). This result is contradictory to the results obtained by Briggs (1955), who found that the angle of best response for right hand movement shifts clockwise as the distance of movement increases.

Table 18

Results of D.N.M.R.T. test as applied on mean response scores of single hand motions for right hand

(1) For Distance 9 inches -

Rank	7	6	5	4	3	2	1
Angles	G	F	A	E	C	D	B
Scores	30.57	32.50	34.65	34.65	34.85	35.28	35.92

(2) For Distance 16 inches -

Rank	7	6	5	4	3	2	1
Angles	G	F	E	A	B	D	C
Scores	24.15	24.57	25.50	25.65	26.28	27.21	28.28

Table 19

Mean response scores, mean error scores, average speed, and index of performance of right hand in single hand motions

Criterion	Distance in inches	Angles						
		A(0°)	B(30°)	C(60°)	D(90°)	E(120°)	F(150°)	G(180°)
Mean response scores	9	34.65	35.92	34.85	35.28	34.65	32.50	30.57
	16	25.65	26.28	28.28	27.21	25.50	24.57	24.15
Mean error scores	9	2.57	2.57	2.07	1.71	1.07	1.21	1.65
	16	3.50	3.85	2.50	2.57	1.85	1.78	2.07
Index of performance	9	11.62	12.02	11.52	11.56	11.15	10.52	10.06
	16	16.18	16.75	17.08	16.55	15.18	14.65	14.55
Average speed, cm/sec.	9	94.50	97.75	93.65	93.90	90.60	85.50	81.65
	16	131.50	136.00	138.80	134.50	123.50	119.00	118.30

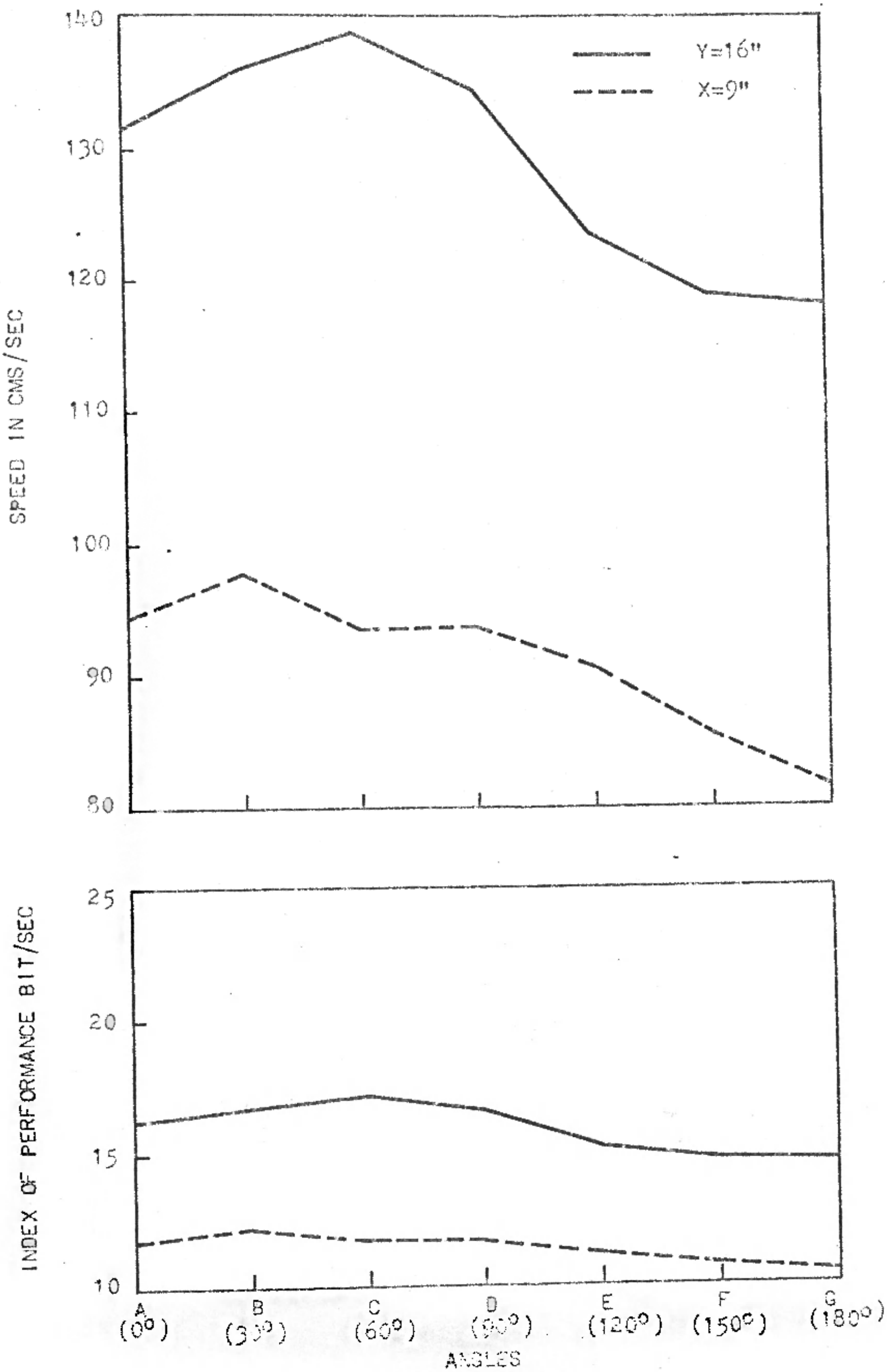


Figure 5

Single Hand Motions - Right Hand

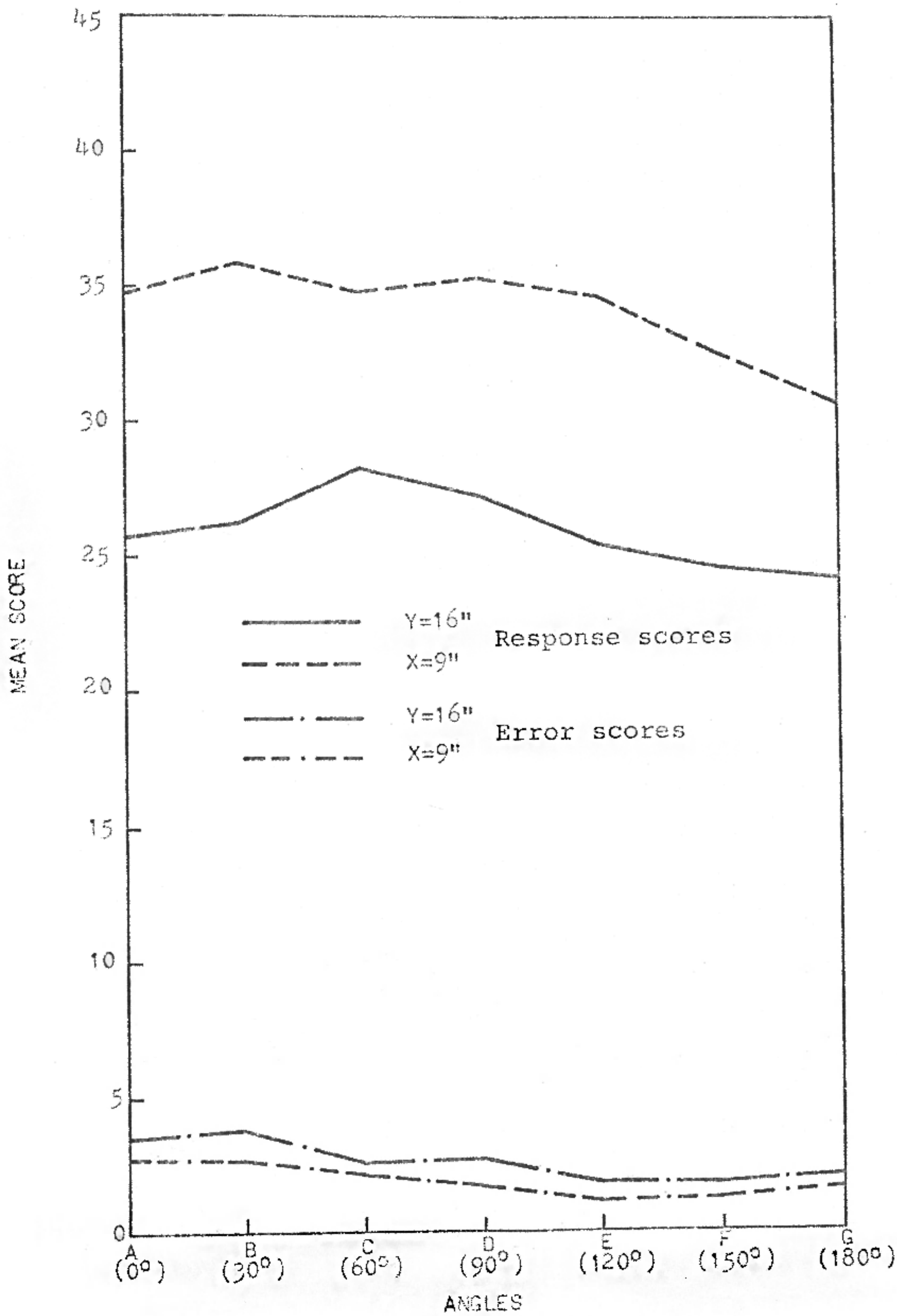


Figure 6

Single Hand Motions - Right Hand

The index of performance, as calculated from Fitts' formula, varied by angle from 14.55 to 17.08 bits/sec. (Table 19 and Fig. 5).

By analysing the response scores of left hand and right hand separately for each distance, (Table 11 and Fig. 4 and 6), it was found that the overall mean score of right hand for each distance was greater than the overall mean score of left hand. From this, it can be concluded that, in single hand motions, the performance of the right hand is superior to the performance of the left hand. Jeans (1966) studied, as one of his conditions, the non-simultaneous motions of hands, i.e. only one hand moving at a time. He concluded that, for right handed women, the left hand exerts more force than the right hand, when the hands are moving at an equal task. Hence the result of present study tallies in general with the results of Jean's study in that the right hand is superior to the left hand, when single hand movements are made. By similar analysis, it was concluded that the speed of the right hand is always greater than the speed of the left hand (Fig. 3 and 5).

Apart from the above results, the following general observations were made:

1. While performing the simultaneous motions of hands, the general tendency of the subjects was to fix their eyes on the movement of their left hand instead of their right hand.

2. In each trial, the beginning of the movement was actually delayed a little by the time taken by the subject in responding

Table 20

Results of D.N.M.R.T. test as applied on overall mean response score averaged over distances for single hand motions

(1) Left Hand -

Rank	7	6	5	4	3	2	1
Angles	B	A	C	G	F	E	D
Scores	48.71	49.07	51.50	52.14	53.86	54.64	55.28

(2) Right Hand -

Rank	7	6	5	4	3	2	1
Angles	G	F	E	A	B	D	C
Scores	54.71	57.07	60.14	60.28	62.21	62.50	63.14

to the starting signal. However in order to avoid biasing of results, this reaction time was not included or recorded in this experiment.

3. It was often observed that the subjects had a general tendency to incline their body towards the direction of the moving hands, in spite of the fact that it was not at all necessary for the completion of movement and that the subjects had particularly been asked not to move their body while performing the task.

4. The movements at most of the angles for small distances were exclusively made from the elbow, whereas the 16 inches movements in most of the cases began from the elbow and were taken up by the shoulder joint and finished from the wrist. The movements made at 90° generally started from the shoulder joint, taken up by elbow and finished from the wrist. Very often the wrist movements were not observed at all.

5. While making the rapid motions, the subjects sometimes got confused and they did not know as to which direction they were to move their hands. They reversed their movements halfway in the air in between the target and the starting point without completing the cycle. The subjects were not able to carry out these movements at their maximum speed, since the effort to be as accurate as possible seemed to be incompatible with that necessary for attaining the maximum speed. It was further observed that the instruction to carry out the movement at maximum accuracy and speed sometimes was not followed by some

subjects, so that they moved at maximum speed. In other cases, the subjects tended to carry out the movement with great precision without having been asked to do so. The subjects usually stated that sometimes they were not aware of a change in the original intention until after it had been made. Sometimes the subjects started their movements at their maximum speed and ended with slow speeds, so the speed of the movements in the entire trial was not perfectly uniform.

6. It was further observed that these repetitive and quick movements did not describe a straight line path, except the movements made at 90°. These movements seemed to describe a curve. The center of the arc was to the right of the line of travel for the right hand and to the left of the line of travel for the left hand. The subjects were not aware of this fact and they always imagined to have described straight line motions.

7. Another result of interest observed during the experiment was that if, in one trial, the subject missed the target with one hand and then attempted to make the motion of that particular hand more accurate in the next trial, there was a tendency to miss the target with the other hand. This observation indicates that there is some interaction effect between the responses of two hands and the response of one hand is affected by the response of the other hand, when two hands are moving simultaneously.

8. For the distance of 16 inches, it was occasionally observed that the movement started with the resolve to be accurate, but changed to one of maximum speed in the course of the trials,

whereas for 9 inches movements, the movement usually started at the maximum speed and ended with comparatively slow speed. According to the above observations, it can be concluded that the speed of movement of the hand or hands in the repetitive type of motions does not remain uniform throughout the trial and it seems very difficult to strike a balance between maximum speed and maximum accuracy.

9. From the computation of speeds, it can be concluded that the time taken to perform movement increases with the length of the path, but this increase is not directly proportional to the length of the movement.

DISCUSSION

The results showed that the direction of path of movement has a significant effect on the speed and accuracy of single hand motions, as well as on the simultaneous motions of both hands. A number of workers in this area (Barnes & Mundel (1939), Briggs (1955), Brown et.al. (1948, 1949), Brogden (1953), Corrigan et. al. (1948), Jeans (1966), Nichols (1958)) have obtained evidence that the simple hand-arm movements are affected by the angles at which the hands are actually moving.

The reason for this effect may be that the movement of hands at different angles require the functioning of different muscles and different number of joints starting from the wrist joint to the shoulder joint. The directions which involve the movement of least complexity may thus have macimum accuracy and speed. The commonest type of the complexity is the involvement of a large number of joints. Thus depending upon the number of joints being utilized for the movement in the various directions, the mass of the actual moving part of the limb also varies simultaneously.

In this study, the subjects were not allowed to change the posture of their body, while performing the task. Thus whenever the angle of the movement was changed, it was not possible for the subject to make the necessary postural adjustments in order to compensate for the relative changes in the stress produced in the various muscles of the arm involved in the movement.

It is evident that, as the direction of path movement changes, the movement of hand(s) requires the operation of different muscles or differences in the operation of the same muscle. Hence, the muscle groups involved, their inter-relationship and the characteristics of the arm as a lever both at different angles and during the course of movement affects the performance of hand-arm motions at different angles and make the effect of the angle significant.

The visual factor may also be one of the factors which influences the movements of the hand at different angles. As a result of change in the angle movement, the subject's view of his hand, arm, stylus and the target also changes.

While making such rapid movements the head or the eyes have to follow the hand-arm movements. Since the movements of the head are, however, accompanied by compensatory counter movements of the eyes, these hinder the visual perception with the extent of hinderance depending upon the orientation of head at different angles. In such quick movements it is very difficult for the eyes to continuously follow the hand-arm movements. Moreover, the eyes always move by making slight jerks, as is clear in the case of reading. Looking to the above facts, it is clear that the visual control only cannot be exercised for such rapid motions of hands. This indicates that there are some other sensory receptors such as the kinaesthetic sense (proprioceptors) etc. which helps to control the movements. The kinaesthetic receptors are the nerves in the muscles, tendons and the covering of the bones, particularly around the joints which are stimulated primarily by the action of the body-members. The sensation transmitted by these receptors enable a person to control the movements of muscles through the motor nerves. This is essentially a feed-back process. Similarly, the stimulations in the non-auditory "labyrinth" of the inner ear arises from the position of movement of the head and these labyrinth organs provide sensory data, which along with the visual and kinaesthetic senses, contribute to the static and dynamic equilibrium of the body.

The effect of these receptors actually depends upon the position of the head and the number of joints involved, while performing the hand movements. Maria Wyke (1965) investigated the effect of orientation of head on the accuracy of the movement of hands and she found that the accuracy of movement is disturbed by changing the orientation of head. As already discussed, the movements at different angles require turning of head to different positions and it involves different number of joints and muscles, thereby affecting the influence of these senses in controlling the motion. The extent of the effect of these sense organs vary with the change of direction of movement. Hence it may also be one of the reasons for the variations in the performance of hand-arm movements at different angles, thereby making the effect of angle significant.

In simultaneous motions of hands, the set of angles of best response was found as DD(90°) and it was further observed that as the spread of the angle between the direction of movement of two hands increases,the response score becomes poorer and poorer.

One of the reasons for the position DD to be the best may be that in this position, the two targets were so close that the subject could see both the targets at a time. This is the reason that the response scores of hand movements for all the conditions of 0° spread were found better than the rest of the angles. At this position (DD), the subject could exercise the visual control as well as the other sensory control for regulating the simultaneous motions of both hands.

As the spread of the angle increases, it becomes very difficult to see both the targets at a time and to exercise the visual control efficiently. Therefore the movement of one hand gets the aid of visual as well as the kinaesthetic senses, while the other simply moves by the help of his kinaesthetic sense only. As a result of this, one of the subject's hands made more and more incorrect hits on one target, while the other hand made more correct hits. Of course, this problem does not arise in the single hand motions, for, in that case, only one eye fixation is required at a time.

Schmidtke and Stier (1961) conducted several studies concerning various types of hand-movements and they concluded that the time required to perform motions is greatly influenced by the path of motion in relation to the operator's body. They further stated that, when considering the successive movement of hands on different diameters of the circle, the upper arm and lower arm are involved to a great extent. Starting from motions involving predominantly the lower arm motions to predominantly the upper arm motions, the counter-clockwise movements becomes slower and slower. These results therefore, further support the results of this study for the significant effect of the angle on hand-arm movements.

Apart from the maximum response scores, the speed of the hand movements was also found maximum at DD(90°) position. While making the hand movements in position DD, the motion starts from shoulder joints and is then taken up by the elbow joint. The upper arm simply makes to and fro motions about its own axis just like a pendulum and it almost remains hanging parallel to the vertical axis of the body. As the upper arm simply keeps hanging from its joint, no extra force is required to balance the weight of the upper arm and, on the contrary, it gets natural swing by its gravity and its pendulum action. In this position, as the hands move symmetrically on both sides of the body, it does not create any unbalancing or tension in the body. This may, therefore, be the reason for the maximum speed of the simultaneous motions at this position.

In this study for determining the effect of angle on the speed and accuracy of simple hand arm movement, most of the angles were found statistically the same and no concrete conclusion could therefore be made for the angle of best response. The probable reason for this non-significant difference among the response scores at different angles might be the effect of practice. There are two possibilities in which practice might have affected the performance of hand-arm-movements at different angles (1). By the amount of practice at each individual angle and (2) by the total number of angles at which the practice was given. In the later case, the transfer effect from one angle to another was involved as well as a direct practice effect in terms of number of trials at each angle. As the practice increases, the difficulty of performance at different angles is changed partly in terms of general improvement in performance and partly in terms of a decrease in the degree of difficulty between the most difficult and the easiest angle. On account of practice, there is a tendency for the most difficult angle to become a less difficult angle and performance at the angle that is initially the easiest although showing improvement, does not improve as much. The practice thus overcomes some of the limitations imposed on the proficiency of performance by anatomical characteristics. Hence it may be due to the above reasons that the mean response scores at most of the angles could not be found statistically different from each other.

In simultaneous motions of hands, it was found that there was a certain inter-action effect between the response of the two hands. The reason for this interaction may be explained as follows.

As reported by Vince (1948) and Welford (1952), the central mechanism behaves as if the brain contained at some point a single channel dealing with only one signal or one set of coordinated signals at a time. Thus in the task requiring two hand simultaneous motions, the hands cannot be treated as independent units. Although they may perform different actions, these must be coordinated if they are to be strictly simultaneous. So the central mechanism executes only one signal at a time and the other signals may therefore have to queue. If they arrive during or shortly after the movement in response to a previous signal, they may clash with kinesthetic sense or other sensory feed-back from the movements. But in simultaneous motions, both the hands have to perform the responses at a time and it is not possible for one hand to wait for the signal from the central mechanism. Therefore in such movements, the central mechanism is able to control the movement of one hand only, while the other hand is deprived of it. Thus it is very difficult for both hands to perform the movements with the same efficiency and the response of one hand affects the response of the other.

One of the important results noted in this study was that the performance of left hand was found superior to the right hand for simultaneous motions. Although both the hands moved at the same speed, the left hand made more correct hits than the right hand. As observed during the experiments, the reason for this surprising result was that, while making the simultaneous motions, the left hand generally got the visual aid, whereas the right hand was always deprived of it. As a result of this, the right hand always moved with the help of kinaesthetic sense only. This shows the peculiar characteristic that the senses also have a tendency to help the weaker member of the body. In this particular case the left hand being weaker than the right hand, the eyes always followed the movements of left hand. Moreover as already discussed, the kinaesthetic sense and labyrinth receptors are most sensitive when the head is oriented towards the direction of movement, otherwise if the movements are made with the head oriented in a different direction, these senses lose their sensitivity and the accuracy is shifted slightly towards the direction of the head. Maria Wyke (1961) proved this particular characteristic of these senses in relation to the orientation of head. Hence this might be one of the reasons that, as the head and eyes were, most of the times, oriented towards the direction of movements of left hand, the left hand was able to get more correct hits, while the right hand generally missed the target.

In general, it was noticed that simultaneous and symmetrical movements were better than simultaneous and assymmetrical movements. The main factors which make the above difference are probably the physiological and anatomical factors. In case of symmetrical movements, both the hands move on either sides of the body at equal angles and thus equal tensions and contractions are developed in the body and the various muscles of hands--such movements keep the whole body in perfect balance without causing any shock or jar or unequal strain. The above reasoning is also supported by the following statement made by Barnes (1940).

"The symmetrical movement of the arms tend to balance each other reducing the shock and jar on the body and enabling the worker to perform his task with less mental and physical effort."

Secondly, the number of muscles and joints of the arm involved in making the symmetrical motions are exactly the same for both the arms and there is no physiological difference between the movement of two hands. Therefore, the effect of physiological difference does not come in picture. Moreover, as the number of joints and muscles involved in these motions are the same for both the hands, the sensitivity of the kineasthetic receptors etc. remains the same for each hand. In simultaneous and assymmetrical motions, however, both hands do not move at equal angles on either sides of the body and thus unequal stresses are developed in the body and the muscles of the arm. According to the situation of task, it is not possible to make postural adjustments and thus compensate for the relative changes in the stress that are placed on the muscles of the arms involved in such motions. Similarly the sensitivity of the various sensory receptors does not remain the same for both the hands, as the number of joints and muscles involved in these movements differ for each hand. It may, therefore, be because of these unequal stresses, unbalancing of body, physiological differences in the nature of arm movements, and differences in the sensitivity of the sensory receptors that the performance of simultaneous and assymmetrical motions of hands is poorer than the simultaneous and symmetrical motions.

In simultaneous motions of hands, the overall results for both the distances (9" and 16") of movements were found statistically the same (as far as the ranking of angles were concerned) and the angle of best response did not vary with the change in distance. This might be because of the findings that the performance of simultaneous movement of hands mainly depends upon the spread of the angle and as the spread increases, the response becomes poorer and poorer. Hence the performance of simultaneous motions is best at minimum angle of spread, i.e. 0°. Therefore, even if the distance of movement is changed, the angle of minimum spread remains the same and thus the change in distance has no effect on the angle of best response.

However, it was noticed that the angle of worst response for a larger distance of movement became the angle of better response for the shorter distance of movement (Tables 12 and 13). This might be because of the fact that in longer movements the motion started at the elbow joint and then was taken up by the shoulder joint and both the upper arm and lower arm were involved in it, which made the movements difficult. But in shorter distance of movements, the motions were restricted to the lower arm only and the lower arm simply pivoted at the elbow joint, thus making the movements easier. In this particular motion, the upper arm was not involved. This was particularly true in case of movements at 0° and 180°.

In single hand motions, the overall performance (including the speed of movement) of the right hand was found superior to the left hand. This might be because of the fact that in daily routine work the muscles of the right hand are used more frequently than that of the left hand and therefore the muscles of the right hand can exercise better control over the movements of the right hand.

Jeans (1966) while making similar conclusions, also explained that since the right hand is used more frequently than the left arm, the muscular action of the right hand is smoother resulting in a smaller amount of physical effort to use it.

As a result of the nonsignificant differences among the mean response scores at various angles, no concrete conclusion can be made regarding the angles of best response and the effect of distance on the angle of best response, but there was slight indication that as the distance increases, the angle of best response shifts counterclockwise for right hand motions and shifts clockwise for left hand movements. This result is in contradiction to the results obtained by Briggs (1955). He concluded that as the distance of movement increases, the angle of best response shifts clockwise for right hand movements. Although the angles of maximum response for right hand movements was found almost the same as found by Briggs, the reason for the shift of the angle of best response in the opposite direction is difficult to explain. It might be due to the fact that only two distances were studied and the distances taken for the single hand motions were quite small as compared to distances taken by Briggs.

The angle of best response of each hand when involved in simultaneous motions was found different from the angle of best response of each hand in single hand motions. This difference was due to the interaction effect as already explained.

After studying the different types of motions of hands, it was observed that, as the distance of movement increased, the total number of cycles decreased, which was quite obvious. A number of workers in this field (Figgs, (1954)/ Craik, (1947)) however, have obtained evidence favoring the conclusion that, as the length of movement increases, the speed of movement increases in proportion, so that the movement time remains approximately constant. Craik reports that the duration of discrete corrective movement is only slightly dependent upon the length of the movement within the range of 0.63 to 11.4 cms. The result of present experiment, however, does not support the contention that the duration of the corrective movement remains the same for different lengths of movement at different angles. While it is true that the speed of movement increases with the increase in the distance moved, the increase is not directly proportional to the distance i.e. the time taken to make the movement also increases. The apparent discrepency between these results and those of previous experimentors (Fitts, 1954) is perhaps not as great as it might appear. The reason may lie in the psycho-physical processes at the beginning and end of the movements, which do not differ much with short or long paths and therefore take up a larger proportion of a short path than a long path of movement. Secondly, the speed of movement is not uniform throughout the distance, but it varies in different phases. When the distance of movement is more, it becomes easy for the hand to accelerate the speed and to keep it moving at maximum speed for a certain middle part of the distance, while in the shorter path of movements, the hand does not get a chance to move freely at its maximum speed and, by the time it has attained its maximum speed, the end point is reached. For longer distances of movement, the increase of speed in the first part of the distance is always followed by a period in which velocity remains almost constant. Hence this may be one of the reasons that as the distance of movement increases, the average speed also increases simultaneously and the movement time is not directly proportional to the actual distance moved.

SUMMARY AND CONCLUSION

The experiment was designed to investigate the effect of angle and distance on the speed and accuracy of single hand motions and two hand simultaneous motions in the horizontal plane. The criterion was the correct response score (number of hits), which reflected the speed and accuracy of a simple repetitive hand-arm motions to and from a fixed inner target to the outer targets positioned at various angles. Seven angles (0°, 30°, 60°, 90°, 120°, 150° and 180°) and two distances of movement (9" and 16") were studied. Seven right handed female students served as subjects.

The data was analyzed by the analysis of variance and Duncan's New Multiple Range Test.

The conclusions were:

1. Direction and distance of movement do have a significant effect on the speed and accuracy of single hand motions and two hand simultaneous motions.

2. In simultaneous motions, as the spread of the angle between the direction of movement of the two hands increases, the response scores become poorer and poorer; the set of angles of best response is DD (90°),when both the hands move at 90° (minimum spread).

3. The above condition of best response is the same for both 9 and 16 inch movements.

4. When both the hands are involved in simultaneous motions, the speed and accuracy of the left hand is better than that of the right hand, whereas in single hand motions, the speed and accuracy of the right hand is better than that of the left hand.

5. Simultaneous and symmetrical motions of hands are faster and more accurate than the simultaneous and assymmetrical motions in the horizontal plane.

6. When both hands are involved in simultaneous motions, the performance of one hand is affected by the performance of the other.

7. As the distance of movement increases, the speed of movement also increases simultaneously, but the increase in the movement time per cycle is not directly proportional to the distance moved.

8. As the distance of movement increases, the number of errors also increases.

9. The angle of best response for each hand, when involved in simultaneous motions, is not the same angle of best response when the same hand is making independent motions. In single hand motions, a hand can move much faster than when it is involved in simultaneous motions.

ACKNOWLEDGEMENTS

It is with great pleasure and gratitude that the author expresses his sincere appreciation to Dr. Stephan A. Konz, major professor, for his guidance, assistance, patience and valuable help during the experimental study and preparation of his master's thesis.

Sincere thanks are extended to Dr. Raja F. Nassar, Assistant Professor, Department of Statistics, for his counsel on statistical analysis.

The author wishes to express his sincere appreciation to his wife, Madhu Kumari, for her patience, understanding and constant encouragement without which this endeavor could not have been accomplished.

The author is indebted and grateful to his father, Mr. Anop Singh Rathore and his mother, Samdar Kumari, for financial assistance received for the advanced studies in the United States of America.

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A STUDY OF EFFECT OF ANGLE AND DISTANCE ON THE SPEED AND ACCURACY OF SINGLE HAND AND TWO HAND SIMULTANEOUS MOTIONS IN THE HORIZONTAL PLANE

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An Abstract of

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1968

ABSTRACT

A study was conducted for investigating the effect of distance and direction of movement on the speed and accuracy of single hand motions and two hand simultaneous motions in the horizontal plane. Seven angles (0°, 30°, 60°, 90°, 120°, 150° and 180°) and two distances (9" and 16") of movement were studied. The conditions for simultaneous motions of hands were designed according to the spread of the angle and, in all, 28 conditions were studied at each distance of movement.

Seven female students served as the subjects and their task consisted of striking the targets with a stylus by making repetitive hand movements between the inner and outer targets. The number of correct hits was recorded electronically by the electronic counters.

It was concluded that:

(i) The direction and distance of movement significantly affects the hits for both single hand and simultaneous motions.

(ii) The hits for simultaneous motions mainly depend upon the angle of spread between the direction of movement of the two hands; 0° spread is the best and this conclusion does not depend upon the length of movement.

(iii) In simultaneous motions, the symmetrical motions have more hits than the assymmetrical motions.

(iv) In simultaneous motions, the accuracy of left hand is better than that of the right hand, whereas in single hand motions,

it is vice-versa. In single hand motions, a hand moving by itself moves faster than when involved in simultaneous motions.

(v) When both hands are involved in simultaneous motions, the performance of one hand is affected by the performance of the other.