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MOVEMENT CONTROL IN SKILLED MOTOR PERFORMANCE [1]

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The speed and accuracy of single movements depend on several factors, such as direction of movement, distance to the target, and accompaniment by simultaneous movements. The relation between speed, accuracy, and distance appears to be determined by the time required to process feedback and to make corrective alterations in the movement. For a repetitive series of movements, there is some evidence suggesting that control is shifted from feedback to a motor program. This view receives further support from demonstrations that the reproduction of single movements may be under programmed control. How the study of movements may be relevant to understanding perceptual and memory skills, as well as motor skills, is briefly mentioned.

The study of movements has great importance for understanding skilled performance. This is, of course, most obvious for motor skills such as walking, driving, typing, parts assembly, athletics and so on. Psychologists long have believed that movements are an important component of nonmotor skills as well. For example, Watson (1924) was a proponent of the view that thought involved minute movements of the vocal apparatus. Such a view has been discounted for many years, but recently motor theories of "thought" have been regaining acceptance. Hintzman (1965, 1967) recently has suggested that the auditory confusion errors in short-term memory are not of acoustic origin but are of articulatory origin. Rehearsal, according to Hintzman, involves subvocal articulatory movements, and it is the kinesthetic feedback from such movements that accounts for short-term memory. Thus, the research on kinesthetic memory reported later in this paper is relevant to theories of auditory short-term memory.

A motor theory of memory need not necessarily involve actual movements. Visual or auditory input might be converted to motor commands that control muscle movements, and the motor commands may be remembered whether or not the movement is actually initiated (Hintzman himself recognized this possibility). Sperling (1967) has proposed just such a mechanism. He suggests that visual information is rapidly "read in" to a buffer store which consists of motor programs for vocalizing the information. One could argue further that "seeing" the visual items is the activation of motor programs. Evidence for this interesting theory has been given by Festinger, Ono, Burnham, and Bamber (1967), and Liberman, Cooper, Shankweiler, and Studdert-Kennedy (1967) have proposed a similar theory for speech perception.

The concept of a motor program may be viewed as a set of muscle commands that are structured before a movement sequence begins, and that allows the entire sequence to be carried out uninfluenced by peripheral feedback. Evidence for motor programs has come from recent physiological studies. Wilson (1961), for example, has shown that the pattern of rapid wing movements in locusts was unchanged when sensory feedback from the wing was eliminated. Kennedy (1967) re-

ported that stimulation of single neurons in the crayfish resulted in complex but highly repeatable movement patterns; stimulation of other neurons resulted in slightly different patterns. It appears quite clear that the entire motion depended solely on the initial stimulation and not on subsequent feedback. Behavioral evidence suggesting that humans are able to learn motor programs will be reported later in this article.

It should be evident from these illustrations that a motor program is *not* a movement in itself, but acts to control movements. It is possible that a program may be activated in some sense without a movement actually being initiated. Such an occurrence, rather than an actual movement, may be important in short-term memory and in perception. Therefore, research on movements may be relevant to understanding perceptual and memory phenomena as well as to understanding skilled motor performance. As will become obvious in the remainder of the paper, however, the emphasis on movements will be primarily toward understanding motor skills. First, a number of variables that influence the speed and accuracy of movements will be reviewed. Then studies on feedback processing time will be presented, and the implications of processing time for understanding the relation between speed, accuracy, and distance of movement will be discussed. These studies will be followed by evidence that for predictable events, movement control is internalized. Finally, theories and data on the memory and reproduction of movements will be reviewed.

The Execution of Movements

The first step in understanding movement control is to discover what variables influence speed and accuracy. There has been a large amount of research on this question, motivated in part by the need for time and motion analysts to determine the time that various tasks should take (see Barnes, 1963, for extensive tables of standard times). Standard times for various classes of movement have been experimentally determined by Bailey and Presgrave (1958). Class A motions are stopped by impact with an object and are the fastest movements. If a movement is stopped by antagonistic muscle action (Classes B and C),

the time is increased. Class B movements (e.g., stopping the upstroke of a hammer) require little precision and, therefore, are faster than Class C motions which require some precision (e.g., grasping or placing an object). Further increases in time are required if the target is not visible until near the end of the movement—BV and CV movements.

Movement time also depends on the distance, degree of precision, force, and number of movements. For example, a Class C movement of 24 in. should take about 666 msec. If the end of the movement requires precision of $\frac{1}{8}$ in., an additional 546 msec. is added. A weight of 8 lbs. would add another 3×78 msec. for starting, carrying, and stopping the weight, and a simultaneous movement with the other arm would add another 180 msec. for movements terminating 6 in. apart. Thus, the total movement time would be 1.626 sec.

Although the standard times developed by Bailey and Presgrave are useful for time analysis of various jobs, the actual tasks used are not well specified, results from several tasks are grouped, and subjects did not make movements as fast as possible. Consequently, their data is of lessened value for theoretical analysis of movements. Nevertheless, Bailey and Presgrave's work serves as an introduction to the many variables that influence movements, some of which have not been rigorously studied by others. Later we shall return to see how their data compare with that obtained in more specific experimental situations.

Direction of movement. An extensive series of experiments on direction of movement has been performed by Brogden and co-workers. Subjects used a stylus to follow a spot of light moving at a constant velocity along a straight track varying from 0° to 360°. With the track in the horizontal plane, 0° represents a motion normal to the frontal plane, and arm motion is away from the body. Ninety degrees involves movement to the left and so on. Accuracy was measured by the number of times the stylus touched the metal sides of the track.

Corrigan and Brogden (1949) studied right-handed movement in a horizontal plane at a velocity of 3 cm/sec. Accuracy (y) as a function of direction of movement (x) was ap-

proximated quite well by the trigonometric relationship:

$$y = a - b \cos 2x + c \sin 2x \qquad [1]$$

where a, b, and c are constants. Movements separated by 180° are approximately equal in accuracy with 135°–315° movements being most accurate and 45°–225° being least accurate. Left-handed movements obey nearly the same relationship except that it is inverted with respect to right-handed movements (Briggs & Brogden, 1953). As target velocity increases from 2.5 to 4.5 cm/sec, there is no change in the number of errors and the trigonometric relationship remains the same (Thompson, Voss, & Brogden, 1956). Brogden (1953) showed that with practice there is a gradual shift of about 15° in the function until worst performance occurs on the 60° axis (only angles from 0° through 150° were used). When the plane of movement is tilted from the horizontal to a near vertical plane facing the subject, the phase angle shifts about 60° (Briggs, Thompson, & Brogden, 1954). Similarly, changing the plane of movement from 30° slant to the right to 30° slant to the left results in a change of phase of about 60° (Thompson & Brogden, 1955).

The trigonometric function apparently does not depend on visual factors. Begbie (1959) had subjects attempt to draw straight lines from one point through another point in a horizontal plane, and calculated the average deviation of the line from the point at which it was aimed. Even when subjects closed their eyes during the movement, they showed the same trigonometric function as long as the movements were not too long.

One possibility is that the function results from movement about two joints: (*a*) movement of the forearm about the elbow and (*b*) movement about the shoulder joint. If the arm were moved in a near horizontal plane starting at a point in the median plane such that the initial angle between forearm and upper arm was about 90°, moving on the 135°–315° axis would involve primarily movement of the forearm about the elbow whereas the 45°–225° axis would involve mainly movement at the shoulder joint. Goldscheider (1899, reported in Howard & Templeton, 1966) showed that the threshold in degrees

for perceiving passive movement of the arm is larger at the elbow than at the shoulder. If it is assumed that arm steadiness is inversely related to the threshold for movement, then as a subject moved along the 135°–315° axis, the relatively large unsteadiness at the elbow would result in fluctuations parallel to the direction of travel. For movement along the 45°–225° axis, unsteadiness at the elbow would be perpendicular to the line of travel. Thus, as the direction of movement is changed from 135° to 225°, there would be a rise in error. As direction progresses to 315°, the error would drop and then rise again as the 45° angle is approached.

Speed-accuracy trade-off. It is clear from the earlier discussion of Bailey and Presgrave's work that movement time is a joint function of the extent and required accuracy of movement. Fitts (1954) reported three experiments in which an attempt was made to quantify the relationship. The tasks were to tap alternately two plates separated by some distance, transfer washers from one pin to another, and transfer pins from one hole to another. He found that movement time is well predicted by:

$$MT = a + b \log_2 (2A/W) \qquad [2]$$

where A is the amplitude of the movement (the distance from the center of one target to the center of the other), W is the width of the target in the tapping task or the tolerance in the other two tasks, and a and b are constants. Perhaps the most interesting aspect of the relationship (hereafter referred to as Fitts' Law) is the trade-off between distance of the movement and width of the target. According to Fitts' Law, if the distance of a movement is doubled, the movement time does not change if the width of the target is also doubled.

The information content of a movement is given by $ID = \log_2 (2A/W)$. Information transmission may be viewed as the "ability to produce consistently one class of movement from among several alternative movement classes . . . [Fitts, 1954, p. 381]." The rate of information transmission was defined by Fitts as $C = ID/MT$ and was found to be approximately 10 bits/sec.

In later experiments Fitts and Peterson

(1964) showed that a discrete tapping task resulted in a faster rate of information transmission (between 14 and 22 bits/sec) than the continuous tapping task of Fitts (1954). The higher rate of transmission was partly due to the fact that time on target was not included in total movement time. In addition, the constant *b* of Equation 2 was smaller than in the earlier study. Fitts and Peterson also showed an increase in movement speed over three sessions of practice due to a decrease in the constant *a* of Equation 2 with *b* remaining the same. However, with 31-days practice on a peg transfer task (Kay, 1962), there was also a decrease in *b* resulting in an increase of transmission rate from about 10 bits/sec to over 20 bits/sec.

In a study by Fitts and Radford (1966), subjects were given monetary payoffs that emphasized either speed or accuracy or were neutral. As would be expected, increasing the payoff for speed resulted in increased speed but more target misses. The critical question is whether the increase in misses balances the increase in speed such that the rate of information transmission is constant under the three conditions. To determine this, Fitts and Radford calculated what target width would be necessary at each speed for 95% of the movements to hit the target (hits were assumed to be distributed normally about the target center). The calculated target width (*W'*) was then substituted for the actual target width (*W*) and solved for the rate of information transmission. Comparing the accuracy condition with the speeded condition, small but consistent increases in the rate of information transmission were found in the latter.

Preparation time apparently has little effect on transmission rate. Fitts and Radford (1966) found little difference whether subjects were directed to hit a target as soon as possible after the appropriate target was indicated or whether they were to take as much time as desired before initiating the movement. These results were substantiated in an unpublished experiment by Keele.

Further applications of Fitts' Law. In order to compare Fitts' Law with the extensive data reported by Bailey and Presgrave (1958) and cited earlier, *ID* was calculated for each distance and tolerance of Class C movements. The relation between movement time and *ID* was reasonably linear, and a least squares linear regression accounted for 95.3% of the variance. The rate of information transmission varied from 6.3 to 9.8 bits/sec and was somewhat less than the rates found by Fitts (1954) and Fitts and Peterson (1964). This difference in rates is probably explained by Bailey and Presgrave's instructions to make movements at a standard rate rather than at a rapid rate.

Although Fitts' Law accounted for a large proportion of Bailey and Presgrave's data, there were systematic deviations from linearity. At a given level of tolerance, movement time showed a slight positive acceleration with the logarithm of distance. Welford (1960) has proposed a modification of the index of difficulty: $ID = \log_2(A + \frac{1}{2}W)/W$. This modification resulted in a slightly better fit to the original data of Fitts (1954) and the more recent data of Fitts and Peterson (1964). Consequently, it was also applied to Bailey and Presgrave's data. A least squares linear regression accounted for 95.6% of the variance, a value nearly the same as for Fitt's original formulation.

Fitts' Law does provide a good fit to Bailey and Presgrave's data for linear movements, but a large discrepancy arises for rotary movements. They reported that the time for turning the hand is linear with the number of degrees turned. Since movement time depends on the level of precision required and Bailey and Presgrave do not report the precision required for different degrees of turn, it is difficult to evaluate their data. In contrast, Crossman and Goodeve (1963) and Knight and Dagnall (1967) controlled the level of precision and reported logarithmic relationships.

Brown and Slater-Hammel (1949) have reported an experiment in which rapid movements were made to a line rather than to a target of finite width. The line was 2.5, 10, or 40 cm. from the starting position. Movement time to come within .5 mm. of the target line increased almost perfectly linearly with the logarithm of the distance. Thus, Fitts' Law also provides a good description for movement time to line targets.

Using a different approach, Woodworth (1899) kept the time of repetitive movements constant for distances of 5, 10, 15, and 20 cm. to a line and measured error. According to Fitts' Law, an increase in distance requires a decrease of the same proportion in precision to maintain equal movement time. Woodworth found that, on the average, the amount of error at long distances was slightly less than predicted. Since he used only three subjects, the discrepancy could be due to individual differences. Another possibility is that movement times may not have been constant for different distances. If, as distance increased, relatively more time were spent in moving and less time spent in reversing direction, then the long movements would be more accurate than predicted. These questions could be answered by experiments with more subjects and with measurements of the actual time spent moving.

Repetitive movements. One might expect that a minimum time is necessary between the muscle activation which starts a movement and the activation of the opposing muscles to end it. The distance traveled in this time should depend on the strength of the initial contraction, and, consequently, the *minimum* time for various length movements (assuming the movement must be stopped by muscular action) should be the same.

Travis (1929) has shown that voluntary movements of the finger normally occur in phase with finger tremors. Such tremors occur at the rate of 8–12 per sec. for the finger, wrist, and forearm (Dresslar, 1892; Stetson & McDill, 1923). Thus, if a tremor is on the upswing, downward movement is delayed until the downward tremor, suggesting that when movement is started in one direction, there is a minimum of 80–120 msec. before opposing action will occur. In accordance with this view, Dresslar (1892) found finger-tapping rate to be about 8–10 taps/sec. Bryan (1892) found a slower rate of tapping (6–7 taps/sec), but the rate was about the same for finger, wrist, elbow, and shoulder movements. Furthermore, the rate was independent of the length of finger excursion, which ranged from 1 to 40 mm. Bryan reported that earlier work by Von Kries also showed tapping rate to be independent of length of finger movement.

Simultaneous and successive movements. A few investigators have determined whether there is any decrement in time per movement when two movements are made. Langfeld (1915) studied tapping rates for: (*a*) single fingers, (*b*) two fingers simultaneously, (*c*) two fingers in alternation—that is, while one finger was being raised the other was lowered, and (*d*) complete alternation in which one finger was moved up and down before the other began. As a rule, for any two fingers the simultaneous tapping rate was no slower than the rate for the slowest finger alone, and in some cases the simultaneous tapping rate was faster than for either finger alone. When fingers were tapped in alternation, the rate per finger averaged about $\frac{2}{3}$ the rate for single fingers. With complete alternation, the rate per finger was only $\frac{1}{4}$ the rate for single fingers. Thus, simultaneous tapping results in no loss of efficiency per finger but alternate tapping does.

In finger tapping, little precision and no visual attention is required. Bailey and Presgrave (1958) have shown for simultaneous movements that as the degree of precision required increases and as the separation between two targets increases, the time for movement increases. With no separation between the targets, there is no decrement over single movements. This can be explained simply by the necessity for looking back and forth between the two targets when they are separated.

Time and motion analysts have long insisted that when motions are made with two hands, they should be symmetrical (e.g., Barnes, 1963). To test this hypothesis, Peterson (1965) had subjects move their hands as rapidly as possible and touch targets with their forefingers. There were four major conditions: (*a*) one-hand movement; (*b*) two hands in symmetry—that is, both forward, both back, both out, or both in; (*c*) two hands in the same plane but not in symmetry —that is, both left, both right, or one forward and one back; and (*d*) two hands moving perpendicular to each other, such as one forward and the other to the left. Two-hand symmetric movements were more accurate and slightly faster than one-hand movements (supporting Langfeld's work). Two-hand motions in the same plane but not symmetric had fewer misses than one-hand motion but were

somewhat slower. Finally, perpendicular movements resulted in the most misses and were as slow as nonsymmetric movements in the same plane.

In a study by Trumbo, Rogers, and Avant (1967), however, symmetry was not important. Subjects moved a pointer in a matrix by turning two cranks in the frontal plane. One crank resulted in left-right movements of the pointer, and the other resulted in up-down movements. The time to move the pointer to predesignated positions for symmetric movements (one crank clockwise and the other counterclockwise) and for nonsymmetric movements (both clockwise or both counterclockwise) was determined; no difference was found. To determine whether motions in different planes interfere with each other, Norris and Spragg (1953) used a two-hand tracking task in which the target follower was controlled by two cranks. Having two cranks in different planes did not result in performance decrement beyond that which resulted when both cranks were in the worst of the two planes.

Consecutive movements, in contrast to simultaneous ones, result in substantial slowing. Langfeld's (1915) study has been mentioned in which the making of alternating finger movements resulted in considerable loss of speed. Subjects, in an experiment by Rubin, Von Treba, and Smith (1952), moved from one knob to another and turned each knob through varying degrees. The time taken to move between knobs increased with the degree of turn required by the knob. Similarly, Simon and Simon (1959) have shown that the time to move between knobs is increased if the knob turn before or after the movement required relatively high precision.

To summarize, multiple movements result in substantial decrement as opposed to single movements only when simultaneous motions require visual guidance to separate targets or when the movements are consecutive. Ambiguities in the importance of symmetry may be due to the different types of motion involved (linear vs. rotary) or to differences in sensitivity of the experiments. In any case the effects of asymmetry are not large. Greater interference may be found between motions of different classes (e.g., one linear and the other

rotary), but apparently there has been no experimental work on this question.

FEEDBACK AND MOVEMENT CONTROL

There are three possible ways in which movements may be controlled and each of these ways will be discussed. First, if movements are made slowly enough, corrections can be made on the basis of visual feedback. Data on the processing time for visual feedback are presented and implications of a feedback processing analysis for understanding Fitts' Law and continuous tracking are discussed. Second, evidence that kinesthetic feedback is important, even in the presence of visual feedback, and data on kinesthetic processing time are reviewed. And last, movements may be preprogrammed in the sense that the amount and timing of innervation to the muscles may be determined before the movement begins, and once it has begun, peripheral feedback would exert no further control.

Visual feedback. An important question in understanding movement control is how long it takes to process visual feedback. Woodworth (1899) and Vince (1948) studied this question by varying the stroke rate of back and forth movements made with the eyes open or closed. In Woodworth's experiment, subjects were asked to reproduce the length of the previous movement; in Vince's, they were asked to move to a fixed line and back. At a rate of 100 to 180 strokes/min, accuracy was no better with eyes open than with eyes closed. This corresponds roughly to about two strokes/sec or 500 msec. to process visual feedback.

One problem with the method of Woodworth and Vince is that some time is spent in reversing movement so that feedback processing time is overestimated. To avoid this problem, Keele and Posner (1968) studied discrete movements from a home position to a target, and only the time in motion was measured. Visual feedback was eliminated on half the trials by turning off the lights as the home position was left. On those trials the movement was completed in the dark. Visual processing time, as estimated by the shortest movement time at which hitting the target

was facilitated by having the lights on, was 190–260 msec.

Subjects in an experiment by Pew (1966a) attempted to maintain a target in the center of an oscilloscope by sequentially pressing two keys, one of which caused target acceleration to the right and the other to the left. When the oscilloscope display was blanked out for periods up to 410 msec. after a response, the modal time before the next corrective response was 300–350 msec. after the end of blanking. Since some of the corrective responses required less than the *modal* time, Pew's data are not inconsistent with that of Keele and Posner which estimate *minimum* processing time. The processing time in Pew's experiment could also be slightly larger due to the nature of the task. The reaction time for pressing a key in response to the direction of movement of a target is probably slower than that for simply moving the hand in the direction which would center the target. Fitts (1964), for example, reported that reaction time to the onset of a light is faster if the response is merely to point at the light rather than to press a key. Supporting this view, Pew, Duffendack, and Fensch (1967) reported that in sine-wave tracking with delayed feedback, corrective responses were made about 190–220 msec. after feedback delay. In that experiment a compatible isometric lever control was used rather than keys.

Feedback interpretation of Fitts' Law. Although Fitts' Law was originated in terms of information theory, it is possible to derive the theory from feedback considerations. The present derivation is similar to one proposed by Crossman and Goodeve (1963).

Assume that there is a minimum time t for processing feedback—that is, the time for an initial movement and each corrective movement is constant. Thus, if there is an initial movement and $n - 1$ corrective movements, the total movement time is $MT = nt$. Next assume that the relative accuracy of a movement is constant, that is, $X_i/X_{i-1} = K$, where X_i is the mean absolute distance from the center of the target after the ith corrective movement, and K is a constant. $X_o = A$ is then the distance from the starting position to the target center. After starting a movement,

corrections are made until it is within the target area. In other words, $X_n \doteq \frac{1}{2}W$ where W is the width of the target. Therefore, $X_n = KX_{n-1} = K^2X_{n-2} = \cdots = K^nA \doteq \frac{1}{2}W$. Solving for n: $n \doteq -\log_2 2A/W/\log_2 K$. Thus:

$$MT = nt = b \log_2 2A/W$$
$$\text{where } b = -t/\log_2 K. \quad [3]$$

If it is assumed that the initial movement takes less time by a constant a than the other corrective movements (since the time to decide how far to make the initial movement is not included in the movement time), then

$$MT = (n - 1)t + (t - a) = nt$$
$$- a = b \log_2 2A/W - a. \quad [4]$$

This equation is the same as Fitts' Law (Equation 2).

The assumption that the time for each corrective movement is constant and independent of distance may not be strictly true. Vince (1948, Exp. IV) and Searle and Taylor (1948) showed that the time from the start of movement to the first inflection in the kymograph record tended to increase as the distance of movement increased. The second assumption that error is proportional to distance is also only approximately true. For movements of so short a duration that visual feedback does not facilitate accuracy, increases in error are not quite proportional to increases in distance (Vince, 1948, Exp. III, and Woodworth, 1899). Woodworth found the proportion of error was less than 4% in most cases, but Vince found the relative error to be about 7%. The small deviations from constant duration and from constant relative error tend to cancel out each other as far as Fitts' Law is concerned.

One test of the adequacy of the model is to determine the constant b in Equation 3 from empirical estimates of t and K. As discussed earlier, Keele and Posner (1968) have suggested that t is between 190 and 260 msec. Setting K equal to 4% (Woodworth's estimate) and $t = 190$ msec., $b = 40$ msec. With K equal to 7% (Vince's estimate) and $t = 260$ msec., $b \doteq 70$ msec. The latter value is quite close to the empirically determined value of 70–75 msec. found by Fitts and Peterson (1964).

According to feedback theory, a disproportionate amount of the movement time should be spent near the target. Peters and Wenborne (1936) had subjects move a stylus rapidly along a track and lift up from the track when the stylus reached a line. They found that movements started somewhat slowly, picked up considerable speed, and slowed drastically near the end of the movement. The initial starting speed probably was inflated slightly due to a small reaction-time component, and the ending time might have been even slower if subjects had had to hit an actual target rather than to lift up the stylus. Annett, Golby, and Kay (1958) analyzed motion pictures of the movements involved in transporting pins and placing them in holes of various tolerance. The initial movement time covering 15/16 of the total distance was nearly constant (about 250–300 msec.) for different tolerances, but the final adjustment time increased as tolerance decreased. Final positioning of the pin varied from about half as long in time as the initial 15/16 of the distance to twice as long, depending on the degree of tolerance. Thus, there seems to be quite good qualitative as well as quantitative agreement for the feedback analysis of Fitts' Law.

Feedback and continuous tracking. An interesting implication of feedback theory is that the amount of error during continuous tracking should be predictable from the accuracy of single movements. As was mentioned in the previous section, a movement to a target may be viewed as a series of submovements, each one reducing the remaining error. In a continuous tracking task, however, the target position has changed after each submovement. Assuming as before that the error of each submovement is proportional to the distance to the target, each submovement should transmit the same amount of information as in the fixed target situation. Further, if the duration of each submovement is the same as for the fixed target situation, then the *rate* of information transmission in continuous tracking should approach that found by Fitts (1954) for reciprocal tapping (10 bits/sec). Crossman (1960) found that as the rate of information input in continuous tracking with preview increased, the rate of transmission increased to about 7 bits/sec. Unfortunately, he did not have a high enough rate of information input to determine whether or not the rate of transmission leveled off at about 10 bits/sec.

Kinesthetic feedback. Howard and Templeton (1966) have suggested that:

Kinaesthesis is best understood as a behavioural term. It includes the discrimination of movement and amplitude of movement of body parts, both passively and actively produced. Visual and auditory information is assumed to be absent. As well as afferents from muscles and joints, touch, stretch, and pressure signals from the skin serve these discriminations. The pattern of motor innervation is almost certainly also available as a source of information for kinaesthetic judgments [pp. 71–72].

The present paper departs slightly from Howard and Templeton's definition by not including motor innervation as part of kinesthesis. The reason for this is that all the other sources of kinesthesis are afferent and of peripheral origin, whereas motor innervation (or a motor program) is of central origin and may have quite different consequences for movement control. For example, when a skill becomes automatized in the sense that it requires little attention, it may be primarily under motor program control.

Some studies have attempted to show the importance of kinesthesis in the control of rapid movements by blocking kinesthetic cues. Lazlo (1966, 1967) found that the loss of kinesthetic sense from ischemia is very detrimental to tapping. It is possible, though, that some of the decrement was due to efferent damage as well as afferent. This technique also incurs novel feelings and considerable discomfort and pain, which could be responsible for some performance loss. In support of these arguments, Provins (1958) found almost no decrement in tapping rate when the index finger was anesthetized with xylocaine. However, in his studies, kinesthetic cues were still available from muscles and tendons, which would account for the lack of decrement.

A different approach is to look for behavioral evidence that kinesthetic cues are being used. Gibbs (1965) noted that when subjects were required to make rapid movements in the opposite direction to step function signals, they occasionally started the movement in the wrong direction. Early in

practice the mean time to correct the erroneous response was .24 sec., but later in practice the correction time was only .11 sec. Gibbs suggests that the latter time is too fast for visual correction and instead is due to kinesthetic correction. An alternative, however, is that at the appearance of a signal, a motor command is issued to move in the most probable direction. As the signal is further processed, the correct direction is determined and compared with the just issued command, and if there is a discrepancy, a motor command to reverse direction is issued. Thus, the feedback involved in the correction could be of central origin rather than peripheral origin. Models of this type are discussed by Rabbitt (1967).

Some studies have attempted to manipulate the quality of kinesthetic feedback. Burke and Gibbs (1965), Gibbs (1954), and North and Lomnicki (1961) compared pressure controls with freemoving (amplitude) controls in both pursuit and compensatory tracking. They found that pressure control using either finger or forearm movements resulted in more accurate tracking. Gibbs argued that the advantage of pressure control is due to the better quality and greater rapidity of kinesthetic information in isometric muscle contractions as opposed to isotonic contractions. These results certainly support the hypothesis that kinesthesis plays an important role in movement control, but they are not conclusive. It could be argued that preprogramming of movements is more accurate for force than for distance control; or, it may be that amplitude controls result in worse performance merely because it takes longer to make large movements than to make the very short isometric movements with pressure controls. Similar arguments may be made for the data of Briggs, Fitts, and Bahrick (1957). They found that manual compensatory tracking was best with a combination of relatively high force and high amplitude movement. Again, it is not clear that this would necessarily imply that kinesthetic information is used.

More conclusive evidence for the role of kinesthesis in tracking comes from a study by Notterman and Page (1962). They compared tracking, with a movable control stick having various degrees of elasticity, viscous damping, and inertia, to performance with an isometric control in which elasticity, damping and inertia were computer-controlled constants. Thus, the relation between an operator's force on the control stick and the oscilloscope output was the same in both cases, but with the movable control, the operator had kinesthetic feedback arising from movement as well as from force. The movable control resulted in better performance.

An experiment by Fleishman and Rich (1963) also indicated the importance of kinesthesis in tracking. They showed that as practice on the Two-hand Coordination Task increased, subjects with high kinesthetic sensitivity, as shown by small difference limens for judgments of lifted weights, became increasingly better than subjects with low sensitivity.

Some attempt has been made to determine how long it takes to process kinesthetic feedback. In an experiment by Chernikoff and Taylor (1952), a blindfolded subject's arm was held horizontally in a sling and then dropped. Reaction time from the onset of the drop until arm direction was reversed was about .11–.12 sec. Subjects in a study by Vince (1948) pulled a pointer down in response to a sudden displacement of a line. On some trials the spring tension opposing the movement was increased. It took subjects about .16 sec. to react to the increased spring tension. This value is slightly larger than Chernikoff and Taylor's estimate, perhaps due to the increased uncertainty of when a correction is necessary. Alternatively, Chernikoff and Taylor could be measuring spinal reflex time rather than central processing time. The rapidity of kinesthetic processing may explain why, apparently, it is important in tracking even with vision being used.

Attention to feedback. One might expect on the basis of studies of the psychological refractory period (see Bertelson, 1966; Smith, 1967; and Welford, 1967, for reviews) that while feedback is being processed, the processing of another signal would be delayed. Recently, Keele and Posner (1967) have reported that in some conditions rapid motions do require attention. The attention demand of a rotary movement was determined by the delay in reaction time to an acoustic signal occurring at various positions within the move-

ment. Attention was greater at the beginning of the movement, decreased to a relatively low value in the middle, and showed a slight increase near the end. At all positions the demand was greater for narrow targets than for wide targets.

Although movements do require attention, Leonard (1953) and Jeeves (1961) have shown that some surplus processing capacity is available. Subjects made a series of responses to lights. After each response, they returned to a home position before making the next response. If the light indicating the next response came on during the return movement, much less time was spent on the home position than when the next light came on only upon reaching the home position.

In the experiments just described, the subjects made movements to visually defined targets. There apparently has been no study of the attention demand of kinesthetically controlled movements, although Welch (1898) has shown that maintenance of a strong handgrip deteriorates in proportion to the difficulty of a simultaneous mental task.

It has been suggested that repetitive movements, rather than requiring attention, might be performed *better* if attention were attracted to a secondary task. Although Bliss (1892) reported that the regularity of rapid tapping increased when attention was diverted by tasks such as mental addition, he did not perform any systematic studies on this question. The data which he did report were so variable that no conclusions can be drawn from them. Boder (1935) also studied finger tapping during simultaneous performance of a secondary task. The secondary task of watching lights and later reporting the order of their occurrence tended to reduce the rate of tapping a slight amount but had very little effect on variability. When the secondary task involved moving a lever in one direction for a red light and in the other direction for a green light, the rate of tapping was considerably slowed, particularly while the lever was being moved. There was also a large increase in variability of tapping during the lever movement.

The data of Boder offer no evidence that performance of a simple tapping task is improved during secondary task performance.

It is possible, nonetheless, that simple repetitive tasks with emphasis on regularity rather than speed could be improved by diverting attention. Scripture (1899) reported that for rhythmic tapping, there is an optimal period at which the variability of the intertap interval is minimum. Faster or slower rates resulted in increased variability. Perhaps deviations from a natural rhythm require attention even for well-practiced tasks. Michon (1966, 1967) has looked at variability in tapping rates ranging to 2,400 msec. between taps. His results indicate that if processing of a secondary task is occurring at the time a tap should be executed, then the timing shows increased variability. If, however, there is time between taps (e.g., with the 2,400 msec. intertap interval) to complete processing of the secondary task, there is no interference. Certainly more study needs to be done on the important question of attention to repetitive movements and to series of nonrepetitive but highly practiced movements, such as in playing a familiar piece of music on a piano.

Formation of motor programs. In a rather trivial sense, all movements involve motor programs. Visual or kinesthetic information indicating the distance to a target must be converted to a muscle command, and once the movement is initiated, it is only under control of the program and cannot be changed until some minimum time for processing feedback. An important question, however, is the modifiability of the motor program. In an experiment by McLaughlin (1967), subjects fixated on a spot of light. Upon signal from a buzzer, they made a rapid eye movement to a target 10° to the left. The initial movement impulse prior to corrective motions was normally accurate within about .3°. Following a few initial trials of that type, the target light was switched after the start of the movement from the 10° position to a position only 9° from the fixation point. At first the eye tended to overshoot the 9° position, but after a few trials the 10° signal came to initiate a now appropriate 9° movement. Upon return to the original condition, undershooting occurred for several trials, indicating that the motor program had indeed been modified. Young, Green, Elkind, and Kelly (1964) similarly showed for continuous tracking that subjects adapted

to changes in polarity and gain of control in about 2 seconds.

The concept of a motor program is much more important when it is related to a series of predictable movements. In that situation, movement control may shift from visual-kinesthetic feedback to preprogrammed control. Such a shift could have at least three advantages. First, the degree of attention required may be reduced. As already mentioned, there has been little work on this important question. Second, successive stimuli may be anticipated so that appropriate movements may coincide with the stimuli rather than lag behind. And third, it may be possible for movements to be made at a much faster rate.

Evidence that subjects learn to anticipate regular stimulus occurrences so that they do not lag behind has been found by Poulton (1952), Noble, Trumbo, and co-workers (see Noble & Trumbo, 1967, for a review of their work), and Stark and Young (1965). Poulton (1957) has shown, in addition, that if subjects closed their eyes for a 5-sec. period while tracking a 60-cpm input, tracking was often maintained as well as when their eyes remained open for a 5-sec. period. The most common error when tracking with eyes closed was a gradual shift in timing.

The timing of movements may not be completely independent of attention, since Trumbo, Noble, and Swink (1967) have shown that a simultaneous mental task (anticipating numbers) interferes with the timing. Nonetheless, with a large amount of practice, the motor task becomes more impervious to secondary task interference (Noble, Trumbo, & Fowler, 1967), suggesting that timing may become somewhat automated.

Recently, Pew (1966b) presented evidence suggestive of a motor program. Subjects attempted to keep an oscilloscope target centered on crosshairs by sequentially pressing two keys, one of which caused target acceleration to the right and the other to the left. After a large amount of practice, the best subjects were making approximately four to five responses per sec. Although the rate of responding is close to the limits for processing visual feedback, the pattern of responding suggested that, rather than modifying each response on the basis of feedback, the subjects were

modifying a motor program. Quoting from Pew:

> *S* maintained a more rapid rate of responding than would have been possible if he were monitoring every response on a closed-loop basis. . . . When the target drifted off center to the left, *S* maintained the high rate of responding, but at the same time gradually increased the length of time the right key was active relative to that of the left key, so that over a series of responses the target was made to drift back toward the center [p. 769].

Other subjects, after drifting off target, made a single long duration corrective movement, suggesting that rather than gradually modifying a motor program, corrections utilizing visual feedback were occasionally interspersed among movements under programmed control.

Related evidence that for predictable events separate movements might be organized as a unit and triggered as a whole was reported by Stark and Young (1965). Subjects responded to short pulses (less than 50-msec. duration) in a visual target by a rapid stroke followed by a return stroke. When the pulse duration was known in advance, there was no delay in the return movement, but when the short pulses were mixed in with long duration pulses, there was a delay of about 200 msec. between the beginning stroke and the end stroke.

The preceding studies quite convincingly show that movement control may become internalized and, at least for short periods of time, free of visual control. There is no evidence, however, that performance is maintained without kinesthetic feedback. In view of the rapid processing of kinesthetic information, it is still possible that the feedback from one movement signals the next. It might be argued that anticipatory timing must be programmed, but Adams and Creamer (1962) have proposed that even timing is based on kinesthesis. They suggest that movement generates a kinesthetic trace which decays over time, and the trace characteristics after various delays can be used for timing the start of the next movement. In support of their argument they have shown that spring loading on a control stick does improve the timing to a regular series of step inputs, and, as will be seen in the next section, there is some evidence that there is a spontaneous decay in some movement cues.

As mentioned in an earlier section, there is evidence indicating that kinesthesis is used in performing a series of movements. Still it is not clear whether the individual movements within the series are initiated by feedback from the previous movement or whether kinesthesis is used only intermittently in correcting a motor program. Separating the role of these two factors in a series of movements appears to be a formidable problem and may be possible only with physiological techniques such as discussed in the introduction.

REPRODUCTION OF MOVEMENTS

Although it appears difficult to determine whether individual movements in a sequence are under programmed control, it may be possible to determine whether an individual movement in isolation is programmed. In this section, therefore, the reproduction of previous movements will be considered, and evidence will be presented that reproduction depends on a motor program, as well as other cues.

Motor program theory. Loeb (reported by Hollingworth, 1909, and Woodworth, 1899) showed that when two successive movements of subjectively equal length were produced, the movement involving the greater amount of active muscular contraction was actually shorter than the other. He assumed that in reproducing a previous movement, the muscles receive the same innervation regardless of kinesthetic spatial information arising from the movement. His results are explained by the further assumption that a given amount of innervation produces smaller movements the more contracted the muscle. This theory is not in accordance with findings of Hollingworth (1909) and Woodworth (1899) that when a series of subjectively equal movements was made from left to right, with each movement starting where the previous ended, the middle movements were longer in extent than the movements on *either* side. Results by other investigators, however, do support a motor program theory.

When no feedback from a movement is available, reproduction should depend solely on remembering the motor program of the previous movement. Lashley (1917) studied an individual in which kinesthetic feedback from leg movements had been lost due to

injury. The patient was unable to perceive or reproduce passive movements of the leg, yet was able to reproduce quite accurately movements that he had previously produced himself. An additional finding of interest was that on some occurrences, the subject stated that he made a movement longer than intended; and indeed, such movements were longer than others intended to be the same length. This seems to imply that there is a central feedback loop in which the issued command is compared with the intended program. (A similar mechanism was suggested earlier in this paper for some results of Gibbs, 1965.)

Even in normal individuals, there appears to be important differences in passive and active movements. Lloyd and Caldwell (1965) compared reports of leg angle when the leg was passively moved to a particular position and of the angle produced when subjects were asked to position actively their leg. The constant errors in the two situations were quite similar for leg extensions but different at leg flexions. One interpretation of this effect is that with passive movements, only kinesthetic cues are available. With active movements, on the other hand, the motor command to the muscles, as well as kinesthetic cues, might influence judgments, resulting in different constant errors.

Other evidence for motor program theory comes from studies on the control of eye movements. Extensive reviews by Festinger and Canon (1965) and Howard and Templeton (1966) have suggested that one of the cues for keeping track of the direction of gaze is reference to preceding commands for eye movement. Of particular relevance is an experiment by Festinger and Canon. Subjects in a dark room followed a spot of light with their eyes. Head position was kept fixed by a bite board. The light was either suddenly switched from the center position to a terminal position or it slowly moved to the terminal position. After the light turned off, they pointed with their arm to the position where the light had disappeared.

According to a motor program theory, a command to move the eye from the center position to the terminal position would be issued in the sudden switching condition. In the slow movement condition, however, no

motor command corresponding to the total distance would be issued because there was no way of knowing how far the light would move before stopping. Since other evidence reviewed by Festinger and Canon and by Howard and Templeton indicates that the eye has little kinesthetic sensation, there would be no distance cues available in the slow condition for directing the arm to the terminal position of the light. As predicted, rapid eye movements resulted in much more accurate arm positioning than slow eye movements. When the head was not held by a bite board, kinesthetic cues from the neck were available from the slow movement condition, and subjects then were able to position the arm as accurately as in the step movement condition.

The evidence appears fairly conclusive that motor programs *may* be used in reproducing active movements, but other cues might also be important.

Movement duration. Kramer and Moskiewicz, as reported by Hollingworth (1909), proposed that Loeb's results were due to the production of equal movement durations rather than equal motor commands. If movements with greater muscle contraction were also made at a slower speed, then they would be shorter in extent. To test this hypothesis, Hollingworth (1909) measured the duration as well as the extent of subjectively equal-length successive movements. He found little systematic difference in duration of successive movements, and durations were less variable than extent even though the subjects had been instructed to reproduce extent. These results give some support to Kramer and Moskiewicz's interpretation.

Leuba (1909) had people make a standard forearm movement of 8°. This was followed by a movement of 7°, 8.5°, or 10°, and the subjects judged whether the second movement was less, equal to, or greater in extent than the standard movement. When the second movement of a given length was longer in duration than the standard, there was a tendency to judge it longer in extent; when less in duration, the tendency was to judge it less in length. Unfortunately, Leuba presented very little data to support these trends. In other data the duration of movement was confounded with the actual extent.

Duration by itself is not a sufficient cue for reproducing movement, since the speeds might differ. It is possible that, rather than preprogramming the total amount of innervation to the muscles, people program the rate and duration of innervation. If one adopts this view, there is actually little difference between the motor program theory of Loeb and the duration theory of Kramer and Moskiewicz. Alternatively, duration information may be combined with *kinesthetic* speed or force information. Leuba (1909) showed that if a constant resistance were added to the second movement, there was an increase in duration, but there was little change in the accuracy of judged extent. He concluded that subjects were able to use kinesthetic information to judge the speed and made compensatory changes in duration. When the resistance to the movement changed throughout the movement, judgment of extent deteriorated, implying that, in this situation, subjects were less able to judge the speed of movement and compensate with changes in duration.

Movement extent. The experiment by Festinger and Canon (1965), as discussed earlier, presented evidence that kinesthetic cues from the neck could be used for movement reproduction. Kinesthetic senses could give information on the speed of movement, and, as discussed previously, that information could be combined with duration to determine extent. Alternatively, there could be a direct kinesthetic sense of extent that does not depend on speed or duration. In an experiment by Woodworth (1899), subjects with their eyes closed drew a line and then attempted to place a dot at each end of the line. They were nearly as accurate in reproducing the end points as when they attempted to reproduce the previous line, suggesting that people have a direct sense of the distance between two points. Such a cue would seem to depend on kinesthetic knowledge of *locations* in space rather than distance per se.

Memory for movements. As noted earlier, the internalization of movement control has important implications for understanding skilled performance. However, for such internalization to be of much use, the timing and extent of movements must be retained for at least short periods of time. Results by Poulton

(1957) have already been mentioned which indicate that the timing of successive movements may be very accurately retained for periods as long as 5 sec. Work on the retention of distance information will now be reviewed.

Several studies have shown that the accuracy of reproduction decreases as the time between the original movement and the reproduction increases. Hollingworth (1909) showed a loss of accuracy between 2 and 30 sec. A similar decrease in accuracy over a period of 60 sec. was reported by Scripture, Cooke, and Warren (1897), but their data are so variable they are inconclusive. Schnieder (reported by Hollingworth, 1909) found that the decrease in accuracy continued over a period of 15 min., and it has been more recently reported by Bilodeau and Levy (1964) that increased forgetting of the movement occurs between 2 days and 6 weeks.

As with memory for other types of material, increasing the number of repetitions of a movement increases the accuracy of reproduction (Adams & Dijkstra, 1966). This is important because it indicates that the internalization of movement control may have long lasting as well as transitory effects. However, even after as many as 15 repetitions prior to reproduction, there is still some decline in the accuracy over a retention period of two minutes. As Adams and Dijkstra point out, the forgetting occurs even with an unfilled interval between an original movement and the reproduction. Moreover, Posner and Konick (1967) have shown that the retention of movements is not further degraded by an interpolated mental task, even though it involves hand movements from writing. Short-term memory for verbal units, in contrast, shows little loss during an unfilled interval, but a large loss with an interpolated mental task (Posner & Rossman, 1965). Boulter (1964) and Blick and Bilodeau (1963) have also found that an interpolated verbal or movement task has no effect on movement reproduction. Boswell and Bilodeau (1964), on the other hand, found that the simple act of picking up a pencil from the floor between a movement and its reproduction 28 sec. later resulted in greater inaccuracy. Although special rules for posture were given, it is possible that there were some postural changes after picking up a pencil which would account for the greater inaccuracy in that situation.

A few studies have varied the type of movement in order to separate the various components of movement control and to determine whether there are differences in memory. Hollingworth (1909) compared memory for extent with memory for duration and found similar changes over time. Recently, Posner (1967) compared memory for movement extent starting from the same position as the original movement with memory for extent in which the two movements started in different positions. Although the overall accuracy was greater when reproduction was from the same starting position, there was no significant difference in the loss of accuracy over time. When reproduction was from the same starting position, there was a slight, but nonsignificant, trend for memory loss to increase with an interpolated mental task. Only an experiment by Keele [2] has found different memory functions for different types of movement. Memory for location in space, like memory for verbal material, underwent little spontaneous forgetting but did show forgetting with an interpolated mental task. Similar results were also found for memory of short distances, but results more congruent with those of Posner were found for longer distances, suggesting that different cues are involved in the memory of long and short movements.

More research is clearly needed before it can be determined what cues are different in short and long movements, whether the forgetting of motor programs is different than for kinesthetic cues, and whether different kinesthetic cues show differential forgetting. With regard to the last point, Howard and Templeton (1966) state that muscle spindle afferents do not project as far as the sensory cortex, whereas joint receptors do. If it were true that only cues having cortical projections are rehearsable, then movements depending on spindle information might be expected to show different forgetting functions than movements depending on joint information.

[2] S. Keele, unpublished manuscript (1968).

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