The Movement Speed-Accuracy Relationship in Space-Time

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Introduction

In this chapter we synthesize extant descriptions of the movement speed-accuracy relationship and develop, from these orientations, a space-time approach to movement accuracy. This new space-time perspective provides a cohesive account of spatial and temporal movement error functions in the face of changing kinematics. The space-time function is posited as a statistical manifestation of the organismic, environmental, and task constraints inherent to the given action.

The relationship between movement speed and accuracy is an issue that has enjoyed considerable theoretical and empirical activity in the psychological domain. Since the seminal experimental work of Fullerton and Cattell (1892), descriptions of the movement speed-accuracy relationship have focused almost exclusively on errors in a single or dual spatial dimension (e.g., Beggs and Howarth 1970; Crossman and Goodeve 1963; Fitts 1954; Woodworth 1899). Moreover, these formulations have been confined to spatial errors which have been produced principally at or toward the upper end of the velocity continuum for prescribed movement amplitude and target tolerance conditions. A recent account of the movement-speed timing-accuracy relationship has examined a wide range of movement velocities but has also been limited to tasks with criteria in only one or two spatial dimensions (Newell 1980; Newell, Hoshizaki, Carlton, and Halbert 1979; Newell, Carlton, Carlton, and Halbert 1980).

The above formulations of the movement speed-accuracy function have accounted for restricted segments of the overall speed-accuracy relationship. We propose that a complete description of this relationship should examine both spatial and temporal components of movement across the complete range of movement generation available to the human performer in the accomplishment of discrete motoric acts. The chapter shows that when both temporal and spatial errors are measured in the same plane of motion, the movement-speed error functions for each moment of the error distribution are consonant.

This space-time approach to movement speed-accuracy provides an enhanced perspective from which to view previous descriptions of the relationship between movement parameters and resulting movement accuracy. Traditional accounts of the speed-accuracy function are shown to be either inaccurate or incomplete. Furthermore, previous postulates have failed to incorporate movement timing error, or, where it is a part of the speed-accuracy description (e.g., Schmidt, Zelaznik, Hawkins, Frank, and Quinn, 1979), the timing error function is independent of and incongruent with the spatial error function. The proposed space-time description provides an alternative perspective from which to assess the extant explanatory interpretations of the speed-accuracy phenomenon. These include information transmission (Fitts 1954), discrete error correction (Crossman and Goodeve 1963; Keele 1968). and motor-output variability (Schmidt, Zelaznik, and Frank 1978; Schmidt et al. 1979).

Movement Speed and Spatial Error

The speed-accuracy trade-off is the most reliable relationship in the movement control literature. Its essence is that spatial error, irrespective of the particular dependent variable, tends to increase with gain in movement velocity. Consequently, the principal tactic available to the performer to ameliorate such error is the reduction of movement speed so that, as the law implies, a trade-off is made between movement speed and resultant accuracy.

There have been many attempts to describe and to explain the speed-accuracy relationship. The major approaches are examined here in order to provide a basis for the proposed space-time description. At this juncture, focus is directed toward the various descriptive relationships that have been advanced between the kinematic variables and movement spatial-error, rather than the accompanying explanatory constructs. The individual accounts provide insight into restricted elements of the speed-accuracy function but none offers a comprehensive picture.

Woodworth. Woodworth (1899) in his dissertation research is often credited with being the first to examine the movement speed-accuracy relationship. However, an earlier treatise by Fullerton and Cattell (1892) on the psychophysics of movement preempts Woodworth's investigation and, in addition, references earlier experimental work by both German and French investigators on this problem. Although acknowledged as the seminal behavioral work in motor control, Woodworth's contribution might be viewed more veridically as a crystallization of the previous and somewhat sporadic research. Woodworth, working with his mentor Cattell, examined over 125,000 line drawing movements in an attempt to construct a cohesive account of the accuracy of voluntary movement. Despite the justifiable acclaim that Woodworth has received for this work, it is apparent that the rich description provided in his monograph of the interrelationship between movement time, distance, and velocity in the determination of movement error has been neglected.

It should be noted that in our projection of the Woodworth data, and all subsequent data sets, we examine the various response errors in relation to three movement parameters, namely, amplitude, movement time, and average movement velocity. Utilizing the redundant degree of freedom, average velocity, facilitates an intuitive understanding of the error functions and, in this first pass at synthesizing the speed-accuracy functions, we have kept average movement velocity in our graphical projections. Formal accounts of the speed-accuracy function should be able to accommodate the error function in terms of amplitude and time.

In experiments constructed to test the applicability of Weber's (1834) psychophysical theory to the movement domain, Woodworth independently manipulated 4 distances (5, 10, 15, and 20 cm) and 10 movement durations (300–3,000 ms) in a line drawing task. Only three subjects performed this experiment of which only one subject completed all conditions. The standard unit er-

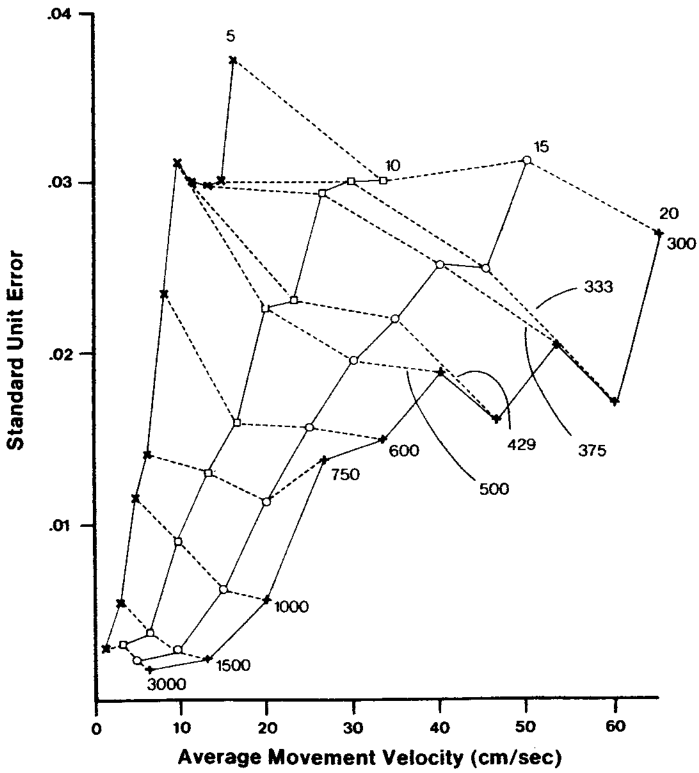

Fig. 1. Standard unit error as a function of average movement velocity. Within the body of the illustration movement times (*dotted lines*) extend from 300 to 3000 ms and movement amplitudes (*solid lines*) range from 5 to 20 cm in 5-cm increments. (Data redrawn from Woodworth 1899, Tables XVI–XVIII)

ror for each of the three subjects has been collapsed to form a group mean error for each time-distance combination and these means are depicted in Fig. 1.

As can be seen in the illustration we have had occasion to reference a newly labeled movement error called standard unit error which will recur throughout our treatise. This measurement is constructed from the within-subject standard deviation of response errors, commonly denoted as variable error (VE), together with the imposed spatial or temporal movement criteria. VE may be derived for both spatial and temporal aspects of response errors. The standard unit error for space represents the VE of amplitude divided by the imposed movement distance at which the error was observed. In essence, this form of error encapsulates the proportion of variable error made per imposed unit distance. In order that no misconception be formulated as to the dimension of this error, because it is dimensionless, we have referred to this as standard unit error. As we subsequently show, when standard unit error is calculated on the same principle for temporal error, these space-time aspects of movement error are homeomorphic in that they possess equivalent morphological features. The standard unit error is distinct from the coefficient of variation, for example, which divides the standard deviation of error by the attained mean, rather than the imposed mean as in the case of the present condition. Thus, the standard unit error is independent of constant error functions, which are subsequently developed in a separate section.

The decrease of standard unit error with increments of average velocity per given movement time indicates that the gains in variable error are not proportional to the distance moved, which would be consistent with Weber's theory, as error increases at a slower rate than changes in extent. However, the variable error increases at a faster rate than the square root of stimulus magnitude, a formulation originally postulated and tested by Fullerton and Cattell (1892). Woodworth's data also indicate degrees of alternating curvilinearity in the standard unit error at low- and high-velocity conditions within a single amplitude. Also, increases in movement time within a given distance reduce the standard unit error but by an amount less than would be proportional to the change in temporal duration.

Figure 1 clearly displays certain random trends particularly at the shortest movement times. This is presumably because some data points are based upon observations derived from a single subject. However, in contrast to the interpretation advanced by Keele (1968, p. 391), we choose to interpret the nonproportional and curvilinear trends exhibited in Woodworth's data as the basis for a veridical description of the speed-accuracy function.

Woodworth also reported systematic constant error shifts with changes in kinematics. The general trend within a given movement amplitude was for overshooting and undershooting to occur at low- and high-velocity conditions, respectively.

Woodworth's observations imply an intricate relationship between movement duration, amplitude, and velocity in the determination of movement error. However, this perspective has failed to emerge from subsequent reference to this work. This is surprising because Woodworth's dissertation still provides one of

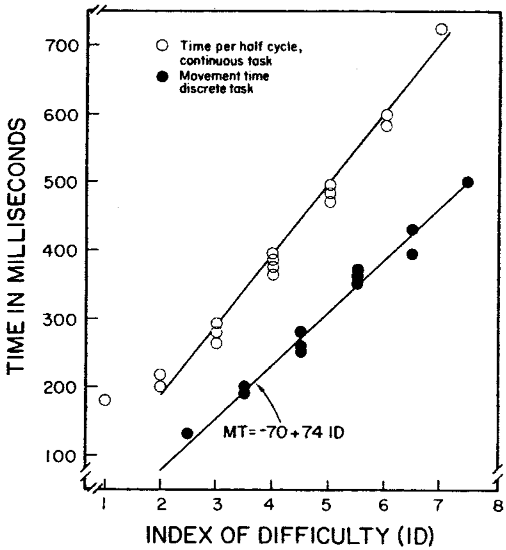

Fig. 2. Movement time (ms) as a function of index of difficulty (ID) in tapping (Fitts 1954) and discrete (Fitts and Peterson 1964) movement tasks. (Adapted from Fitts and Peterson 1964)

the most comprehensive investigations pertaining to the speed-accuracy relationship and, as we subsequently demonstrate, the data are consistent with more recent empirical observations (e.g., Schmidt et al. 1979).

Fitts. While Garrett (1922), Philip (1936), and Craik and Vince (1963 a, b)[1] pursued descriptions of the speed-accuracy functions, it was Fitts (1954) who proposed a formal relationship:

$$MT = a + b \log_2 (2A/W). \quad (1)$$

where MT is movement time, A represents the amplitude of movement, W is the target width, and a and b are empirically determined constants. Data reflecting the accuracy of this mathematical relationship are shown in Fig. 2, which is taken from the discrete movement analysis of Fitts and Peterson (1964) and includes movement time data from the original tapping task protocol employed by Fitts (1954).

In Fitts' formulation, an index of movement difficulty (ID) is manipulated by the ratio of target width to amplitude of movement and is calculated by:

$$ID = \log_2 (2A/W). \quad (2)$$

Since Fitts' original proposal, several elaborations to Equation 1 have been advanced. Welford (1968) suggested that subjects utilize only the near half of the target area and modified the equation accordingly to accommodate a greater percentage of performance variance in the form:

$$MT = K \log_2 (A/W + 0.5). \quad (3)$$

[1] The original dates of these manuscripts were August, 1943 and March, 1944, respectively, published as APU reports, Cambridge University, England.

Subsequently, Welford, Norris, and Shock (1969) advanced an equation relating movement time separately to amplitude and target tolerance:

$$MT = a + b \log_2 A + b \log_2 (1/W). \tag{4}$$

Other investigators have followed Fullerton and Cattell (1892) and used the actual spatial error from a point or line target. These measures of error[2] of a distribution of trial responses have been labeled mean error square (E^2) and the effective target width (W_e), respectively (Beggs and Howarth 1970; Welford 1968). These procedures have allowed a more precise description of the distribution of the outcome of responses compared with a score of percentage of movements missed for any particular target width. However, these approaches do not preclude an error derived from the method of measurement employed. For example, Schmidt et al. (1978) estimated that with their procedure the measurement error of W_e in the stylus-aiming task was equal to 0.6 mm. The contribution of measurement error to the overall estimation of movement accuracy may be small, although it is still an important factor to consider in the full description of the speed-accuracy relationship.

The suggested modifications to Fitts' equation have added a marginal degree of precision to the quantification of the speed-accuracy formulation but they have not changed the essence of the relationship inherent in the original equation. Moreover, the relationship proposed by Fitts has been demonstrated as robust over a wide range of populations (e.g., Wade, Newell, and Wallace 1978; Wallace, Newell, and Wade 1978), with different anatomical units (e.g., Langolf, Chaffin, and Foulke 1976), in an underwater environment (e.g., Kerr 1973), and under microscopic conditions (e.g., Hancock, Langolf, and Clark 1973). It is only fitting, therefore, that Equation 1 is generally known as Fitts' law.

There are several factors indicating limitations to the potential of Fitts' law as a general description of the movement speed-accuracy relationship. With respect to its internal consistency, it has been observed that the lawful relationship fails at very low *ID*s (e.g., Crossman and Goodeve 1963; Klapp 1975), a feature illustrated in the original Fitts data (see the deviation from the regression line of the movement time for the tapping task at *ID* of 1 in Fig. 2). Secondly, in contrast to the implicit assumption of Fitts' law, it has been suggested that amplitude and target width do not possess equal weighting in the determination of movement time (Sheridan 1979). This criticism centers on the observation that in several aiming studies the movement times for amplitude-target combinations, within a particular *ID*, tend to be aligned in an inverse order with respect to target size so that smaller targets possess longer movement times. Unfortunately, it is uncertain whether this trend reflects departures from Fitts' law or experimental

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[2] The confusion surrounding the use of the term "effective target width" has been compounded by different interpretations for this common label. Welford (1968), following Crossman (1957), took W_e to represent an error range represented by four standard deviations. Schmidt et al. (1979) utilized W_e as the within-subject standard deviation of response errors.

artifacts. For example, it is possible that this effect could be the result of a speed-accuracy trade-off within amplitude-target width conditions. However, this argument cannot be utilized with Fitts' (1954) original data as the smaller targets also possess the larger error rates.

A further possible confounding element is that larger targets increase the likelihood of a higher number of contacts occurring in the near half of the target. The outcome of such a constant error shift would be that the average distance traveled would decrease as target size increases at a given distance so that movement time also decreases proportionally for a given error rate. Consequently, there appear to be limitations in the Fitts formulation of the speed-accuracy function although problems with the aiming task protocol also compromise its internal validity.

In addition to the foregoing problems, the term speed when used in relation to Fitts' law has, in effect, assumed the burden of representing both a velocity and a time dimension as, in the Fitts discrete and reciprocal aiming tasks, the average movement velocity and movement time covary. The independent effects of movement amplitude, velocity, and duration on spatial accuracy were not presented by Fitts, or indeed in subsequent work concerning the Fitts protocol, although such relationships may be derived from Equation 1. Fig. 3 depicts the data originally presented in Fitts (1954, Experiment 1) but redrawn such that the relationships between movement time, amplitude, average velocity, and error (target tolerance) are explicit.

One striking relationship revealed in Fig. 3 is that error, as assessed by target tolerance, decreases in a curvilinear manner as average movement velocity decreases at any movement amplitude. If lines for prescribed movement times were drawn through the appropriate points of target tolerance, although this is not possible with Fitts' data set as there are no identical movement times despite the original prediction, then they would increase at a negatively accelerating rate

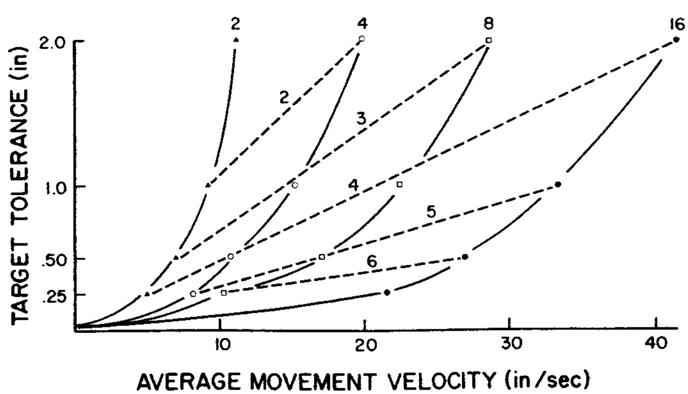

Fig. 3. Target tolerance (in.) as a function of average movement velocity (in./s), movement amplitude (in.) (continuous lines), and index of difficulty (*dashed lines*). (Redrawn from Fitts 1954, Table 1)

with gains in average movement velocity in a fashion consistent with the Woodworth data previously reviewed. The *ID*-error (target tolerance) lines appear linear with a common intercept on the ordinate above the intersection of the axes. Our interpretation is that Fig. 3 is more revealing as an exposition of the basic relationships that exist between the kinematic parameters and movement error than was originally presented (see Fig. 2).

In addition to the above specific limitations, it is the case that all verifications of Fitts' law have occurred in aiming tasks with only one or two spatial criteria. There have been no attempts to determine whether Fitts' equation applies to a task with three measured spatial criteria. A more important restriction of the Fitts protocol is that movement time is a dependent rather than an independent variable and this excludes the concomitant consideration of temporal error to movement accuracy. This is a serious limitation particularly in considering tasks which have time as a criterion, as for example when a limb, or an extension of a limb, is required to make contact with a moving object.

Fitts' law also describes the movement speed-accuracy relationship principally at the upper end of the movement velocity continuum for any particular anatomical unit over any given movement amplitude-target tolerance condition. It is only in limited circumstances that tasks demand limb movement at or approaching that of maximum velocity for any particular movement amplitude. Even within this limited range of movement velocities, it has been suggested that the points utilized in the construction of the Fitts relationship may be more appropriately fitted to curves other than logarithmic transform (Jagacinski, Repperger, Ward, and Moran 1980; Kantowitz and Knight 1978). Indeed, Kvålseth (1980) has shown that a power function produces a marginally superior fit to data derived from Fitts' protocol, although only at the expense of adding an additional degree of freedom to the equation. Parenthetically, the base of the log component of Fitts' equation is immaterial to the description (Bainbridge and Sanders 1972). The binary base was chosen presumably to maintain a degree of concordance with the information theoretic approach of the original conceptions of Shannon and Weaver (1949), although the mathematical assumptions upon which such a connection to Fitts' formulation is founded have been suggested as flawed (Kvålseth 1979).

Given these reservations concerning Fitts' law, it seems necessary to consider the nature of the speed-accuracy relationship over a wider range of kinematic conditions and unbound by the particular constraints of the stylus-aiming protocol. While Fitts' law provides a good approximation of the movement-speed spatial accuracy phenomenon, over a reasonably wide range of the movement velocity continuum, Equation 1 clearly cannot represent the comprehensive description of it. Moreover, it masks certain systematic relationships that exist between accuracy and the kinematic parameters of movement.

Finally, it should be recognized that it is important to distinguish between Fitts' equation as a description or curve-fitting operation of the relationship between movement time and target tolerance and as an information transmission explanation which attempts to account for the speed-accuracy function. Regardless of the veracity of Fitts' law as a description it does not necessarily demand a tacit or explicit acceptance of the information transmission explanation by characterizing the relationship of *ID* to movement time in terms of channel capacity. There are grounds upon which to question the analogy drawn by Fitts between the information capacity of a band-limited communication channel and the human motor system. For example, Kvålseth (1979) has argued that in the classical model the input signals are stochastic whereas Fitts (1954) implied that the input to the motor system is deterministic. This latter assumption leads to fixed and consequently erroneous estimates of the information capacity of the human motor system. However, even with an appropriate use of communication theory, the derived channel capacity is merely an alternate form of description of the outcome variability for given kinematic conditions, in that it is obtained by rearranging the terms in Fitts' equation.

Bailey and Presgrave. In the course of developing principles and procedures relative to time and motion studies in the work place, Bailey and Presgrave (1958) conducted several analyses of the relationship between the speed and accuracy of simple limb movements. This work is not recognized generally in accounts of the movement speed-accuracy relationship, which is unfortunate as the data on the accuracy of simple arm movements represent one of the most comprehensive examinations conducted.

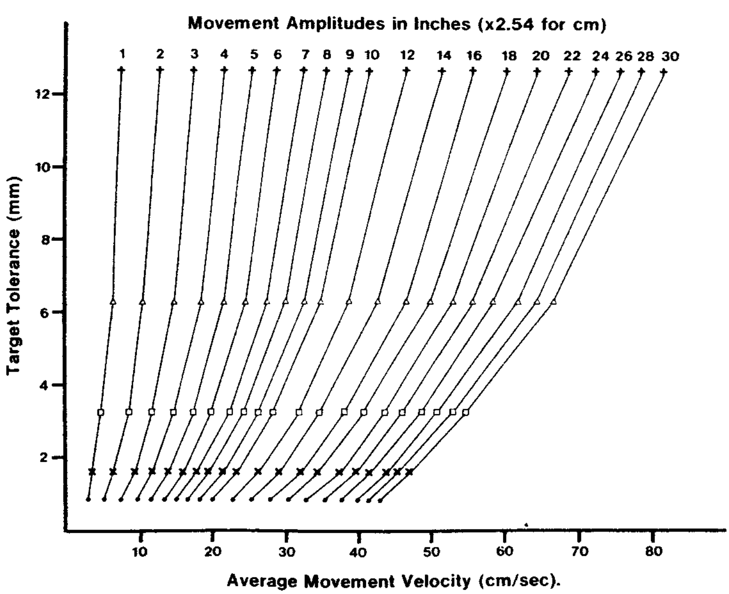

Fig. 4. Target tolerance (mm) as a function of average movement velocity (cm/s) and movement amplitude (in.). (Adapted from Bailey and Presgrave 1958; Figures 10, 13. The original scale for movement amplitudes is preserved for ease of illustration)

Figure 4 is adapted from data originally presented in Bailey and Presgrave (1958, Figures 10, 13) and describes the average velocities of arm movements to a target in terms of the 20 amplitudes and 5 target tolerances manipulated. Details of the experimental procedures are somewhat sparse but apparently there were no error rates as subjects were always required to contact the target regardless of temporal constraint. The data are consistent, however, in demonstrating the curvilinear relationship of movement velocity and target tolerance within a prescribed movement amplitude. In this respect the data of Bailey and Presgrave (1958) provide substantial support for the reinterpretation of the observations of Fitts (1954), which we have discussed above. Figure 4 also reveals that constant increments of amplitude at any given target tolerance lead to a negatively decelerating increase in the average movement velocity produced. Consistent effects are also noted for slope of the amplitude lines, which decrease systematically with equal increments of movement amplitude.

In each case the data points presented are based on CV movements, those which Bailey and Presgrave note as requiring precision in movement (C) with the use of vision (V). From the current perspective one limiting factor of this work is the lack of specification of a defined temporal criterion. As a consequence, the picture presented in Fig. 4 may not be as veridical a representation as could be desired concerning the movement time contribution to overall accuracy.

Beggs and Howarth. On the basis of a series of hand-aiming experiments (Beggs and Howarth 1970, 1972a, b), Howarth, Beggs, and Bowden (1971) determined that the mean square error (E^2) of the deviations from a target line was predicted by the equation:

$$E^2 = E_0^2 \, (o_\Theta d_u)^2. \qquad (5)$$

where E_0 and o_Θ are empirically determined constants. Howarth et al. (1971) speculated that E^2 was made up of the sum of two independent sources of error. E_0^2 was taken to represent some kind of uncontrollable tremor while $(o_\Theta d_u)^2$ is a variance due to the angle (o_Θ) and length (d_u) respectively of what Howarth and colleagues referred to as the uncontrollable movement, which represents that portion of the movement produced by the last discrete error correction. It was determined that the aiming data revealed a linear relationship between mean square error (E^2) and the distance traveled during this last discrete correction.

Howarth et al. (1971) indicated that the speed-accuracy data generated from their experiments were incompatible with Fitts' formulation. However, there are several differences between the respective experimental protocols employed. The task utilized by Howarth et al. (1971) was distinct in that the aiming movement occurred in the sagittal plane, the duration of each tapping movement was relatively long (416–1428 ms) compared with that in Fitts' (1954) original work (180–731 ms), and the measures of spatial accuracy were orthogonal to the principal plane of motion. Kerr and Langolf (1977) have demonstrated that Fitts' law operates for movements in the sagittal plane and therefore the difference between the formulation of Fitts and that of Beggs and Howarth is unlikely to be due simply to the influence of the selected plane of motion. Another possible source of incongruence is the difference in the duration of each individual movement. In the studies conducted by Beggs and Howarth, the movement times were considerably greater than those in Fitts' experiments and presumably allowed for a higher probability of discrete corrections over a group of trials.

Howarth et al. (1971), based upon earlier work (Beggs and Howarth 1970), fixed the temporal estimate of the last error correction from target impact at 290 ms. Consequently, the distance traveled during the last error correction covaried with the average velocity of the discrete correction. A reanalysis of the root mean square error (*E*) data reported by Howarth et al. (1971) reveals that *E* also increases as the average velocity of last discrete correction increases (see Fig. 5). Furthermore, when *E* is divided by the distance traveled during the proposed last error correction, the error decreases with increases in the average velocity of the corrective response (see Fig. 5). This implies that increases in *E* are not proportional to gains in both distance and velocity of the last discrete correction.

Discrete correction interpretations of Fitts' law (Crossman and Goodeve 1963; Keele 1968) operationally define a correction as an inflexion point on a trace of a kinematic parameter (e.g., Carlton 1979a, 1980; Langolf et al. 1976). Howarth and his associates did not measure the discrete movement corrections directly and in consequence their interpretation of the speed-accuracy relationship relies on the implication that a discrete correction occurred as the movement

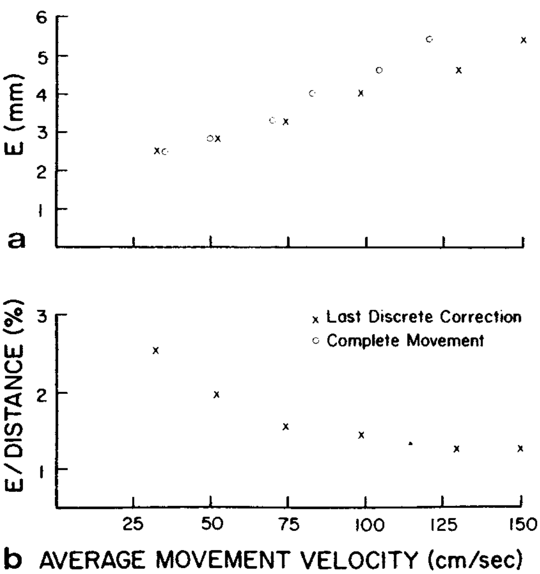

Fig. 5. **a** *E*, Root mean error square (mm) as a function of average movement velocity and average velocity of the final discrete correction. **b** *E*, divided by movement amplitude (%) as a function of the average velocity of the final discrete correction. (Adapted from Howarth, Beggs and Bowden 1971, Table 2)

times exceeded that of a visually based movement correction time. The temporal duration of a movement is insufficient a criterion from which to establish the presence or absence of a discrete correction.

Current estimates of the minimum visual processing time in discrete movements are considerably lower than the traditionally accepted 190–260 ms (Keele and Posner 1968) and 290 ms proposed by Beggs and Howarth (1970). Carlton (1981) utilizing high-speed film techniques has shown visually based discrete corrections with a latency of 135 ms, and Smith and Bowen (1980) have provided evidence that visually based response corrections can occur in less than 90 ms. Hence, even if discrete corrections occurred, the 290-ms estimate of minimal visual processing time by Beggs and Howarth is conservative. Indeed, Carlton (1979b) has argued that perusal of the Beggs and Howarth (1970) data suggests that contrary to their own assessment the mean corrective reaction times were 165 ms when vision was withdrawn with the hand close to the target. The discrepant estimates apparently are due to the point in the movement trajectory where vision was withdrawn. When vision is withdrawn with the hand close to the target, Carlton proposes that the estimate of visual processing time is shorter than 290 ms and this estimate increases when the hand is farther from the target.

The summary kinematic data presented by Howarth et al. (1971, Figure 1) suggest that a continuous movement occurred on average although it is possible that these group data mask individual trial corrections which may have occurred. The failure to provide direct evidence of discrete corrections on individual trials undermines the interpretation offered by Beggs and Howarth for their speed-accuracy function. In addition, it raises the issue of whether the temporal duration of the response is the key factor which affords different functions for the speed-accuracy data sets presented by Fitts (1954), Beggs and Howarth (1970), and indeed, as will be subsequently discussed, Schmidt et al. (1979). Reanalysis of the data provided by Howarth et al. (1971) and Beggs, Graham, Monk, Shaw, and Howarth (1972) in terms of E divided by the amplitude of movement suggests that E increases nonproportionally regardless of whether it is related to the average velocity of the last discrete correction or the average velocity of each movement (see Fig. 5).

In summary, the formulation of Beggs and Howarth cannot represent a general account of the movement-speed accuracy relationship as it is limited to measurements of spatial error and constrained to movements that are assumed to contain a discrete correction. It is our contention that the actual data of Fitts and those of Beggs and Howarth are qualitatively similar and differ only quantitatively due to the differing task demands alluded to previously. In addition, apparent differences may be generated by the use of a logarithmic axis as is given in Howarth et al. (1971). The absolute size of the movement errors will inevitably be smaller when they are measured on the basis of aiming movements to a target line and in a plane orthogonal to the principal direction of motion, which probably renders the employment of Crossman's (1957) estimate of effective target width by Howarth et al. (1971) inappropriate for contrasting the data sets.

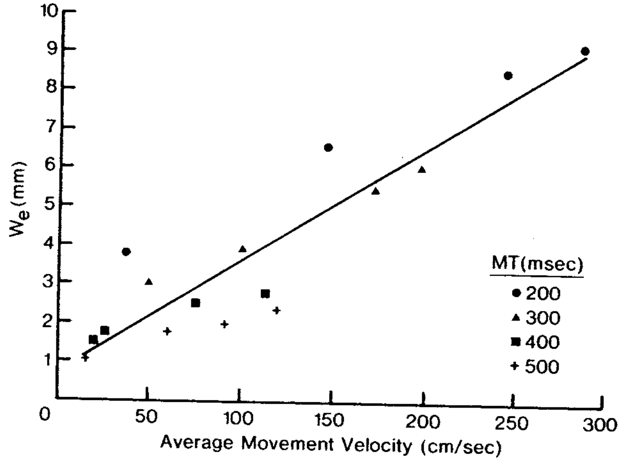

Fig. 6. Effective target width (W_e) or standard deviation of spatial error as a function of average movement velocity. (From "Motor output variability: A theory for the accuracy of rapid motor acts" by Schmidt, Zelaznik, Hawkins, Frank and Quinn, Psychological Review, 1979, *86*, 415–451, Figure 7. Copyright 1979 by the American Psychological Association. Adapted by permission of the publisher and author)

Schmidt, Zelaznik, Frank, Hawkins, and Quinn. In support of a motor-output variability theory of the movement speed-accuracy trade-off, Schmidt et al. (1978, 1979) have presented spatial-accuracy data for aiming movements, over a range of average movement velocities (15–300 cm/s) and movement times (140–500 ms). Figure 6, which is derived from Schmidt et al. (1979, Figure 7), provides their picture of movement spatial error in a two-dimensional aiming task. Schmidt et al. recognized two trends in the data depicted in Fig. 6: firstly, a linear relationship between average movement velocity and spatial error in the form of W_e, a finding which is consistent with Weber's law and, secondly, the tendency for both slope and intercept of the regression line on W_e to increase as movement time decreases. This suggests that movement time and average movement velocity interact in determining spatial error (W_e) measured in the principal direction of motion. Increases in movement velocity have been shown also to increase error in the plane orthogonal to the principal direction of motion (Begbie 1959; Beggs and Howarth 1970; Drury 1971), although the absolute size of error is reduced in this plane (Siddall, Holding, and Draper 1957; and compare Schmidt et al. 1979; Figures 8, 10).

A linear relationship between actual variable spatial error and movement velocity was reported by Schmidt et al. (1979) in the form:

$$W_e \propto (A/MT) \tag{6}$$

where A is movement amplitude and MT is movement time. However, there are reasons to doubt the validity of this description. If the relationship was linear, it would be in direct conflict with each of the preceding descriptions of the movement-speed spatial-accuracy phenomenon, including Fitts' formulation, which only appears linear by virtue of the logarithmic term in Equation 1. In addition, a proportional function is incongruent with the curvilinear relationship established between movement velocity and timing error (Newell et al. 1979, 1980). Consequently, there are grounds upon which to postulate that the spatial error movement-velocity relationship is not a simple linear function. A linear function between response variability and movement velocity for prescribed amplitudes was rejected by Fullerton and Cattell (1892) and Woodworth (1899) in their original investigations of Weber's law concerning movement precision.

Indeed we propose that a more veridical picture emerges from a reanalysis of the data of Schmidt et al. (1979) presented in Fig. 6. Although Schmidt and his colleagues interpreted the speed-accuracy function from their data as linear it is our contention that a curvilinear function is more appropriate. One problem encountered is that linear trends may often be fitted to a small number of data points and interpretation may be also biased by the relative scales chosen for use on ordinates and abscissae. Figure 7 reflects a reexamination of the actual values presented in Schmidt et al. (1979) and reveals the curvilinearity of the movement-speed, spatial-accuracy function.

Figure 7 shows some interesting trends relative to the movement speed-accuracy relationship. Firstly, the standard unit error actually *decreases* curvilinearly as movement velocity increases with a given movement time. This finding is consistent with the functions generated from Woodworth's data which were presented in Fig. 1. Secondly, decreasing movement time at any given average velocity generates a negatively accelerating increase in the standard unit error.

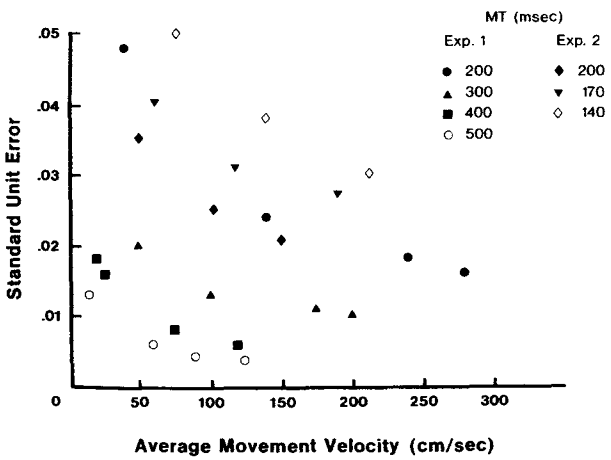

Fig. 7. Standard unit error as a function of average movement velocity and movement time. (From "Motor output variability: A theory for the accuracy of rapid motor acts" by Schmidt, Zelaznik, Hawkins, Frank, and Quinn, Psychological Review, 1979, *86*, 415–451, Figures 7, 9. Copyright 1979 by the American Psychological Association. Adapted by permission of the publisher and author)

This holds for movement times ranging from 140 to 500 ms in the data of Schmidt et al. and from 300 to 3,000 ms in the investigation of Woodworth. Thirdly, the rate of gain of error with decreases in movement time reduces at a negatively accelerating rate as distance increases. Thus, the trends exhibited in Fig. 7 show a remarkable degree of similarity to those depicted in Fig. 1 from Woodworth, despite the different task and time-distance constraints imposed.

We recognize the potential flaw in equating differing data sets on the graphical reinterpretation expressed in standard unit error terms. Indeed, various functions including both constant and straight-line relationships provide similar graphical morphologies when expressed in this manner. However, this only arises when the functions contain intercepts other than at the origin. We believe that when the subject engages in no movement, no error is made. Or in variable error terms the function tends toward zero as movement velocity decreases. As we have indicated earlier, this important tendency may be masked by measurement error. However, the passage of the variable error function through the origin makes the resulting expressions in standard unit error a veridical reflection of nonproportionality, rather than an artifact of dividing a straight-line function with an intercept by a constant.

The data presented by Schmidt and his colleagues provide interesting insights into the relationship between movement speed and accuracy, particularly with respect to isolating the impact of the various movement parameters upon the speed-accuracy phenomenon. However, Schmidt et al. (1979) failed to exploit fully the relationships indicated in their extensive data. Meyer, Smith, and Wright (1982) have utilized the empirical data provided by Schmidt and his colleagues and have claimed to provide a superior mathematical derivation of the linear trend noted. However, this model continues to adhere to a proportional interpretation of the relationship between the variability of error and movement velocity, a position which has been demonstrated to be essentially untenable.

Summary. It should be apparent from the preceding analysis that a comprehensive description of the movement speed-accuracy relationship has still to be realized. The existing accounts are either fundamentally incorrect or at best incomplete. Fitts' law has proved to be robust over numerous experimental conditions but does not account for the complete range of movement amplitude, time, and velocity manipulations and, indeed, has other limitations with regard to its potential as a general account of movement accuracy in three spatial dimensions with time as an added consideration. Furthermore, the speed-accuracy link between movements which are presumed to have (Howarth et al. 1971) and not have (Schmidt et al. 1979) a discrete correction prior to target impact is far from clear.

We now lay out a movement speed spatial-accuracy description which is based on the reinterpretations of the data sets previously presented together with other speed-accuracy analyses (e.g., Philip 1936). This description provides a basis for an understanding of the relative contribution of the various movement parameters to movement accuracy. Furthermore, this formulation is consonant with the movement-speed timing-error function, which is an essential precondition to the development of a space-time formulation of the speed-accuracy relationship.

The Movement-Velocity Spatial-Error Function

Initially it is necessary to consider the appropriate error measure(s) for depicting the movement speed-accuracy function. Most empirical examinations of this function have followed Fitts (1954) in utilizing a designated target width for aiming tasks. This is presumably, in part, for the purposes of ease of measurement and to preserve the theoretical link to Fitts' law. Although it has been suggested that estimates of W_e may be generated from this approach (e.g., Welford 1968), this proposal is dependent upon the assumption of normality of the response distribution across the target. An analysis of actual distributions belies this inference (Fullerton and Cattell 1892). It is appropriate, therefore, to measure the actual outcome obtained as precisely as possible in order that an accuracy representation may be generated of the total distribution of response outcomes at any given movement time-amplitude condition. This approach is consistent with the strategy initiated originally by Fullerton and Cattell (1892) and Woodworth (1899) to examine the speed–accuracy relationship.

The estimation of the distribution of response outcome errors for the speed-accuracy function is usually based upon two descriptive statistics, namely the mean and the standard deviation. In early investigations both statistics were reported separately (e.g., Fullerton and Cattell 1892; Woodworth 1899). In most subsequent investigations the performance mean or constant error either has not been provided (e.g., Schmidt et al. 1979) or it has been combined with variable error to form a root mean square measure (e.g., Howarth et al., 1971). One problem with omitting an independent assessment of mean performance from the speed–accuracy relationship is that the variability function is developed on the basis of the imposed amplitude-time constraints without consideration of the actual average velocity which is produced. The significance of imposed versus attained performance is particularly important at low and high average velocity conditions within any criterion amplitude, as constant spatial error shifts occur in the form of overshooting and undershooting, respectively (e.g., Fullerton and Cattell 1892; Woodworth 1899). Even if both the constant error and standard deviation functions are plotted there are additional features of the response error distribution which have not been considered in previous descriptions of the speed-accuracy function.

Accounts of the speed-accuracy function implicitly assume a normal distribution of response outcomes (e.g., Welford 1968). Consequently, descriptions of response outcome have been formulated upon only the first and second moments of a distribution. Skewness and kurtosis have not been considered, despite the fact that they may bias the estimates of the standard deviation if they are manipulated independently over a set of related distributions (Newell and Hancock 1984). Thus accounts of the speed-accuracy function have failed to consider the complete statistical properties of the response outcome distribution. This may be due in part to the misleading labels such as effective target width W_e (Schmidt et al. 1979), which are utilized for what in essence is simply the standard deviation of the response error.

The above statistical considerations have been raised as elaboration of the existing speed-accuracy accounts into a unified comprehensive function clearly depends upon an established and common set of descriptive statistical procedures. Furthermore, our interpretation is that discrepancies which occur between extant accounts are, in part, based upon statistical properties of distributions observed. Consequently, we begin our account of movement-speed and spatial accuracy by reference to the first distributional moment reflected in the functions for constant error (CE).

Fullerton and Cattell (1892, Figures 3, 4) demonstrated that constant error shifts occurred with changes in the amplitude of movement. However, Woodworth's experiments (1899, Tables XVI, XVIII) illustrate more systematic and revealing functions for constant error. As velocity demands increase within a given movement amplitude, the absolute value for constant error alters from a positive to a negative value. This connotes the change in tendency from spatial overshooting to undershooting as velocity increases. This is reflective in part of the range effect which occurs in the reproduction of amplitudes without time constraints (e.g., Brown, Knauft, and Rosenbaum 1958) and in the estimation of prescribed temporal intervals (Clausen 1950). Woodworth's data also show that the absolute size of constant error which occurs in undershooting is greater than in overshooting. Thus the effect noted for constant error does not appear symmetrical over the velocity continuum for any particular amplitude. Finally, Woodworth's experiments suggest that the zero crossing point for constant error occurs at approximately 50% of the maximum velocity for any prescribed amplitude.

Figure 8 depicts the proposed constant error function in the principal direction of motion for increases of average movement velocity, with four movement

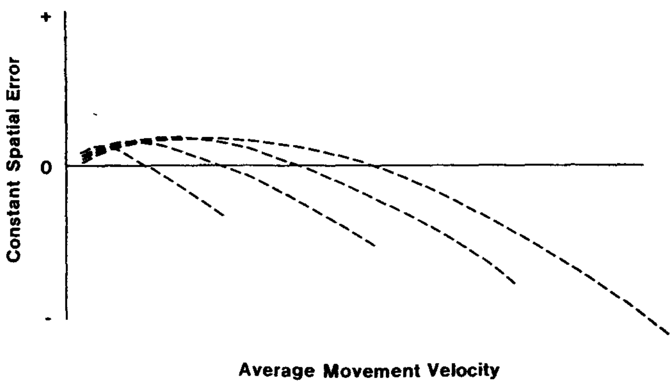

Fig. 8. Constant spatial error as a function of average movement velocity for equal increments of movement amplitude

amplitudes of equal increasing increments. Within each amplitude illustrated, positive constant error increases initially to be followed by an apparent peak which leads to a subsequent decrease up to approximately 50% of the maximum velocity. After crossing zero, constant error follows an increasing negative trend. However, in absolute terms the size of this negative constant error is increased and undershooting continues up to a maximum average velocity for any prescribed amplitude. The exact function for the asymmetry of under- and overshooting and the relative increment in constant error as a function of amplitude cannot be ascertained from existing data. For example, it is not certain whether the peak overshooting error increases with equal increments of movement amplitude. Nevertheless, the general function presented in Fig. 8 is consistent with the available constant error data given by Fullerton and Cattell (1892) and Woodworth (1899).

In practice it is expected that the proposed constant error functions are masked in the middle portion of the velocity range for a given movement amplitude. This is because measurement errors at these conditions are as large as average constant error which will tend in practice to distort estimates of the proposed function. This bias will be reduced at the extremes of the velocity range, particularly the high-velocity conditions, where, because of absolute size, constant error shifts are most easily observed (e.g., Woodworth 1899).

An appreciation of the constant error function is important as it indicates that the average *attained* response is not always equivalent to the *imposed* task conditions. Thus assessment of the response variability functions must be made in light of these constant error shifts. In the functions that follow we do not accommodate this problem directly by plotting the variability function on the basis of the attained average velocity. Rather, the obtained variability function is plotted on the basis of the imposed task velocity constraints to allow direct contrast with the attained constant error function illustrated in Fig. 8.

The proposed relationship between movement duration, amplitude, and standard unit error across the complete range of the movement velocity continuum is depicted in Fig. 9. The error function is for the standard unit error generated in the principal direction of motion for a discrete aiming task. A qualitative assessment is provided below concerning movement parameter–error relationships, which are shown within the boundary constraints of Fig. 9.

Figure 9 is constructed with the dashed lines representative of equal increments between movement amplitude and the continuous lines representative of equal increments between movement time. Three important and related aspects of the movement speed–accuracy relationship for variability are revealed. Firstly, within a given movement time, the standard unit error decreases at a negatively decelerating rate with constant increments in movement velocity. Secondly, within a given distance, the standard unit error increases in an ogival fashion with increments in average movement velocity. Thirdly, gains in standard unit error are not proportional to equal increments in either amplitude or time. Each of these general functions is now considered in some detail.

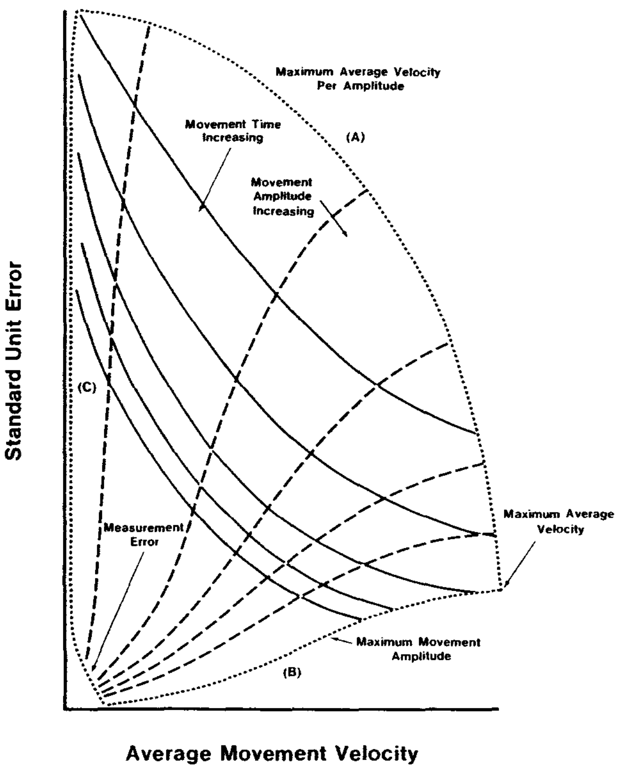

Fig. 9. Standard unit error as a function of average movement velocity, movement time, and movement amplitude. The error shown for movement amplitude (*dashed lines*) and movement time (*solid lines*) represents equal increments within each movement parameter. Physical, volitional, and measurement boundaries are represented by *dotted lines,* the description of which appear in the text

The reduction of the standard unit error with increments of movement velocity at a given movement time is consistent with the reinterpretation of the data of Woodworth (see Figure 1) and Schmidt et al. (see Figure 7). This relationship is apparently independent of feedback factors associated with time constraints, as the function is observed with movement times as short as 140 ms (Schmidt et al. 1979) and as long as 3,000 ms (Woodworth 1899). Thus response variability is not proportional to distance within a given movement time.

The ogival type error function for increments of movement velocity within a given distance has not been generally recognized. This is because most examinations of the speed-accuracy function have employed targets of a designated width and on those occasions where actual measurement error has been recorded the full velocity range has not been manipulated within a given distance.

Furthermore, as Philip (1936) has indicated, veridical estimates of error are difficult to determine at less than 10% and greater than 90% of maximum velocity. The ogival-type function indicates that the standard unit error for a given distance increases at an increasing rate to 50% of maximum velocity and then increases at a decreasing rate to maximum velocity. The curvilinear function at the lower end of the velocity continuum is consistent with the data sets of Woodworth (1899) and Schmidt et al. (1979) and also, in absolute values, with those using target tolerances (see the reinterpretation of Fitts' data in Figure 3 and the data of Bailey and Presgrave 1958, in their Figures 10 and 13). The data given by Woodworth (1899) confirm a curvilinear function at the upper end of the velocity continuum for any given amplitude.

Philip (1936) provided a clear demonstration of an ogival error function for increments of velocity in a stylus-aiming task. The task was different from Fitts' protocol in that subjects aimed a stylus at a hole inserted in a band of paper which was affixed to a drum rotating at varying velocities. As the velocity of the drum increased for a given preview amplitude the percentage of misses followed an ogival error function. Thus the complete function for standard unit error within a given distance is of an ogival morphology. It is unclear whether the amplitude function is symmetrical, as is the case with a true ogive, but there are no available data which contradict this supposition.

Increasing movement time at any given amplitude decreases the standard unit error in the form of a negative descending exponential. This implies that estimates of temporal duration in discrete aiming movements do not follow the proportional principles as given in Weber's law. An exponential function for timing variability as a function of temporal interval has been reported previously in time estimation studies (e.g., Michon 1967; Wing and Kristofferson 1973a, b). It is important to note that increasing amplitude at a given movement time produces a similar standard unit error function.

Analysis of skewness and kurtosis of the response distribution lends coherence to the proposed interpretation of the constant error and standard deviation functions for movement speed-accuracy (Newell and Hancock 1984). Figure 10 shows the response distribution of error for a given amplitude over the range of achievable average movement velocities. The response distribution shifts from high leptokurticness and a modicum of positive skewness at low velocity through a normal distribution at 50% average velocity to high negative skewness and a modicum of platykurticness at high average velocity (Fullerton and Cattell 1892). Changes in either skewness or kurtosis do not *cause* changes in the standard unit error function of the response error, although they may influence the second moment (or its variants) in particular circumstances (Newell and Hancock 1984). Rather, an understanding of how all four moments vary with the kinematic conditions is required to depict fully the speed-accuracy function. In principle, N moments of a distribution can be calculated but in practice moments beyond the fourth power tend to be unstable (Hoel 1971).

Given the deviation from normality of the error distribution illustrated in Fig. 10, it is apparent that discussion of the standard unit error or any variability statistic of error cannot be undertaken meaningfully without reference to concomitant variations in the third and fourth moments or indeed the first moment.

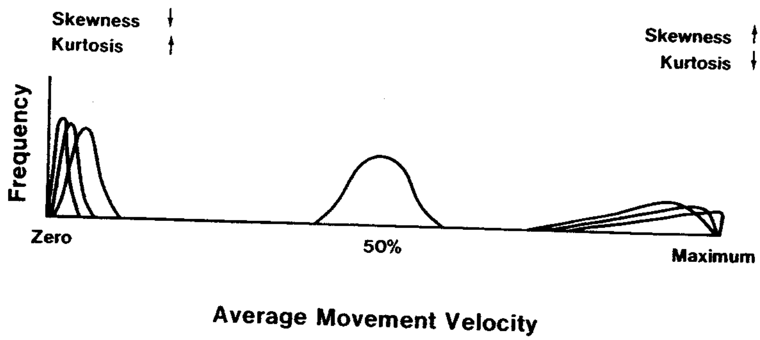

Fig. 10. Frequency distributions, each with an equal number of observations, for conditions at a constant movement amplitude throughout the average movement velocity continuum. Deviations of skewness and kurtosis are presented and detailed in the text

Thus changes in kinematic constraints produce variations in response error which are not captured sufficiently by assessment of the mean and standard deviation. As an example, the ogival type function for standard unit error for velocity increments within a given amplitude holds a different significance if the distributions are normal than if they are skewed and peaked. We cannot ascertain the relative contribution of shifts in the third and fourth moments and changes in variability per se to the ogival function for standard unit error. Consequently, in order to describe adequately differing distributions, the four descriptive statistics are at least necessary. This is particularly significant in examining inferences from distributions of response errors generated over the movement-velocity continuum.

Within the body of Fig. 9 the movement amplitude and time lines exhibit systematic changes in slope as both amplitude and time increase. A graphic example of this sequential change in slope is particularly obvious in the data of Bailey and Presgrave (1958) as given in Fig. 4. As may be seen the slope of the lines for amplitude decreases with equal increments across the range of values shown. In addition, the separation between the lines of amplitude also decreases as the absolute value ascends. In the illustration from the work of Bailey and Presgrave, there is an interruption in this smooth incrementation where amplitude change increases from 1 in. (2.54 cm) to 2 in. (5.08 cm) at the 10 in. (25.4 cm) value (see Fig. 4). These regularities for both slope and separation between increments of lines of amplitude are also true for the lines of movement time as shown for empirical data in Figs. 1 and 7 and for our idealized version in Fig. 9.

We have attempted to plot such regularities and specifically have taken values for the slope of amplitude and time lines as shown in the data set of Schmidt and his colleagues (Fig. 6). These data form what have been labeled *K* functions, which relate the veridical value of each slope with the amplitude or time from which it was derived. In calculating the respective *K* functions for amplitude and time we have as noted taken advantage of the absolute values reported in the extensive data set of Schmidt and his colleagues, although these may have equally as well been generated from the values reported by Woodworth (1899) as shown in Fig. 1. The subsequent *K* functions as given in Fig. 11 illustrate that for variable error, slopes of both movement amplitude and movement time decrease as both time and amplitude increase. If, as is possible, these *K* functions were generated for amplitude and time in standard unit error, rather than variable error as illustrated, then slopes for the amplitude lines should remain positive while slopes for the movement time would be negative. This latter observation indicates the juxtaposed nature of amplitude and time lines in standard unit error (see Fig. 9). However, it does not disturb the homeomorphic nature of the space-time picture. Although the ordinates have not been equated (except for illustrative purpose) the similarity of morphology is suggestive of an equal incrementation between values of time and amplitude within the constraints of the data produced by Schmidt et al. (1979).

To appreciate the limits of the relationship proposed in Fig. 9, it is useful to explore the various boundary conditions that may be assumed to exist. The distribution of errors at small amplitudes may not include the case where a trial or trials are generated in a direction diametrically opposed to the criterion direction of motion. In this situation, subjects are failing to achieve the objective of the task in a qualitative rather than quantitative manner.

There is a maximum average velocity which may be generated at any given movement amplitude. Fullerton and Cattell (1892, p. 115) demonstrated that the minimum time to move through ascending amplitudes (10–70 cm) increases at a

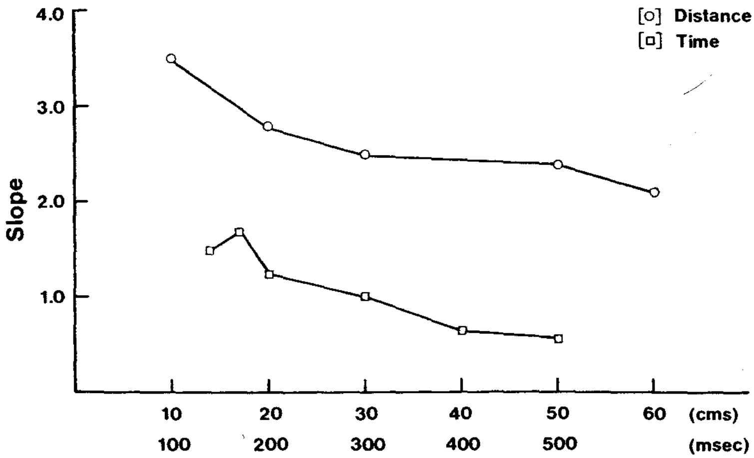

Fig. 11. The *K* functions (change of slope) for distance and movement time. One coincident point in the movement time function has been exempted from the construction of the respective *K* functions. (From "Motor output variability: A theory for the accuracy of rapid motor acts" by Schmidt, Zelaznik, Hawkins, Frank, and Quinn, Psychological Review, 1979, *86*, 415–451, Figures 7, 9. Copyright 1979 by the American Psychological Association. Adapted by permission of the publisher and author)

decreasing rate. Wadman, Denier van der Gon, Geuze, and Mol (1979, Figure 3) indicated that over a limited range (6–32 cm), this relationship was essentially linear, although an analysis of their slope and intercept indicates that such a function is most probably curvilinear toward the origin at decreased movement amplitudes. These studies have examined a limited range of conditions concerning the maximum average velocity–movement amplitude relationship.

In a recent experiment, we (Newell, Hancock, and Robertson, 1984) have examined minimum movement times to traverse ranges of motion from 2½% to 100% in an elbow flexion task. Results indicated that the maximum average velocity increased at a negatively accelerating rate with increments of distance up to 95% of the range of motion and this velocity limitation is reflected by Line A in Fig. 9. This function suggests an additional physical boundary. There is a limitation on the maximum average movement velocity that may be generated which occurs at the intersection of Line A with the amplitude constraint dependent on the length of the limb(s) utilized for activity (Line B). The functional limit to the present relationship is probably dependent upon anatomical and morphological constraints imposed upon the limb(s) used for movement. In practical terms this boundary may be in part dictated by the constraints of the task at hand.

The above boundaries are determined by the task constraints and the physical capabilities of the human system while the final limitation (Fig. 9, Line C) is related to the precision of the recording method(s). This boundary to the observable movement-velocity spatial error function represents measurement error. Although this is consistent across differing amplitude and time conditions it is reflected by the curvilinear function C in Fig. 9 due to the nature of the measure of standard unit error. As previously noted, Schmidt et al. (1978), without stating their precise method of assessment, estimated measurement error as approximately 0.6 mm. Although relatively small, such error is important as it aids in masking the curvilinear nature of the contribution of varying movement amplitudes as movement velocity decreases toward the origin.

To summarize, Figs. 8–11 represent our interpretation of the movement-velocity spatial-error relationship. They have been developed from existing data for simple hand-aiming tasks. Some of the details of the function for each moment remain to be determined and others remain to be verified. Nevertheless, the functions developed represent a coherent framework which is consistent with the data sets available including recent empirical findings (cf., Wright and Meyer 1983).

The speed-accuracy functions represent statistical manifestations of the movement outcome for a range of movement amplitude-time combinations. The functions demonstrate that movement accuracy must be considered on the basis of the error distributions for the first four moments of each amplitude-time combination, rather than reliance on any single descriptive statistic. Furthermore, the functions provide a basis for the prediction of movement error based upon the estimate of minimal movement time for the amplitude traversed under a given set of task constraints. This is possible because the estimate of minimal movement time across the range of amplitudes represents the 100% maximal average velocity boundary. It is anticipated that the functions hold for all tasks although the absolute level of movement error will vary with the task constraints.

The shifts in error on a proportional basis are small for any single descriptive statistic. For example, the standard unit errors from Woodworth (1899) and Schmidt et al. (1979) indicate that although the shifts are consistent across amplitude-time conditions the change is within a bandwidth of 5% of the given amplitude. These small changes have been masked in previous accounts because only a limited range of the speed-accuracy function has been considered and the general reliance on absolute measures of response accuracy rather than relative measures.

Although the function for standard unit error is proposed as being consistent across differing practice conditions, the precise relationship between the movement parameters and the absolute size of error may change. Woodworth (1899) noted that as any performer approaches his maximum speed or accuracy for any task individual trials agree more and more closely, this being a phenomenon of practice curves. He also stated that should a point be reached at which trials were quite unvarying the absolute limit for that mode of particular task performance would have been reached. The nature of the internal relationship between the various movement parameters and how they contribute to standard unit error will depend not only upon elements of practice but also upon the intrinsic space-time bias of any individual task undertaken.

In accordance with previous findings (e.g., Begbie 1959; Beggs and Howarth 1970; Drury 1971) it is proposed that the movement-velocity spatial-error functions will also apply to error generated in planes orthogonal to the principal direction of motion, although the absolute size of such error will be considerably diminished. We recognize that the measurement of spatial error in three dimensions holds certain intrinsic problems. However, these specific problems are not elaborated in the present chapter. There is no evidence available to indicate what the function may be for tasks requiring radically different response dynamics but there are, at present, no fundamental objections to the assertion that they will follow the general relationships exhibited.

Attempts at relating spatial and temporal errors have been limited (Howells, Knight Weiss, and Kak 1979; Newell 1980) partly because of the confinement of studies to the original Fitts paradigm, where movement time is not an independent variable. However, there have been descriptions of timing error as a function of movement velocity (e.g., Newell et al. 1979, 1980) and these are now discussed as a precursor to the development of a movement speed timing-error function and subsequently the space-time account of movement speed-accuracy.

Movement Speed and Timing Error

Movements may be constrained solely by spatial criteria but this cannot be the case with time, as movement tasks always have spatial boundaries. Nevertheless, certain tasks have time as a criterion in the sense of moving through a prescribed amplitude or arriving at a precise location in a criterion movement time. Timing tasks have been employed to examine various theoretical issues in motor learning (e.g., Ellis, Schmidt, and Wade 1968; Newell 1974), but it is only recently that descriptions have been developed of a unidimensional movement-speed timing-accuracy relationship (Newell et al. 1979, 1980, 1982).

A consistent finding in discrete timing responses is that the shorter the movement time the smaller the timing error (Newell 1976; Schmidt 1969). Timing error is the difference between the criterion movement time and the obtained movement time for traversing a given amplitude. This may be the result of a range effect, as with greater movement time more time is available for the response to vary. Indeed, time-estimation studies involving simply key press responses suggest that such a range effect may be a contributor to error in temporal estimation (e.g., Woodrow 1951).

A problem with most extant movement timing studies is that the independent variables of duration and velocity have been confounded (e.g., Ellis 1969). Rarely has movement time been manipulated independently of average movement velocity. Consequently, it is commonly the case that high-velocity movements have short durations and low-velocity movements have long durations. The data from early studies which systematically varied movement time and velocity suggested that movement velocity may affect timing accuracy (Ellis et al. 1968; Schmidt and Russell 1972), although little was made at that time of these statistically nonsignificant effects.

In our laboratory we have developed a description of the movement-speed timing-accuracy relationship (Newell 1980; Newell et al. 1979; Newell, Carlton,

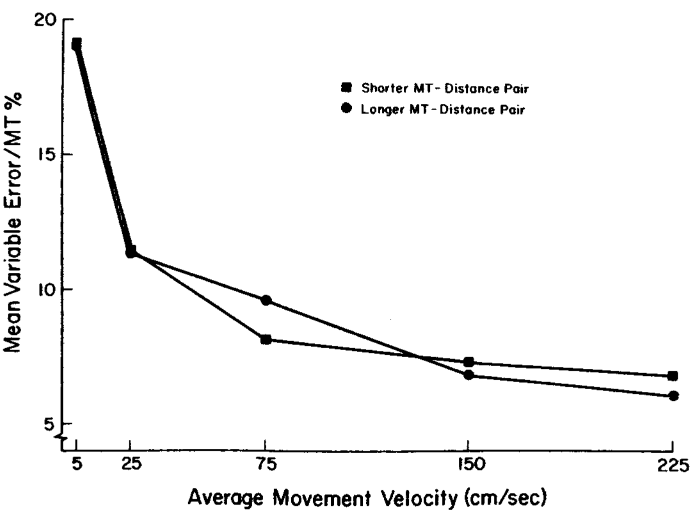

Fig. 12. Mean variability error movement time percentage (analogous to standard unit error) as a function of average movement velocity. (From Newell, Carlton, Carlton, and Halbert 1980, Experiment 3)

and Carlton 1982). At low velocities within a given distance subjects move too quickly and undershoot the temporal criterion whereas at high velocities they move too slowly and overshoot the criterion (e.g., Newell et al. 1980, Tables 2, 3). The constant timing error function is the complement of the constant spatial error function.

Figure 12 is adapted from Newell et al. (1980, Experiment 3) and reflects the movement-speed timing-accuracy function over movement velocities which range from 5 to 225 cm/s. The variable timing error is plotted as a percentage of movement time (standard unit error) in order to compare directly the timing error adduced from different movement times (100–600 ms). As Fig. 12 illustrates standard unit error decreases curvilinearly as a function of the average velocity of the discrete response. In Fig. 12 there is little or no difference for the standard unit error between different movement times at the same average velocity, but a graded movement time effect on the standard unit error has been shown with the proportionality of error to movement time decreasing as the duration of the response increased (Newell 1980; Newell et al. 1980, Figure 3). Timing error data consistent with this velocity function have also been reported by Sherwood and Schmidt (1980) and Tyldesly (1980).

In summary, the relative movement-speed timing error function appears to be homeomorphic with the spatial-error function. This is particularly clear in unidimensional tasks as the timing error may be directly reinterpreted in terms of concomitant spatial error (Newell et al. 1982) but the function also holds for timing error measured in a stylus-aiming task (Newell 1980). There are only a few data sets available to support the general timing error function which is presented in the following section. Nevertheless, the synthesis given above reflects a coherent description and one that is consistent with the spatial-error formulation presented previously.

The Movement-Velocity Temporal-Error Function

The work presented in the previous section together with that of the earlier projections of the standard unit error indicates that when temporal and spatial error are measured in the same movement plane, the error functions are homeomorphic. To facilitate contrast with the constant spatial error and standard unit error functions presented in Figs. 8 and 9, the constant temporal error and associated standard unit error functions will be shown separately.

The constant temporal error function is depicted in Fig. 13. Within a given amplitude, the constant temporal error increases from zero to a modicum of undershooting at low velocities, through zero constant error at approximately 50% of maximum velocity to a high degree of overshooting at high velocities. The constant temporal error function is in effect the complement of the constant spatial error function (cf., Figs. 8 and 13) in that movements are completed in a time shorter than the respective criterion at low velocities, with the reverse occurring at high velocities. Again, the constant error shift is not symmetrical around the 50% of maximum velocity for any given distance.

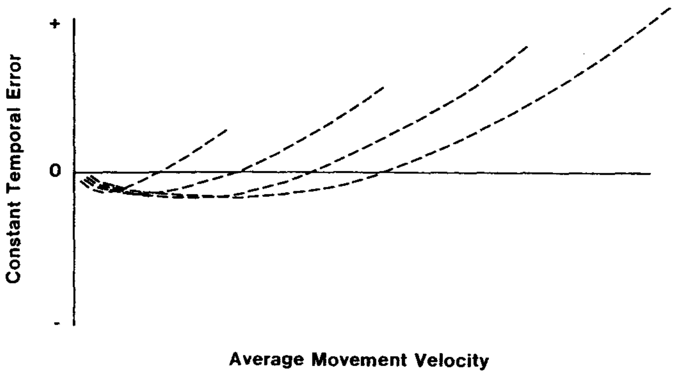

Fig. 13. Constant temporal error as a function of average movement velocity, for equal increments of movement time

The standard unit error function for time appears equivalent to the standard unit error function for space. It is probable that the actual proportions for these errors may differ but their form will be homeomorphic. Therefore, the standard unit error function for space, depicted in Fig. 9, also represents that for time. The standard unit error for time is generally about 5%–15% of the response duration whereas the standard unit error for space is between 0% and 5% of the amplitude moved. As shown previously in Fig. 11, the slopes of the standard unit error lines for amplitude and movement time (*K* functions) are in consonance with the homeomorphic interpretation of the independent space and time functions. It is worth noting that, unlike spatial error, timing error for a given movement time decreases with gains in movement velocity regardless of whether error is measured on a relative or absolute basis. This is because variable timing error is considered in relation to the same movement time over changing velocities whereas variable spatial error is considered over differing distances.

The response distributions for temporal error will also complement those for spatial error (Fig. 10). High negative skewness and a modicum of platykurticness will occur at lower velocities for a given distance and high leptokurticness and a modicum of positive skewness will result at the upper end of the velocity continuum. This bias in the third and fourth moments of the temporal error distributions for a given amplitude is shown in Fig. 14. Again the distributions are the complement of the respective spatial error distribution depicted in Fig. 10.

When timing error is measured in a plane orthogonal to that employed for spatial error the two functions may not be directly equated. The relationships expressed in Fig. 9 may be consistent for both temporal and spatial functions; however, the absolute size of error will vary in accordance with the plane of measurement (e.g., Begbie 1959). For example, in the Fitts tapping task, movement time is measured by contacting the horizontal plane, while spatial error is determined by the distance from the vertical plane placed through the target, with which contact is subsequently made. Hence, in studies which utilize Fitts' protocol the

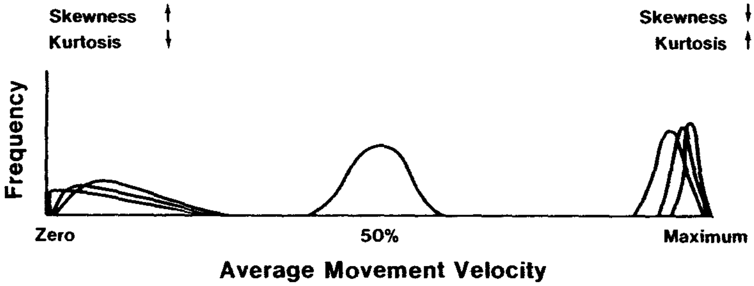

Fig. 14. Frequency distributions, each with an equal number of observations, for conditions at a constant movement time throughout the average movement velocity continuum. Deviations of skewness and kurtosis are presented and detailed in the text

movement time and spatial error functions are determined by cutting differing planes of motion.

In addition, the constraints of the Fitts stylus-aiming task dictate that there is a minimum movement time for the task which is considerably longer than both the interval scale of most time-keeping instruments and zero time. This is because a certain finite time is taken to raise and lower the stylus irrespective of the distance traveled in the principal direction of motion. Hence, the movement speed-accuracy function does not pass through the origin for the Fitts' stylus task (Crossman and Goodeve 1963; Fitts 1954; Fitts and Peterson 1964). Our speed-accuracy functions have been developed on the basis that graded movement times from zero time can occur on a very small interval scale and thus the functions (e.g., Fig. 9) tend toward the origin.

It is significant to note that in tasks with both space and time as criteria one cannot trade speed for accuracy in the traditional sense. We have indicated that one may trade spatial error for timing error but as these are different descriptions of the same event a trade, in the traditional sense, is untenable. Only where spatial and temporal errors are measured with reference to differing planes can a trade of spatial and temporal error occur. Again, Fitts' protocol may be viewed as creating a somewhat artificial condition for a movement trade-off in this case. This is not particularly useful if both space and time are criteria, although much depends upon the constraints of the task under consideration.

The independent development of the spatial and temporal error functions demonstrate that when both space and time are criteria for a task only a comprehensive space-time description of movement velocity–accuracy relationships is sufficient. The spatial and temporal error functions are homeomorphic, providing a unitary description and suggesting a common ground for explanation. To our knowledge there have been no attempts to describe movement–speed accuracy relationship in these terms.

It should be recognized that the space-time functions proposed reflect the movement outcome that *typically* occurs due to the constraints imposed in speed-accuracy studies. Changing the constraints on the subject in a movement accuracy task could alter the resultant movement speed-accuracy functions. Thus there is not a single space-time error function but rather a limited range of space-time functions according to task constraints (Newell, Carlton, and Hancock 1984). We now elaborate on the space-time perspective.

Movement Accuracy and Space-Time Considerations

The distinction between space and time as disparate entities may be perhaps simply a function of essential human experience. In scientific endeavour, the artificiality of this division has long been acknowledged. Locke (1690) commented upon the interdependency when he observed that expansion and duration mutually embrace and comprehend each other, where every part of space was in every part of duration. This position is in contrast to Newton's conception of time as a homogeneous medium in which events occur. Bergson (1910) criticized Newton's conception on philosophical grounds and suggested that time is event related. Subsequently, physicists have demonstrated the observer dependence of event order when events occur at highly disparate spatial locations. Minkowski (1908) in advocating the concept of space-time through the proposal of "world-points" enquired whether anybody had ever noticed a place except at a time or a time except at a place. In fact such was the mutual interdependency that Minkowski proposed the complete elimination of the concepts of space and time, leaving only "space-time."

It is axiomatic that movements which are generated to engage in action occur within this referential frame. However, as human action occurs essentially within a highly restricted spatial range, events *appear* upon a human scale as observer independent. As a consequence and in spite of both philosophical and physical developments, the Newtonian concept of time as absolute and measurable in a systematic manner has been and still is used in the motor control domain and in psychological investigation in general. Our current treatise has taken studies which have used the Newtonian referential frame and has constructed a space-time description account therefrom. However, we are aware that this space-time description differs from that in which Lee (1980) has observers navigate through the "world" (after Minkowski). It is conceivable that a space-time account of movement accuracy in the latter sense of the concept may emerge from the current work, which extracts information from accounts where the spatial and temporal contributions to movement accuracy are viewed as separate entities.

From the Newtonian perspective, it is clear that in many actions a movement or sequence of movements may be constrained to adhere to some greater or lesser degree to either spatial or temporal criteria. In the motor learning domain this is most evident in open skills where environmental contingencies are not entirely predictable between successive trials (Poulton 1957). The preceding discussion, which independently formulated space and time speed-accuracy functions, provides precursory arguments for the development of a space-time description of movement accuracy. In addition, it should be apparent that a space-time account is particularly appropriate where time is a set criterion of the performance rather than a dependent variable.

The unity of the space and time functions depends to a certain extent upon the technique employed to measure each dependent variable. When the errors are measured in relation to the same point in space and on the basis of movement in the same plane then the space and time error functions are homeomorphic. An example of this situation was demonstrated by Newell et al. (1982) when timing errors were determined for a variety of movement time-amplitude combinations on the basis of the difference from the criterion time on passing a point on a trackway, whereas spatial errors were determined by the distance from the target point at the criterion time. When the subject crosses the criterion spatial location earlier than the criterion movement time and decelerates after crossing the spatial target, departures from the homeomorphic nature of the spatial and temporal error functions may occur. However, for most movement conditions the spatial and temporal errors when measured in this manner will be homeomorphic as shown in Fig. 15A and B. In Fig. 15C and D the same recording technique was utilized but now subjects have different amounts of preload on the arm but attempt to travel the same distance in the same time (Carlton and Newell 1985). The standard unit error for the spatial and temporal functions is homeomorphic, reflecting the proposed space-time account of movement accuracy.

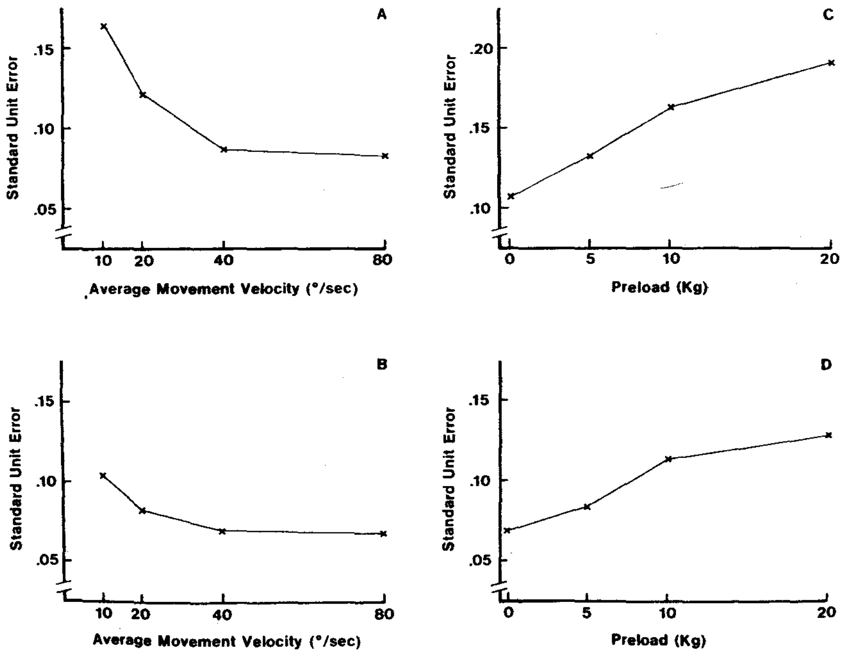

Fig. 15A–D. Standard unit error derived from timing error scores **A** and spatial error scores **B** adapted from Newell et al. (1982). **C** and **D** are standard unit errors derived from timing and spatial error scores of Carlton and Newell (1985)

In summary, the movement speed–accuracy relationship is a space-time problem. Emphasis may be placed upon the spatial or temporal consideration in training procedures but understanding the entire problem requires a merging of spatial and temporal measures into a space-time solution of the movement speed–accuracy relationship. Such an approach is not unique to the domain of movement.

Lee (1980) has recently proposed a space-time orientation in relation to the general problem of visual-motor coordination and specifically the nature of the information which is visually assimilated by the performer when interacting with the environment. As a result, Lee has developed a formerly dimensionless variable τ which affords information for controlling space-time activity. Finally, from an observer-independent perspective, Viviani and Terzuolo (1980) have demonstrated the principle of an invariant space-time domain in skills such as cursive handwriting and typewriting. In these skills the space-time topology is preserved independent of the absolute level of scaling observed in the spatial and temporal scales.

Implications of the Space-Time Description for Motor Control

In this treatise we have provided a coherent description of the speed-accuracy relationship in movement control. In order to promulgate such cohesion we have adopted a space-time perspective from which to approach the problem. This space-time approach is predicated on the notion that individual consideration of space and time artificially dichotomizes the phenomenon.

When space-time measures are considered in a single plane of motion their functions for variability are homeomorphic and the functions for the primary measure of central tendency, namely the distributional mean, are reflective images. Consequently space and time are not disparate entities but rather are direct reflections of each other in discrete movements. We point to Fitts' reciprocal tapping protocol as responsible for obfuscating this observation as errors of space and time in this approach, when measured, are for different movement planes.

An immediate ramification of our approach is that in space-time tasks one may not trade speed for accuracy; rather one may only trade spatial and temporal error and often this trade is dictated by the nature of the task under consideration. While most tasks have spatial criteria, fewer exhibit necessary temporal criteria. However, this does not make the latter any the less space-time tasks, it merely highlights one criterion in juxtaposition with the other.

In formulating the space-time approach it was observed that previous constructs were based upon limited consideration of the distribution of responses in demand to kinematic impositions. In our work we have suggested that in addition to distinct consideration of both the mean (central tendency) and standard deviation (variability), higher distributional moments must be considered as they are positive and implicit in distributions. Particularly they are noticeable at the extremes of movement capability (i.e., maximum and minimum velocity for any amplitude). Such considerations are necessary to understand the homeomorphic space-time function for movement variability at differing kinematic coordinates.

The cohesion of the current account and its contrast with previous, limited descriptions implies important failures in former theoretical accounts of the phenomenon at hand. We suggest, not only do these constructs fail quantitatively as they have accounted for only segments of the movement-speed trade-off, but also qualitatively in that they fail to meet the self-imposed criteria for causality in theoretical development. The appeals to lower levels of analysis for explanatory power have largely confused rather than facilitated further development. We do not feel it incumbent upon us to produce a similar and poorly founded theoretical position. Rather, we would care to make clear the importance of the current description.

First, there is a strong, although not causal, link between the kinematics and kinetics of movement, as Newtonian mechanics dictates. This position, previously advocated by Schmidt et al. (1979), implies principled relationships between kinematic and kinetic parameters of movement. However, unlike Schmidt and his colleagues we do not wish to suggest that this is causal in nature. The space-time description herein contained facilitates the development of understanding such connections and is the subject of current research efforts (Newell, Carlton, and Hancock, 1984; Schmidt and Sherwood 1982). Second, although our description militates against an iterative feedback model, and in this we are not the first (Legge and Barber 1976), we do envisage a role for feedback in movement control. However, our central concern is that such a process is not *manifest* in our description due to the distributional nature of the error measure. We believe the multiple-trial approach masks modes of control by a process of trial averaging. It is these specific elements of control that a *causal* theory would wish to address. In consequence, a single-trial analysis is advocated as one which, if receiving more attention, may be used to approach such problems.

Furthermore, although single-trial analysis may elucidate certain control processes, ongoing strategies for minimizing variation in performance should be addressed by some form of time-series examination. Our description suggests that the output of the motor system, in response to kinematic criteria, is a parametric production which is modified in consideration of physical limitations. That such output occurs suggests some form of sequential selection of response and those processes which produce such a response are those which it is necessary for future research to address.

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References

Bailey, G. B., and Presgrave, R. (1958). *Basic motion timestudy.* New York: McGraw-Hill.

Bainbridge, L., and Sanders, M. (1972). The generality of Fitts' Law. *Journal of Experimental Psychology, 96,* 130–133.

Begbie, G. H. (1959). Accuracy in timing in linear hand movements. *Quarterly Journal of Experimental Psychology, 21,* 65–75.

Beggs, W. D. A., and Howarth, C. I. (1970). Movement control in a repetitive motor task. *Nature, 225,* 752–753.

Beggs, W. D. A., and Howarth, C. I. (1972). The movement of the hand towards a target. *Quarterly Journal of Experimental Psychology, 24,* 448–453.

Beggs, W. D. A., and Howarth, C. I. (1972). The accuracy of aiming at a target: Some further evidence for a theory of intermittent control. *Acta Psychologica, 36,* 171–177.

Beggs, W. D. A., Graham, J. C., Monk, T. H., Shaw, M. R. W., and Howarth, C. I. (1972). Can Hick's Law and Fitts' Law be combined? *Acta Psychologica, 36,* 348–357.

Bergson, H. (1910). *Time and free will.* New York: Macmillan.

Brown, J. S., Knauft, E.B., and Rosenbaum, C. (1958). The accuracy of positioning reactions as a function of their direction and extent. *American Journal of Psychology, 61,* 167–182.

Carlton, L. G. (1979a). Control processes in the production of discrete aiming responses. *Journal of Human Movement Studies, 5,* 115–124.

Carlton, L. G. (1979b). *The role of vision for the control of aiming movements.* Unpublished Doctoral Dissertation, University of Illinois.

Carlton, L. G. (1980). Movement control characteristics of aiming responses. *Ergonomics, 23,* 1019–1032.

Carlton, L. G. (1981). Processing visual feedback information for movement control. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 1019–1030.

Carlton, L. G., and Newell, K. M. (1985). *Response variability as a function of force parameters in dynamic tasks.* Manuscript in preparation.

Clausen, J. (1950). An evaluation of experimental methods of time judgment. *Journal of Experimental Psychology, 40,*756–761.

Craik, K. J. W., and Vince, M. A. (1963a). Psychological and physiological aspects of control mechanisms with special reference to tank gunnery I. *Ergonomics, 6,* 1–33.

Craik, K. J. W., and Vince, M. A. (1963b). Psychological and physiological aspects of control mechanisms II. *Ergonomics, 6,* 419–440.

Crossman, E. R. F. W., (1957). The speed and accuracy of simple hand movements. In E. R. F. W. Crossman and W. D. Seymour (Eds.), *The nature and acquisition of industrial skills.* Report to M. R. C. and D. S. I. R. Joint Committee on Individual Efficiency in Industry.

Crossman, E. R. F. W. and Goodeve, P. J. (1963). *Feedback control of hand movements and Fitts' Law.* Paper presented at the Experimental Psychology Meeting, Oxford, England, 1963. Published in *Quarterly Journal of Experimental Psychology 35A,* 251–278.

Drury, C. G. (1971). *Movements with lateral constraints. Ergonomics, 14,* 239–305.

Ellis, M. J. (1969). Control dynamics and timing a discrete response. *Journal of Motor Behavior, 1,* 119–134.

Ellis, M. J., Schmidt, R. A., and Wade, M. G. (1968). Proprioception variables as determinants of lapsed-time estimation. *Ergonomics, 11,* 557–586.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47,* 381–391.

Fitts, P. M., and Peterson, J. R. (1964). Information capacity of discrete motor responses. *Journal of Experimental Psychology, 67,* 103–112.

Fullerton, G. S., and Cattell, J. McK. (1892). On the perception of small differences. *University of Pennsylvania Philosophical Series,* No. 2.

Garrett, H. E. (1922). A study of the relation of accuracy to speed. *Archives of Psychology, 8,* No. 56.

Hancock, W. M., Langolf, G., and Clark, D. O. (1973). Development of standard data for stereoscopic microscope work. *AIIE Transactions, 5,* 113–118.

Hoel, P. G. (1971). *Introduction to mathematical statistics* (4th ed.). New York: Wiley.

Howarth, C. I., Beggs, W. D. A., and Bowden, J. M. (1971). The relationship between the speed and accuracy of movement aimed at a target. *Acta Psychologica, 35,* 207–218.

Howells, R. A., Knight, J. L., Weiss, S. M., and Kak, A. V. (1979). Micro-timesharing within a single task. *Proceedings of the Human Factors Society Meeting, 23,* 523–526.

Jagacinski, R. J., Repperger, D. W., Ward, S. L., and Moran, M. S. (1980). A test of Fitts Law with moving targets. *Human Factors, 22,* 225–233.

Kantowitz, B. H., and Knight, J. L., Jr. (1978). Testing tapping time-sharing attention demands of movement amplitude target width. In G. E. Stelmach (Ed.), *Information processing in motor control and learning.* New York: Academic.

Keele, S. W. (1968). Movement control in skilled motor performance. *Psychological Bulletin, 70,* 387–403.

Keele, S. W., and Posner, M. I. (1968). Processing visual feedback in rapid movements. *Journal of Experimental Psychology, 77,* 155–158.

Kerr, B., and Langolf, G. D. (1977). Speed of aiming movements. *Quarterly Journal of Experimental Psychology, 19,* 474–481.

Kerr, R. (1973). Movement time in an underwater environment. *Journal of Motor Behavior, 5,* 175–178.

Klapp, S. T. (1975). Feedback versus motor programming in the control of aimed movements. *Journal of Experimental Psychology: Human Perception and Performance, 104,* 147–153.

Kvålseth, T. O. (1979). Note on information capacity of discrete motor responses. *Perceptual and Motor Skills, 49,* 291–296.

Kvålseth, T. O. (1980). An alternative to Fitts' Law. *Bulletin of the Psychonomic Society, 16,* 371–373.

Langolf, G. D., Chaffin, D. B., and Foulke, J. A. (1976). An investigation of Fitts' Law using a wide range of movement amplitudes. *Journal of Motor Behavior, 8,* 113–128.

Lee, D. N. (1980). Visuo-motor coordination in space-time. In G. E. Stelmach and J. Requin (Eds.), *Tutorials in motor behavior.* Amsterdam: North Holland.

Legge, D., and Barber, P. J. (1976). *Information and skill.* London: Methuen.

Locke, J. (1959). *An essay concerning human understanding.* Edited by A. C. Fraser. London: Dover. (Originally published 1690).

Meyer, D. E., Smith, J. E. K., and Wright, C. E. (1982). Models for the speed and accuracy of aimed limb movements. *Psychological Review, 89,* 449–482.

Michon, J. A. (1967). *Timing in temporal tracking.* Soesterberg, The Netherlands: Institute for Perception RVO-TNO.

Minkowski, H. (1923). Space and time, 1908. In H. A. Lorentz, A. Einstein, H. Minkowski, and H. Weyl (Eds.), *The principle of relativity.* London: Dover.

Newell, K. M. (1974). Knowledge of results and motor learning. *Journal of Motor Behavior, 6,* 235–243.

Newell, K. M. (1976). Motor learning without knowledge of results through the development of a response recognition mechanism. *Journal of Motor Behavior, 8,* 209–217.

Newell, K. M. (1980). The speed-accuracy paradox in movement control: Errors of time and space. In G. E. Stelmach and J. Requin (Eds.), *Tutorials in motor behavior.* Amsterdam: North Holland.

Newell, K. M., Carlton, L. G., Carlton, M. J. (1982). The relationship of impulse to timing error. *Journal of Motor Behavior, 14,* 24–45.

Newell, K. M., Carlton, L. G., and Hancock, P. A (1984). A kinetic analysis of response variability. *Psychological Bulletin, 96,* 133–151.

Newell, K. M., Carlton, M. J., Carlton, L. G., and Halbert, J. A. (1980). Velocity as a factor in movement timing accuracy. *Journal of Motor Behavior, 12,* 47–56.

Newell, K. M., and Hancock, P. A. (1984). Forgotten moments: Skewness and kurtosis as influential factors in inferences extrapolated from response distributions. *Journal of Motor Behavior, 16,* 320–335.

Newell, K. M., Hancock, P. A., and Robertson, R. N. (1984). A note on the speed-amplitude function in movement control. *Journal of Motor Behavior, 16,* 460–468.

Newell, K. M., Hoshizaki, L. E. F., Carlton, M. J., and Halbert, J. A. (1979). Movement time and velocity as determinants of movement timing accuracy. *Journal of Motor Behavior, 11,* 49–58.

Philip, B. R. (1936). The relationship between speed and accuracy in a motor task. *Journal of Experimental Psychology, 19,* 24–50.

Poulton, E. C. (1957). On prediction in skilled movement. *Psychological Bulletin, 54,* 467–478.

Schmidt, R. A. (1969). Movement time as a determiner of timing accuracy. *Journal of Experimental Psychology, 79,* 43–47.

Schmidt, R. A., and Russell, D. G. (1972). Movement velocity and movement time as determiners of the degree of preprogramming in simple movements. *Journal of Experimental Psychology, 96,* 315–320.

Schmidt, R. A., and Sherwood, D. E. (1982). An inverted-U relation between spatial error and force requirements in rapid limb movements: Further evidence for the impulse variability model. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 158–170.

Schmidt, R. A., Zelaznik, H. N., and Frank, J. S. (1978). Sources of inaccuracy in rapid movement. In G. E. Stelmach (Ed.), *Information processing in motor control and learning.* New York: Academic.

Schmidt, R. A., Zelaznik, H. N., Hawkins, B., Frank, J. S., and Quinn, J. T. Jr. (1979). Motor output variability: A theory for the accuracy of rapid motor acts. *Psychological Review, 86,* 415–451.

Shannon, C. E., and Weaver, W. (1949). *The mathematical theory of communication.* Urbana: University of Illinois Press.

Sheridan, M. R. (1979). A reappraisal of Fitts' Law. *Journal of Motor Behavior, 11,* 179–188.

Sherwood, D. E., and Schmidt, R. A. (1980). The relationship between force and force variability in minimal and near-maximal static and dynamic contractions. *Journal of Motor Behavior, 12,* 75–89.

Siddall, G. J., Holding, D. H., and Draper, J. (1957). Errors of aim and extent in manual point to point movement. *Occupational Psychology, 31,* 185–195.

Smith, W. M., and Bowen, K. F. (1980). The effects of delayed and displaced visual feedback on motor control. *Journal of Motor Behavior, 12,* 91–102.

Tyldesley, D. A. (1980). The role of the movement structure in anticipatory timing. In G. E. Stelmach and J. Requin (Eds.), *Tutorials in motor behavior.* Amsterdam: North Holland.

Viviani, P., and Terzuolo, V. (1980). Space-time invariance in learned motor skills. In G. E. Stelmach and J. Requin (Eds.), *Tutorials in motor behavior.* Amsterdam: North Holland.

Wade, M. G., Newell, K. M., and Wallace, S. A. (1978). Decision time and movement time as a function of response complexity in retarded persons. *American Journal of Mental Deficiency, 63,* 135–144.

Wadman, W. J., Denier van der Gon, J. J., Geuze, R. H., and Mol, C. R. (1979). Control of fast goal directed arm movements. *Journal of Human Movement Studies, 5,* 3–17.

Wallace, S. A., Newell, K. M., and Wade, M. G. (1978). Decision and response times as a function of movement difficulty in preschool children. *Child Development, 49,* 509–512.

Weber, E. H. (1834). De pulsu, resorptione, auditu et tactu: Annotationes anatomicae et physiologicae. Leipzig: Koehler, 1834, R. J. Herrnstein and E. G. Boring (Eds.) *A source book in the history of psychology.* Cambridge, MA: Harvard University Press, 1965.

Welford, A. T. (1968). *Fundamentals of skill.* London: Methuen.
Welford, A. T., Norris, A. H., and Shock, N. W. (1969). Speed and accuracy of movement and their changes with age. In W. G. Koster (Ed.) *Attention and performance II.* Amsterdam: North Holland.
Wing, A. M., and Kristofferson, A. B. (1973a). The timing of interresponse intervals. *Perception and Psychophysics, 13,* 455–560.
Wing, A. M., and Kristofferson, A. B. (1973b). Response delays and the timing of discrete motor responses. *Perception and Psychophysics, 14,* 5–12.
Woodrow, H. (1951). Time perception. In S. S. Stevens (Ed.) *Handbook of experimental psychology.* New York: Wiley.
Woodworth, R. S. (1899). The accuracy of voluntary movements. *Psychological Review,* Monograph Supplement 3, Whole No. 13, No. 3.
Wright, C. E., and Meyer, D. E. (1983). Sources of the linear speed-accuracy trade-off in aimed movements. *Quarterly Journal of Experimental Psychology, 35A,* 279–296.