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TEMPORALLY CONSTRAINED MOVEMENTS, LEARNING AND VISUAL FEEDBACK PROCESSING TIME

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ABSTRACT

The common observation that an individual's aiming performance depends upon visual feedback has led to a great deal of investigation in order to assess the potential of this feedback source. Since it has been hypothesized that an aiming response consists of an initial programmed sequence followed by a control phase, research has been focused on the specific role of vision in the control phase of the aiming response. It has been suggested (e.g. Carlton, 1979,1980; Keele, 1968) that the discrepancy between the stylus and the target is evaluated in order to modify an existing error. This visually based corrective process is thought to be represented in the movement patterns as a re-acceleration, or an abrupt change in the deceleration phase of the aiming response (Carlton, 1980, 1981b).

The goal of the present thesis was to examine if Carlton's results could be replicated after low and extensive training of the aiming movement. Furthermore, we investigated the control process when vision of the ongoing arm was not available.

Subjects (n =6) were trained for 1 200 trials (400 trials a day for 3 consecutive days) to move a stylus to a small visible target located in front of them. The movement was made in the sagittal plane, and involved the displacement of a stylus by 80 cm in 550 ms. During training (with KR on the movement time and spatial accuracy on the X and Y axes), subjects were tested six times; once at the beginning and once at the end of each session.

At the beginning of each session each test condition consisted of 20 trials with vision but no KR while at the end of the session the test condition consisted of 20 trials with no vision and no KR. The execution of the aiming movement required the activation of the shoulder, elbow and wrist articulations. The subject's arm was secured in a poly-articulated arm. A perfect correspondance between the articulations of the mechanical arm and the articulations of the subject was therefore made possible. A potentiometer attached to each of the rotation points of the mechanical arm allowed the displacement of the shoulder, elbow and wrist to be recorded. Furthermore, the action of the tip of the stylus (attached to the end of the mechanical arm) was followed. The behavioral and kinematic data were analyzed.

The behavioral analysis showed that the subjects were more accurate on movement time and the X-axis as practice increased, and that they performed more consistently on the Y-axis. Furthermore, the visual manipulation did not influence the movement time performance. In contrast, spatial accuracy was strongly affected (Proteau and Girouard, note 3; Proteau, Marteniuk, Girouard & Dugas, 1987). The difference in the accuracy results in the vision condition over the no-vision condition led us to conclude that the incorporation of visual information is important, even after extensive practice, for a high degree of accuracy to be achieved in the execution of the aiming movement. Finally, the training helped to improve the performance in the no-visual condition to the same extent as in the visual condition.

The kinematic results do not support a visually based correction concept, since the initiation of the corrective sequence was also observed when vision of the moving arm was not available. This means that modifications during the aiming movement do not solely depend on seeing where the hand is in relation to the target position. Therefore, it can be suggested that independent of wether or not the moving arm can be seen, the initial command will be followed by a corrective sequence part with the incorporation of feedback information coming from the available channel(s). It is suggested that since we rely heavily upon visual feedback (Posner, Nissen & Klein, 1976), visual information will be incorporated to sharpen precision if their is enough time for this information to be analyzed. If no visual cues are available, then the movement's outcome will be determined by central monitoring, and additional proprioceptive information may serve to update the initial programmed phase.

As training increased, the programmed phase increased indicating a relatively longer open-loop control mechanism during the execution of the discrete response. Furthermore, this training time-shift effect was also observed in the non-visual condition, suggesting that this process is not a visually-based control mechanism, but rather a central control process in close interaction with the peripheral feedback mechanisms.

The concept of separating the central and peripheral control processes seems to be inadequate for explaining the control process involved in the discrete movements. Rather, it is proposed that a mixed control approach would be more appropriate, with each factor having its own functional role (Keele, 1981).

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CHAPTER I

Introduction

Understanding how coordinated movements occur is crucial to the study of human behavior. The researchers engaged in the study of motor behavior are involved in explaining the underlying processes characterizing human and animal movement.

One particular area of research which has attracted interest is how we control movement: man's ability to direct his limbs in an efficient and purposeful manner. Without a doubt, conflicting ideas concerning the locus of movement control have for years been the cause of one of the most persistent controversies in the field (Schmidt, 1980). Although much has been learned about the nature of motor control in man, through the use of neurophysiological (e.g., Eccles, 1973) and behavioral techniques (e.g., Adams, 1971), knowledge of the underlying mechanisms remains incomplete. MacKenzie and Marteniuk (1985) consider three factors which must be examined more thoroughly in order to come to a better understanding of the control of skilled aiming movements: (a) the minimum time that central processes need to use feedback, either to change the plan of action or to modify an existing movement in order to keep up with tasks demands, (b) the visual feedback sources individuals use during aiming movements, and (c) whether highly integrated stores of sensorimotor information serve as the basis of representation and control of highly practiced movements.

The integration of visual information seems to be crucial for movements in which spatial accuracy is needed (Glencross & Barrett, 1983). The important role played by vision in the guidance and control of human movement has long been hypothesized according to the observation that many motor skills, like throwing a ball, depend upon visual feedback (Zelaznik, Hawkins & Kisselburgh, 1983). However, the understanding and explanations of these functions are often assumed. Furthermore, the fact is that relatively little is known regarding the role of vision in guiding and controlling motor behavior (Zelaznik et al., 1983).

One of the first questions about visual motor control has been concerned with discovering the visual feedback processing time. That is, the time necessary to identify, decide and initiate within-movement corrections, based upon visual feedback. The processing time has been an important issue, because its estimation is directly related to the relative importance that one should give to the contribution of peripheral and central mechanisms in the control of limited duration movements (Carlton, 1981a). Long processing delays have been used to argue for the existence of central mechanisms that structure movement and run it off without involvement from peripheral feedback sources (Brooks, 1974; Evans, 1967; Keele, 1968, 1973; Keele & Summers, 1976; Pew, 1974; Posner & Keele, 1968, 1970; Schmidt, 1975; Schmidt & Russel, 1972).[1] The major

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[1] Schmidt (1975,1976) has modified this statement slightly to allow for the use of feedback, primarily associated with the muscle spindles and gamma loop, to correct for some deviations from the planned pattern of movement. However, all such deviations may not be corrected.

argument was that if the processing of visual feedback information requires more time than the duration of the movement, a motor program must have controlled the movement execution. This point of view suggests that movements are controlled in an open-loop system; this has been opposed by Adams (1971), who argues that feedback information can be used quite quickly for closed-loop control. However, a third option is possible; that is, an interaction between both kinds of processes (Schmidt, Kleinbeck & Hoppenbreck, 1985). It can be proposed that in an aiming task, the first part of the movement is centrally controlled, while the last part of the same movement is under feedback control. This proposition has already been made by Crossman and Goodeve (1963/1983), but was rejected because it was thought that the visual correction time for an ongoing movement was much too long to be realistic. However, researchers have shown that the time needed to establish a visual feedback loop is about 100 to 135 ms (Bard, Hay & Fleury,1985; Carlton, 1981a; Elliott & Allard, 1985; Hay & Beaubaton, 1985,1986; Smith & Bowen, 1980; Zelaznik et al., 1983). Hence the model proposed by Crossman and Goodeve could be appropriate after all, especially if one considers that those approximations were obtained after only a little practice.

An interesting proposition is that the visual processing time would shorten even more when subjects have more practice trials, arguing for an interaction between a motor program and the utilization of visual feedback loops. This proposition is based upon results recently obtained in our laboratories (Proteau & Girouard, note 3). It was shown that in an aiming task when only the target to be reached was visually available during the movement,the accuracy deteriorated if the subjects had practiced 2 000 trials than if they had practiced only 200 trials with total vision available throughout the movement. These results led us to the conclusion that visual feedback was used more efficiently with practice. Thus, when visual feedback was not available, the performance decreased dramatically. This line of thinking would be supported if it can be shown that with practice the last correction, in an aiming task, is made more efficiently and closer to the target. If this proposition is not supported, an alternative explanation could be that with training the first part of an aiming movement becomes less variable. Reducing the variability of the ballistic part of the movement could enable the subject to predict more effectively where and when a correction might be needed and realized. The goal of the present thesis is to examine these possibilities.

The presentation of the next parts is as follows. Firstly, some definitions are given. They are followed by a comprehensive review of the pertinent scientific documentation, our rationale, a statement of the problem and a methodological section. Finally, the results and the discussion are presented.

Definitions

Closed-loop system

Is a control system employing feedback, a reference of correctness, computation of error and subsequent correction in order to maintain a desired state of the environment.

Feedback or response produced feedback

Is the sensory information that is received during and/or after the execution of a movement.

Index of difficulty (ID)

Represents the theoretical difficulty of a movement which jointly relates to the distance that the limb moves as well as to the narrowness of the target at which it is aimed, ($ID = \log_2 2$ amplitude / target width).

Mathematical form or shape of impulse

Two impulses have the same shape, if and only if, their amplitudes measured at the same relative time are proportional.

Knowledge of results (KR)

Refers to the information about success in the task that the performer receives after the trial has been completed. This feedback can be either quantitative or qualitative.

Motor impulse

Refers to the area under a force-time curve, with force representing the height of the curve and time representing the duration of the movement.

Motor program

May be viewed as a set of muscle commands that are structured before a movement sequence begins, and that allows the entire sequence to be carried out uninfluenced by peripheral feedback.

Motor schema

Is an internal representation (or code) of some population of movements and consists of a set of rules serving as instructions for producing a population prototype.

Movement time (MT)

Is the time from the initiation of the response to the completion of the movement.

Open-loop system

Is a control system where the instructions are structured in advance and are executed without regard to the effects they may have on the environment.

Phasing of a response

Is the temporal relationship (timing) among various contractions within a movement pattern.

CHAPTER II

Review of the literature

Open-loop theory

The idea that the human being has a set of stored muscle commands ready for action at any time has been with us for a long time. The first important documentation showing that movement was centrally controlled, was provided by Lashley (1917). He observed that a subject who suffered from sensory loss in the lower limbs was still able to move his legs accurately. This means that even though he could not feel movement in his legs, he was nevertheless able to move them with accuracy. This finding led Lashley to argue for a position in which movement was controlled centrally, since there was little possibility that the subject could have been using feedback to guide his movements (Schmidt, 1975). This idea has been re-stated many times, and with the advent of computers, the centralist notion was presented as an analogy with programs used by computers.

A well known statement is that of Keele (1968) who defined the motor program as" a set of muscle commands that are structured before a movement sequence begins, and that allows the entire sequence to be carried out uninfluenced by peripheral feedback" (p. 387). The motor program carries itself out, and when something happens in the environment, implying that some new movement must be planned, the performer does not accomplish any such changes until the program has run its course. The control is open-loop because stimuli from the periphery can not initiate a new program until some minimum time has elapsed. While it is true that sensory information could operate, it will not be used for error correction during the execution of the movement. If available, feedback information will be analyzed at the end of the movement. This knowledge is needed to alter the program so that the same error will not be repeated at the next trial. The original form of the motor program implies that every movement must have a separate motor program associated with it (Keele, 1968).

In early motor program theories, learning a motor skill means a shift in the mode for controlling the movement. In the early stages of practice, as the motor program becomes established, the emphasis changes from feedback control to open-loop control. Visual feedback no longer appears to control the movement, but instead seems to be used for periodic correction or modulation of a pre-programmed sequence (Keele, 1973, 1981).

Closed-loop theory

Over the years, a number of closed-loop accounts for human motor performance have been proposed (e.g., Adams, 1971; Craik, 1947,1948), the most cited being that of Adams'. These theories have been formulated on the premise that an ongoing movement is continually controlled via monitoring of feedback arising from that movement. It has been proposed that this feedback is compared to a reference of correctness. Movement error may thus be detected and eventually corrected. The designation of two separate mechanisms, one for recall and one for recognition, is the feature that distinguishes Adams' theory (1971) from the other closed-loop models of motor control. Firstly, the memory trace (recall mechanism) is responsible for selecting and initiating the response. Secondly, the perceptual trace (recognition mechanism) operates after the response has been initiated. It evaluates response-produced feedback (vision, proprioception...) from the movement, for error detection and correction purposes. The memory trace is seen as strengthening through stimulus response contiguity over practice trials. The perceptual trace is a representation of feedback stimuli obtained from past movements. Its strength is a function of the exposure to, and amount of knowledge of results (KR). Furthermore, Adams (1971) states that after each trial the subject stores a sensory trace associated with the movement. As the subject learns the task and becomes consistently accurate, the stored sensory trace approximates more and more the feedback representation of the criterion response.

Animal studies (Bizzi, Polit & Morasso, 1976; Bizzi, Dev, Morasso & Polit, 1978; Cooke, 1980; Grillner, 1975; Polit & Bizzi, 1978, 1979; Taub 1977; Taub & Berman, 1968) have provided evidence against the view that peripheral feedback necessarily controls all patterned movements. In these studies feedback was eliminated and movement still persisted. If feedback mechanisms are important for controlling an ongoing movement, why then were the animals still able to move their limbs, to a defined target, even though they were deafferented? Studies of this sort were taken as evidence that the feedback image theories do not universally apply to the control of complex motor patterns (Schmidt, 1980).

Adams (1977) criticized the use of deafferentation research to study the peripheral feedback control. Firstly, deafferentation does affect the animal's proprioceptive feedback but leaves other senses to guide behavior intact. Secondly, physiological research (Clifton, Coggeshall, Vance & Willis, 1976; Coggeshall, Applebaum, Fasen, Stubbs & Sykes, 1975; Coggeshall, Coulter & Willis, 1974) has shown that very fine afferent unmyelinated fibers exist in the ventral root of the spine. These authors showed that about 30% of the nerve fibers in the ventral root carry sensory information. It was found that two thirds of these afferent fibers could be activated by stimulation of the viscera but that one third was associated with the skin and deep tissues of the body and limbs. This means that cutting the dorsal root fibers does not remove all sensory feedback from the limbs. A great deal of sensory feedback continues to get through the ventral pathways. Since the existence of only a few sensory fibers is sufficient to sustain coordinated behavior (Bossom & Ommaya, 1968), it can be accepted that many sensory fibers have remained intact after dorsal root deafferentation. Therefore, the information coming through these fibers could have been used to control the movements of the deafferented animals. Finally, the quality and the accuracy of movements from deafferented animals have rarely been evaluated. It can thus be argued that the primary role of peripheral feedback is to make fine adjustments. If so, the procedures used by Polit and Bizzi (1978, 1979) for defining accuracy (target of 15 degrees of arc) may not have permitted an evaluation of the role of peripheral feedback for controlling an ongoing movement.

The open and closed-loop models lead to different predictions concerning practice. On the one hand, Adams (1971) predicts that dependence on visual feedback will be greater after extended practice[2], while the programming theorists suggest that subjects could perform more effectively because they have ruled out the visual feedback from the control process (Smyth, 1977). For Adams, this means that after a few practice trials, or if the amount of feedback stimuli has been small, a weak perceptual trace will have been formed. However, after a large number of trials followed by KR, the correct response or a close approximation of it has been made a number of times, and the perceptual trace for the movement is strong and dominant. When the feedback stays unchanged, there is maximum compatibility between the perceptual trace already laid down and the current feedback stimuli generated by the response by these same stimuli. When feedback is changed, incompatibility exists and a substantial decrement in performance results (Adams, Goetz & Marshall, 1972). The decrement in performance, after the removal of visual feedback was already reported by Annett (1959). This

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[2] However, Adams, Gopher and Lintern (1977) have shown that the role of proprioception, in a slow positioning movement, increases with training.

means that the perceptual trace built up after 50 trials was largely dominated by visual information, and that there was considerable error when this informative feedback was removed. On the other hand, open-loop theorists would propose that the response-produced feedback should become less important for movement control as practice increases. Subjects who are repeating a visually controlled movement can use their knowledge of previous movements to increase the size of the pre-selected portion of the movement, and so decrease their dependence on visual feedback during practice. If this occurs, then performance without vision after extended practice would be expected to not deteriorate as much as after a small number of trials (Smyth, 1977). It should, however, be mentioned that this would be the case if, and only if, the precision of that first portion remained constant whatever its length. This difference will be discussed in a following section.

Weaknesses of open and closed-loop models

Both theories, whether they stress the open or closed-loop aspects of movement control, have some weaknesses. They are implicitly based on the assumption that for each movement that is to be made, there must be either a motor program or a reference standard against which to compare feedback. This implies that there is a one-to-one mapping between stored states and movements to be made. This may represent a problem for the central nervous system in terms of the amount of material that must be stored, because when we consider the numerous ways in which individuals move their musculature, we must have a nearly countless supply of either programs or reference standards in storage. Another problem is how one produces a "novel" movement. When we make a motor response in a game situation, for example, we do not execute the movement exactly as we have made it before (Bartlett, 1932; Higgins & Spaeth, 1972). If the response is based on a stored trace or motor program, and if this memory representation develops via practice with KR, how then can we initiate and execute a new movement, since there exists no perceptual trace or motor program for that particular movement (Schmidt, 1975) ? Therefore, there is a need for a more generalized concept theory, as proposed by Pew (1974) and Schmidt (1975,1976), to accommodate for the versatile nature of skilled movements.

The motor schema and motor-output variability notions

In order to correct the shortcomings of the already existing open and closed-loop theories, Schmidt (1975), based on the work of Pew (1974), has formulated the schema theory of discrete motor skill learning. The author stated that a subject does not store the movement, but instead he/she abstracts four types of information: (a) the initial conditions, (b) the response specifications for the motor program, (c) the sensory consequences of the response and (d) the outcome of the movement, in order to construct a schema for a given class of movement.

A schema is an abstract memory structure containing codes capable of being transformed into patterns of movement (motor program). The patterns produced from a given program have certain invariant properties, even though two responses from the same program might have large differences in respect to other variant features. According to this view the program is generalized, so that parameters are required to specify the particular way in which the "specified program" is to be executed. At the same time that the subject chooses the specified schema, he also generates the expected sensory consequences of the movement (proprioceptive and exteroceptive feedback). During and/or after the movement, each of these expected sensory consequences is compared with its respective inflow of sensory information. A mismatch produces an error that is fed back to the schema. At that moment, there exist several possibilities. Firstly, the expected and actual outcome are identical. Secondly, there is a slight difference between the two outcomes, because an error has occurred in the execution of the program. Finally, the difference between the expected and actual response is large, because an error has occurred in the selection of the program. The principal difference between these two types of errors lies in the processing time requirements for error correction. Small errors in the execution of the program can be corrected quite quickly (30 to 50 ms), leaving the activated program intact. Selection errors mean that the appropriate program for the movement has not been chosen. Therefore, the response can only be altered by selecting a new motor program in times corresponding to reaction time delays (Schmidt, 1982).

It should also be pointed out that Keele (1981) made a rejoinder to the generalized motor program. He explained that for each variation in a movement, there does not necessarily have to be completely different programs. As he argues, there may be more variability in the product than in the program. Since the final product depends on the interaction with forces in the environment and changing mechanical interaction within the members themselves, one part of the program can be changed while the other parts remain constant.

The principal limitation of Schmidt's (1975) theory is that the generalized motor program, followed by its specifications, is determined by the discrepancy between the sensory-motor system and the intended goal. In other words, the travelled distance appears to be an important factor. However, Bizzi et al. (1976,1978) have shown that for an aimed movement, the travelled distance is not the primary factor with respect to the accuracy of the movement. In fact, the authors showed that a knowledge of the end position is sufficient enough to attain the target. Comparable results have been obtained by Schmidt and Mc Gown (1980) for human arm movement. These results led Schmidt (1982) to review his position. Schmidt (1982) characterized a motor skill as being an organized set of contractions and relaxations of the relevant musculature spread over time, so that the response produced by the summation of this activity is elegant and smooth. It had already been recognized from the control of gait (Grillner, 1975; Wetzel & Stuart, 1976) and from the control of complex multicomponent actions in humans (e.g. Shapiro, 1977,1978; Summers, 1978) that the position of these musculature impulses at the proper time in the skill is an aspect critical to effective performance. The temporal organization of the response, usually termed "phasing", has to do not only with the production of contractions in the proper order of the skill, but also with the production of these contractions at the most effective times with respect to the other contractions in the response (coordination). Schmidt (1982) saw the generalized motor program as being totally responsible, with the possible involvement of reflex-based corrections, for the temporally placed patterns of force in the muscles, and hence for the trajectories assumed by the limbs.

Accuracy of a motor program

Schmidt, Zelaznik and Frank (1978) and Schmidt, Zelaznik, Frank and Quinn (1979) proposed that in an unidirectional arm movement, the motor program produces impulses (force applied over time) that serve to accelerate the limbs. Impulses have an important physical property, in that the velocity of an object, after an impulse has been applied to it, is directly proportional to the impulse size, i.e. to the area under the force-time curve. Furthermore, the size of the impulses (amplitude and duration) determine where the limb will eventually stop, and how rapidly it will travel as well as the achieved spatial trajectory.

Schmidt et al. (1978, 1979) recognized the variability of the human movement, and hypothesized that the determinant of accuracy, in aiming movements, is the variability of the impulse[3]. To control for the inherent variabilities of the impulse, the subject will manipulate movement time (MT), which of course changes the movement average velocity. Here, the travelled distance is a function of two variables: the amplitude and duration of the contraction. In fact, Schmidt and his co-workers showed that the variability of impulse duration and amplitude are linearly related to their respective magnitude. As a consequence, the variability and thus the accuracy of the movement is linearly related to the speed of that movement; accuracy is defined as the variability in the movement's endpoint. The authors proposed that:

$$We \infty D/MT \qquad (1)$$

Here We is the standard deviation of the landing points of a stylus on successive trials; D is the distance between the starting point and the target point, and MT is the average time taken to make the movement (as specified by the experimenter).

It should be noted that this point of view is tenable, if and only if, the movement is not corrected during its course via conscious and/or visual

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[3] One premise of the motor-output variability model is that repeated responses enable the same motor program; so that variability from the central mechanisms is minimized experimentally (Schmidt et al., 1979). Therefore, with this approach, it is the noise in the neuromuscular system, inherent in the repeated execution of a specific motor program, that is responsible for response variability, rather than intrinsic variation in the program itself (Newell, Carlton & Hancock, 1984).

feedback loops. According to Schmidt this should not be an important limitation of this theory. This is because: (a) Schmidt (1975) as well as Keele (1968) proposed that an individual, with a lot of practice, lessens his utilization of visual feedback loops, and (b) Schmidt's theory is limited to those movements made without visual information involvement. However, the movement speed-accuracy data suggest that the availability of vision does not change the function for response variability ; rather, it only changes the intercept of the function relating to the absolute level of movement accuracy (Hancock & Newell, 1986).

According to Meyer, Smith and Wright (1982) there are three weaknesses of the "impulse-variability" model as proposed by Schmidt et al. (1978,1979). The first criticism states that there is an oversimplification of movement dynamics. This is because the model does not explicitly incorporate a deceleration phase or provide a mathematical account of how deceleration influences the overall movement speed and accuracy. Deceleration of movement for the single aiming task may have arisen from two distinct sources: (a) opposition of the antagonist muscles, (b) impact of the arm with the region around the target. The contribution of the antagonist muscles should not be overlooked. It plays an important role during deceleration and should be modeled accordingly. In reaction to this criticism, Schmidt, Sherwood, Zelaznik and Leikind (1986) pointed out that although they did not model this movement feature formally, they were truly aware of the complete action as the limb approached the target area.

The second criticism relates to a misapplication of physical laws. According to Meyer et al. (1982), Schmidt et al. (1978,1979) assumed that the distance travelled by a movement is directly proportional to the impulse for acceleration, because the maximum velocity increases directly with the magnitude of the impulse for acceleration. The argument goes as follows: suppose that the accelerative force is applied for some proportion K_i (of the total MT) and that the limb continues to travel in free fall thereafter until impact. Then, according to Meyer et al. (1982) the movement distance would be directly proportional to the impulse for acceleration, if and only if, the MT was kept constant. This is because the following equation must hold from Newton's second law of motion:

$$D = K_i\,(2 - K_i)\,ft^2/2M \qquad (2)$$

where D is the distance to be moved, K_i is a positive constant, f is the acceleration force applied to the limb, M is the limb's mass and t is the MT.

Because the impulse for acceleration here would be $i = K_i ft$, the only way to obtain a proportional relation between D and i is to have the t remain constant as i and D vary with f. If instead, f remains constant as i and D vary with t, then the relation between i and D would not be proportional; D would be proportional to i^2. Thus in effect, Schmidt et al.'s derivations violate one of the basic principles of physical motion. Schmidt et al. (1986) recognized the point made by Meyer et al. (1982), and explained that the error arose from an additional assumption about how the stylus landed on the target surface, rather than a misapplication of Newtonian kinematics. The reasoning was that their model (considered on the horizontal plane only) predicts that We is independent of MT. In an attempt to solve this problem, the authors assumed that the variability in the velocity of the stylus at about the movement midpoint is proportional to D/MT. Since the stylus travels horizontally as it is dropping vertically near the target, variability in horizontal velocity would be translated into variability in where the stylus lands. Therefore, the authors hypothesized that the variability in where the stylus landed (We) should also be proportional to D/MT. While the early reasoning might appear correct, it ignored the fact that the variability in the time to drop is not constant, but rather proportional to MT. The error thus originated from the failure to take the latter point into consideration.

The third criticism is that the model violates some basic principles of probability theory. The argument is as follows: suppose that a subject wants to generate two movements each concerning a specified distance D, and force is the random variable. The first movement takes a certain time Ta and the second movement involves Tb where Tb is equal to 0.5 Ta. The amount of force required to complete the second movement would have to be four times as great as the amount required to complete the first movement. From this fact, Schmidt et al. (1978, 1979) concluded that the standard deviation of the impulse would be four times as great in the second case, and that We is proportional to $1/T^2$. This is because they assumed that: (a) the standard deviation of the force parameter is proportional to its mean and (b) We is proportional to the standard deviation of the impulse for acceleration. Based on simple probability theory, the standard deviation for the impulse can be calculated, assuming temporarily that MT is not a random variable, but force is. If this rationale is followed , We would be proportional to $1/T$ and not to $1/T^2$, which would lead to the conclusion that:

$$We \infty D \qquad (3)$$

Of course, equation 3 contradicts the results published by Schmidt and his colleagues, where the relation between impulse and accuracy could best be described by the following equation (Keele, 1981):

$$We = a + b\,(D/MT) \qquad (4)$$

where a and b are empirical positive constants. In reaction to this third criticism, Schmidt et al. (1986) explained that they should have written that the variability in the force component was related to $1/MT^2$, and the variability in the temporal component to MT. In consequence, the variability in the impulse will still be related to $1/MT$. Thus, there is really no disagreement about the nature of this relationship.

Although Meyer et al. (1982) criticized the impulse-variability model, they put forward a theory based on the same assumptions as Schmidt et al. (1978,1979). The authors proposed a new variability model, and considered their model to give a better account of the speed-accuracy trade-off in aimed movements. It should be mentioned that the authors accepted equation 1 as theoretically sound, even if the results are best described by equation 4.

Various problems with both models such as: (a) inadequacy in explaining the three dimensional nature of aiming movements (b) non-linear relationship between We and D/MT , (c) shape constancy assumption and (d) force variability-force relationship have recently been outlined by Schmidt et al. (1986). Because this topic is not directly related to the purpose of the present thesis, it is not dealt with in the main body of the thesis. A full treatment of these problems is, however, given in Appendix A .

Even though not perfect, the models proposed by Schmidt et al. (1978,1979) and Meyer et al. (1982) do give a good approximation for tasks defined as "temporally constrained". Temporally constrained tasks include ones where a subject must produce movements of a specified duration, while trying to come as close as possible to a target point. Here, emphasis is placed on achieving the specified MT (Wright & Meyer, 1983). In these kinds of tasks, the role of vision in controlling an ongoing movement has been minimized, even if it has not been experimentally ruled out.

There exists a second type of aiming tasks: those which are "spatially constrained". Spatially constrained tasks include ones where a subject must stop within a specific target region while attempting to minimize the MT. Here, emphasis is placed on hitting the target region.

Using this procedure, Fitts (1954) found a logarithmic trade-off function between the speed and spatial accuracy of aimed limb movements, as expressed in equation 5:

$$MT = a + b \log(2D/W) \qquad (5)$$

where a and b are constants, D is the distance between the starting point and the target and W is the target width.

This latter statement, which has become known as Fitts' law, appears to hold under a wide variety of circumstances involving different aimed movements, body parts, manipulanda, target arrangements and physical environments. Because of its generality and simplicity, Fitts' law has led to several movement control models (Abrams, Kornblum, & Meyer, note 1; Crossman & Goodeve, 1963/1983; Jagacinski, Repperger, Moran, Ward & Glass, 1980; Keele, 1968, 1981; Langolf, Chaffin & Foulke, 1976; Meyer et al., 1982; Welford, 1968).

The model proposed by Crossman and Goodeve (1963/1983) is certainly the most often cited, and is primarily based on visual corrections of the ongoing movement. Because the presence of visual feedback loops has not been ruled out by Schmidt et al. (1978,1979) nor by Meyer et al. (1982) and the time to establish a visual feedback loop is faster than originally thought, this model becomes very interesting. This model and a second one proposed by Abrams et al. (note 1), will be discussed in the next section.

Alternative models for motor control

Controversy still exists over what type of model best explains Fitts' law. The controversy can best be understood in terms of a distinction drawn by Woodworth (1899). He suggested that a movement consists of a programmed ballistic initial-impulse phase followed by a current control phase. In the latter phase, sensory feedback is used to correct unintended errors after the movement has started. Following this distinction, some investigators have attributed Fitts' results to the nature of the initial-impulse phase (Abrams et al., note 1; Meyer et al., 1982), whereas others have attributed it to the nature of the current control phase (Carlton, 1979, 1980; Crossman & Goodeve, 1963/1983; Keele, 1968). Both models have been hypothesized to underlie the logarithmic trade-off observed by Fitts, and will now be presented.

The iterative-corrections model

The iterative-corrections model was originally proposed by Crossman and Goodeve (1963/1983) and subsequently made available by Keele (1968). According to the model, an aimed movement to a target consists of a series of submovements, each of the same duration and relative accuracy. Moreover, each submovement is defined as an impulse responding to, and reducing, a visually detected error. The authors claimed that an initial movement, before any visually based correction takes place, covers most of the distance to the target in a time that is independent of the travelled distance and target precision. This is the case since precision affects the number of corrections needed, not the time needed for each correction. With these assumptions, the iterative-corrections model accounts directly for Fitts' law. In principle, the feedback for the corrective submovements could be either visual or kinesthetic. However, there is strong evidence that rapid corrective submovements can not be made very effectively based on kinesthetic feedback alone (Carlton, 1981a; Prablanc, Echallier, Komilis & Jeannerod, 1979; Wallace & Newell, 1983). Thus, it seems plausible to assume that visual feedback plays a major role in making corrections.

Keele (1981) identifies a few potential problems with the Crossman and Goodeve (1963/1983) model. Firstly, the statements make sense only if the MT covers a range sufficient enough to generate a reasonable number of visually based corrections. This is because following the model, the greater the relative precision, the more such corrections are required. Usually, only two or three corrections are possible in approximately 500 ms, and this is too restrictive to account for the much more continuous changes in MT that occur as a function of distance and precision. Moreover, considerable variation of MT in response to variation of movement length and precision occurs in movements lasting less than 250-300 ms, a range of time thought to be too short to allow visually based corrections [4].

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[4] However, as will be discussed later, evidence is found that the visual processing time is approximately 100 to 135 ms.

The optimized initial-impulse model

The optimized initial-impulse model (Abrams et al., note 1) has emerged from the work of Meyer et al. (1982)[5] and Schmidt et al. (1979). Here the assumption is that in a spatially constrained task, an aimed movement always consists of either one or two discrete submovements regardless of the target distance and width. The initial impulse is programmed to hit the center of the target region. If this first submovement is judged to end anywhere within the target, then no corrective submovement follows. However, the initial impulse may not permit the subject to hit the target. This may be due to perturbations caused by internal neuromotor noise. If this first submovement is not accurate enough, a corrective submovement based on visual feedback is executed to eliminate the error from the initial impulse. The variability in the endpoints of the initial impulses were shown (Wright, note 2) to have a standard deviation that increases proportionally with the average velocity generated by the initial impulse. Furthermore, the initial impulses are assumed to have an ideal average velocity that minimizes the average total MT. This ideal is achieved by making an optimal compromise

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[5] This model, called the "overlapping-impulse" model, was orginally proposed to unify the linear and logarithmic trade-offs without attributing Fitts' law to iterative corrections or visual feedback <u>per se.</u> Under this unification, precisely timed movements (e. g. Schmidt et al., 1979) would be mediated by a single pair of opposing force pulses, which minimizes temporal but not spatial variability. In contrast, spatially precise movements (e. g. Fitts, 1954) would be mediated by a pre-programmed serie of overlapping force pulses which increase temporal variability.

between the mean duration of the initial impulse and the mean duration of the secondary corrective submovements. A compromise is necessary for several reasons. In particular, although faster initial impulses add less to the total MT, they increase the frequency and magnitude of the first movement error and corrections must be made. Thus, to keep the duration of the average total MT to a minimum, the initial impulses should not be too fast in order to reduce error. If a correction is needed, it is influenced by neuromotor noise, just as the initial impulse is. Therefore, to reach the target, corrective submovements must have a distribution of endpoints located at the center of the target with a standard deviation sufficiently small so that only a few (approximately 5%) of them fall outside the target region. Endpoint variability depends on adjusting the duration of the corrective submovements appropriately. Given these assumptions, the optimized initial-impulse model attributes Fitts' law primarily to the nature of the initial impulse phase[6] .

Predictions of the iterative-corrections and optimized initial-impulse models

The predictions, as a consequence of the iterative-corrections and the optimized initial-impulse models, can be divided into three aspects, as laid out by Abrams et al. (note 1). The first prediction involves the

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[6] The main difference between the present theoretical approach and the overlapping-impulse model of Meyer et al. (1982) is that whereas the optimized initial-impulse model requires only two submovements, the overlapping-impulse model includes a set of two or more pre-programmed impulses that overlap each other temporally to account for Fitts' law.

speed-accuracy trade-off without visual feedback. On the one hand, under the iterative-corrections model, an absence of visual feedback during an aimed movement should substantially alter the parameters of the trade-off function, perhaps even induce a breakdown of Fitts' law. This follows because eliminating visual feedback removes the principal basis for making corrective submovements, and the iterative-corrections model cannot predict Fitts' law without the occurrence of such corrections. It should be noted that kinesthesis may serve that function, although at the expense of accuracy. On the other hand, under the optimized initial-impulse model, Fitts' law should hold even when visual feedback is eliminated completely. This follows because the initial impulse allows the first ballistic part of an aimed movement to exhibit a quasi-logarithmic speed-accuracy trade-off (just like the overall movement does). Thus under this second view, corrective submovements are not required for Fitts' law to hold.

A second prediction concerns the kinematics of the initial impulses. Under the iterative-corrections model, the velocity of the first submovement should not depend on the width of the target (W). Regardless of W, the first submovement supposedly takes a fixed amount of time to cover a constant proportion of the distance between the starting point and the center of the target. Under the optimized initial-impulse model, the velocity of the first submovement should increase as the target width increases.

A third prediction considers the variability of the initial-impulse endpoints. Under the iterative-corrections model, the endpoints should have the same spatial variability regardless of their average velocity. This is the case, because the model as expressed by Keele (1968) includes no formal quantitative assumptions about the effects of neuromotor noise. In contrast, under the optimized initial-impulse model, the variability in the endpoints of the initial impulses should be proportional to their average velocity.

Results of the comparison of the iterative-corrections and optimized initial-impulse model

Abrams et al. (note 1) tested these predictions simultaneously in a study where the subjects had to perform rapid wrist rotations. The angular position of the handle controlled the horizontal location of a cursor on a display screen. Hitting the target region required moving the upper point of the cursor so that it fell inside the target. Information about speed and accuracy of the movement was given to the subject at the end of each trial. The experiment included 12 different combinations of target distance and width (ID ranged from 2.32 to 4.96). Visual feedback was manipulated by the cursor, which either remained visible throughout the movement, providing complete visual feedback, or disappeared from view as soon as the movement began and did not reappear until the movement ended.

Firstly, concerning the speed-accuracy trade-off without visual feedback, the results revealed that there were more errors when the subjects could not see the cursor, and the error rate was at its greatest for the difficult targets. This indicated that the no-vision condition disrupted performance. It meant that visual feedback was needed to make fine corrective movements, as would be expected by both the iterative-corrections and optimized initial-impulse models. Unlike the error rates, the MT data revealed only a very small effect of eliminating visual feedback during the movements. The invisible cursor condition tended to yield slighty shorter MTs than those in the visible cursor condition. This presumably happened because subjects omitted some time-consuming movement corrections when they could not see the cursor. It should be mentioned, however, that corrections are always assumed but never measured. Nevertheless, Fitts' law fitted the data reasonably well for both conditions, as predicted by the optimized initial-impulse model. Contrary to the iterative-corrections model prediction, the authors did not observe a large change in MTs or a breakdown of Fitts' law when subjects were deprived of visual feedback to guide their corrections. Wallace and Newell (1983), using the original Fitts' tapping task (Fitts, 1954; Fitts & Peterson, 1964) obtained identical results. They showed that Fitts' law (equation 4) was valid in both vision and no-vision conditions. However, for ID greater than 3.58 bits, they found that movement accuracy was better when visual feedback was available. These results are quite puzzling. Although their MTs results and those of Abrams et al. (note 1) supported the optimized initial-impulse model, the data obtained for accuracy did not. It was clearly shown that the proportion of errors was much greater in the no-vision condition. As far as we understand it, Fitts' law applies for movements that are accurate between 90% and 100% of the time. If we are right, how could Abrams et al. (note 1) have compared MTs for vision and no-vision condition and conclude in favor of their model, whilst error rates were not equivalent? We feel that this is a definite case of confounded effects, and it is thus impossible to favor one model over the other on the basis of these particular results. Furthermore, it must be noted that kinesthetic feedback was still present, and as has been shown by Prablanc et al. (1979), this feedback source does not give accuracy.

Secondly, regarding the kinematics of the movements, the data revealed that each velocity trace (velocity plotted as a function of handle position) had approximately the same shape, but that the peaks were significantly related to target width. This is predicted by the optimized initial-impulse model and violates the iterative-corrections model. It should also be mentioned that Langolf et al. (1976) provided similar evidence against the iterative-corrections model. They observed that the initial relative velocity of an aimed movement increased as W increases (D was held constant). In both studies, average velocities during the initial impulse increased as the target became wider, even though the target distance remained constant. This was probably because wider targets provided more room for the endpoints of the initial impulse; it thus allows the initial impulse to have a higher average velocity without excessively increasing the risk of missing the target. Furthermore, regardless of whether or not the subject had visual feedback, target width systematically affected the velocity of the initial impulse. This outcome is consistent with Abrams et al.'s (note 1) model since the initial impulse does not depend on visual feedback. However, perhaps subjects were relying on kinesthetic information? Finally, concerning the endpoints of the initial impulses, the results showed that the variability increased linearly with the average velocities of the initial impulses, as predicted by the optimized initial-impulse model.

The study of Abrams et al. (note 1) supports the optimized initial-impulse model. The model explains : (a) why the authors and other investigators (e.g., Prablanc et al., 1979; Wallace & Newell, 1983) have found that Fitts' law is valid even without visual feedback and (b) why target width affects the velocity of the initial impulse when target distance is held constant (cf. Langolf et al., 1976).

Before accepting the optimized-impulse model as valid, we must consider some interesting results that have recently been published (Carlton, 1980). Abrams et al.'s (note 1) proposition is that, for most of the movements, there is either no or only one correction based on visual feedback. However, Carlton (1980) showed that, in a manual aiming task, many movements were characterized by more than a single correction. The author designed a study to examine whether discrete corrective movements are characteristic of reciprocal tapping, peg transfer and discrete aiming responses. Specific criteria were adopted for determining if corrections took place. The primary criterion for observing the occurrence of a corrective movement was the acceleration of the stylus as it approached the target area. This secondary acceleration, being associated with the initiation of a movement command, was intended to correct the discrepancy between the position of the stylus and the target. Secondly, a corrective response was also associated with abrupt decelerations which took place near the target. That is, where deceleration values were approaching zero and were followed by a large increase in the rate of deceleration.

Carlton's (1980) results, based on 72 trials per ID condition, indicated that for a 4.65 ID condition, the largest number of responses (54%) were characterized by increases in velocity, near the completion of the movement only in the vertical dimension and resultant function. In the 7.00 ID condition, almost all of the trials (93%) were represented by discrete corrections. The reason for this change in the control process is most likely the change in accuracy required for successful completion of the task in the 7.00 ID condition. Carlton went a little further and investigated the possibility of having more than one correction, for an aimed movement under stringent accuracy requirements (ID= 8.74). The results revealed that two thirds of the movements required two corrections for successful completion. Thus, the majority of the trials were characterized by three phases: (a) an initial movement or distance covering phase, (b) an initial correction phase which brought the stylus very close to the target and (c) a final corrective acceleration bringing the stylus into contact with the target.[7]

The apparent discrepancy between Carlton's (1980) and Abrams et al.'s (note 1) results may be explained by considering the ID levels and the type of task used in each study. As for the ID factor, Carlton (1980) observed several corrections only with ID levels higher than those used by Abrams and his co-workers (note 1). It is thus possible that the optimized initial-impulse model is only tenable for low ID levels especially early in learning. What would happen after extensive training? One may suggest that with extensive training, the optimized initial-impulse model is tenable for both low and high ID levels. Here, different explanations are possible. Firstly, as proposed by Smyth (1977), the first part of the movement (the programmed part) may increase with training so that the feedback controlled phase begins closer to the target, and thus permits only one correction based on visual feedback. In fact, if this proposition could be verified, it would mean that the time needed to complete a visually based correction diminishes with learning. It has been postulated by Howarth and Beggs (1981) that the effects of practice are largely due to a strategic change in the trajectory of the hand. This would enable the practiced individual to come nearer to the target before the last correction is being made. Secondly, it is possible that after

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[7] Furthermore, Pélisson, Prablanc, Goodale and Jeannerod (1986) showed that sometimes corrections took place without kinematic evidence. It may thus be that even more corrections occurred than those reported by Carlton (1980).

extensive training, the first submovement becomes less variable, and thus requires only a single correction whatever the ID level. Finally, a combination of both processes could also happen. As far as we know, neither of the preceding propositions have been experimentally tested.

The discrepant results may also result from the type of task which was used. In the Abrams et al.'s (note 1) study, there was no real movement, whilst there was one in Carltons' experiment.

The similarities between hand movements and large saccadic eye movements give reason to believe that there may be a general control process. Evidence from work examining the control of eye movements will now be discussed.

Saccadic eye movements

The eye tracks much like the hand. However, one of the main differences is that eye movements are a lot faster than hand movements, because the eye has a considerable smaller mass than the hand. The second main difference is that the eye uses mainly quick saccadic movements. They correspond to the quick ballistic movements of the hand, which are not used very often. The eye uses only the slower pursuit movements when it follows a moving object, and even then the eye still uses quick saccades from time to time to correct its positioning (Poulton, 1981). Presumably, the eye uses quick saccades most of the time, because movement blurs the image on the retina. Minimizing the time taken to move the eye maximizes the proportion of the time with clear vision (Campbell & Wurtz, 1978).

Experimental investigations have also revealed some similarities between the two types of movement. Firstly, like the hand, the eye has an average simple visual reaction time, to a single known stimulus, of about 200 ms. As for the hand, reaction time (RT) increases when there are two choices of position. But with more than two choices, RT does not increase any further. This corresponds to the manual performance of a person with highly compatible stimulus-response pairings. This is what one would expect, because acquiring a target by moving the eye to the corresponding position is a highly compatible stimulus-response pairing. Secondly, like ballistic hand movements, saccades tend to be accurate to within about 10% of the size of the movement.

Finally, saccades also exhibit many of the response characteristics displayed in the production of aiming responses, in particular those where a certain degree of accuracy is required. It has already been proposed that aiming responses are made up of an initial submovement and at least one correction that brings the hand in contact with the target. This is very similar to when large saccadic responses are required to bring a target onto the fovea of the eye, and two saccadic responses are typically produced. The first saccade tends to undershoot the target (e.g. Becher & Fuchs, 1969; Henson, 1978) because overshooting would put the stimulus on the other side of the fovea, involving the other hemisphere in the task to re-identify and re-locate the target after the movement (Robinson, 1973). The secondary saccade eliminates any discrepancy of the primary saccade, so that the movement can be completed. Henson (1978) suggested that the primary saccade is programmed to fall approximately 10% short of the target, whereas the corrective saccade uses the visual difference between the present position and the target for correcting the response. It does not take much time to sample and process the information because less information is necessary to program the corrective saccades, since its approximate location in time, amplitude and direction has already been determined. Becher and Jurgens (1979) have proposed that the saccades can be prepared simultaneously and independently from one another (parallel programming in time). The authors have found that the second saccade starts after the initial one with almost no latency. This means that the preparation of the corrective saccade must have been taken place prior to and during the execution of the first one. It is as if the individual is able to evaluate the error resulting from his first impulse and from the appropriate corrections as the movement goes on.

Becher and Fuchs (1969) calculated the visual processing time between the completion of the first saccade and the initiation of the corrective saccade, and estimated it to be 130 ms. This calculation appears to be analogous to the time between vision of the stylus and initiation of corrective responses as laid out by Carlton (1981a). A possible criticism of using the 130 ms as an estimate of visual processing time comes from the finding that the secondary saccades occur even in the absence of visual error information. This has been examined by Prablanc, Massé and Echallier (1978) who demonstrated that the secondary saccades, in the absence of a peripheral stimulus, are not really corrective; really corrective saccades occur only when the eye is near the target.

Considering the similarities in the control characteristics of hand movements and large saccades (except for the undershoot feature which occurs less frequently for hand movements),it may be suggested that these movements are controlled in the same manner. When saccades or rapid hand movements (which also need to be accurate) are required, the initial aiming response is not accurate enough to complete the movement. For maximizing the performance, a primary response is produced that ends short of the target and uses the error information to produce the corrective response, leading to longer processing times.

Earlier in the text, it was mentioned that the time needed to correct an ongoing movement via a visual feedback loop was a central concern for motor control theorists. The issue is important because it is linked with the number of corrections an individual can make during a fixed period of time. The documentation concerning this aspect is reviewed in the next section.

Visual feedback processing time

Initial investigation by Woodworth (1899) estimated the visual processing time by examining response accuracy of reciprocal tapping movements. The rationale was that the processing time could be estimated as the shortest MT that allowed sighted responses to be more accurate than those executed without vision. From his results, Woodworth concluded that vision improved accuracy when movement duration was approximately 450 ms or longer.

In their classic study, Keele and Posner (1968) reasoned that the use of reciprocal tapping responses (Woodworth, 1899) may have led to an overestimation of the visual processing time because in this kind of task, the stroke rate also includes the time taken to reverse directions. The authors solved this problem by having the subjects make discrete movements to a defined target. The error rates indicated that the spatial accuracy of 190 ms single aiming movements was not affected by the withdrawal of visual feedback, whilst vision had a facilitating effect on accuracy when MT's were in the 260 to 450 ms range. These results led the authors to conclude that the visual processing time must lie between 190 and 260 ms.

Recently, vision manipulation studies have shown evidence that the visual processing time may be much shorter than these first approximations. Smith and Bowen (1980) delayed visual feedback during the performance of 150 to 650 ms aimed movements (D=15 cm). For the 150 and 250 ms movements, a 66 ms delay produced overshooting compared to a no-delay condition. This observation suggests that the processing time must be about 100 ms, otherwise the 66 ms feedback delay could not have affected the 150 ms movements.

Evidence for the short visual processing time comes from another line of results. Carlton (1981a) stated that for measuring the visual processing time, one has to consider the control process used in the production of aimed responses. The rationale is that in attempting to make movements to a target, subjects make an initial movement that has some error. This error will be corrected, if needed, using primarily visual feedback, regarding the discrepancy between the position of the hand and the target (e.g., Carlton, 1979, 1981a, 1981b; Keele, 1968). Thus,vision appears to be used to control an ongoing movement only on the last half of the response, when the stylus is near the target. This is because information concerning the position of the hand on the initial portion of the movement would seem to give little indication of the subsequent error at the completion of the initial aiming response.[8] By measuring movement patterns using rapid cinematographic sampling techniques, more indication of the visually based corrections in the production of aiming responses may be obtained. Mc Farquhar and Newell (1984) made a rejoinder to that proposition, and argued that examining only the final outcome score does not provide a complete picture of how a subject actually performs a movement.

Carlton (1981a) reasoned that a direct measure of visual processing time can be provided by measuring the actual time between the hand becoming visible and the initiation of a corrective response. By

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[8] It should, however, be noted that Bard et al. (1985) recently showed that information coming from the peripheral field is also used to guide a pointing movement.

withholding the subject's vision of the hand until it reaches an area where visual information is most useful, the time required to initiate a visually based corrective response can accurately be determined. In his experiment, Carlton observed kinematic changes of aimed movements within 135 ms following the appearance of the subject's hand from behind an occlusion. This led the author to conclude that, even after little practice, processing visual feedback takes only 135 ms.

Zelaznik et al. (1983) criticized both the work of Keele and Posner (1968) and Carlton (1981a). For them, Keele and Posner's estimate of visual processing time is an overestimation, and this for three methodological reasons. Firstly, subjects were uncertain of the availability of visual feedback on the upcoming trial (0.5 probability). Although this manipulation might ensure that subjects use identical strategies in the vision and no-vision conditions, the strategy may have been to prepare to control the more difficult movement: that is, the one performed in the absence of visual feedback. As a consequence, there may have been an added delay in processing in the visual feedback condition, due to the cost of preparing for a no-vision trial. Elliott and Allard also (1985) argued in the same way, and proposed that when subjects are uncertain whether or not visual information about the movement will be available, they perform fast movements in a visual open-loop fashion, i.e. without using visual feedback. Secondly, the subjects were given a specific MT. It is possible that less attention was given to the spatial demands so that the desired level of temporal accuracy could be maintained. Such a strategy would reduce the effects of visual feedback upon spatial accuracy, and result in an overestimation of visual processing time. Thirdly, response accuracy was recorded as hits (when the stylus made initial contact with the target surface), or misses (when the stylus contacted the surrounding area). The "hit and miss" analysis may not be sensitive enough to capture the essence of movement endpoint variability (Poulton, 1974), and may have masked possible changes in spatial accuracy as a function of visual feedback.

In regard to Carlton's experiment (1981a), Zelaznik et al. (1983) argued that the subject knew where his hand could be seen, so that a deceleration could have been programmed prior to the point where the hand was visible. As a consequence, an experimental artifice may have played the primary role in the kinematic changes that were observed. In order to avoid these weaknesses, Zelaznik et al. (1983) examined the effects of visual feedback during the performance of MT manipulated (120 to 300 ms) aimed movements. The results of this study provided converging evidence for the notion that concurrent visual feedback aids the performance of a single aiming movement at MTs as short as 120 ms.

Hay and Beaubaton (1985, 1986) also obtained supporting evidence for fast visual processing time. They investigated the effect of three feedback conditions: (a) no feedback, (b) complete feedback and (c) terminal feedback (at the target only) during the performance of 100 to 190 ms aimed movements. The results revealed that complete vision had a facilitating effect even for the fastest MT. These data suggest that very rapid feedback-based corrections of an ongoing movement can occur.

When one compares the long visual processing times, as postulated by Keele and Posner (1968), the recently obtained estimates (Carlton, 1981a; Hay & Beaubaton, 1985, 1986; Smith & Bowen, 1980; Zelaznik et al., 1983) represent a significant departure. This departure is certainly sufficient enough to permit the individual to make several corrections during an ongoing movement, as shown by Carlton (1980). This possibility of visually based corrections is reinforced even more if one considers that visual processing time may shorten with practice.

In examining discrete movements to a target, it appears that the subject does not actually watch his/her hand during the entire course of the movement, but instead focuses his/her attention near the target. On this basis, accurate visual error information may not be available until the hand approaches the target location (Keele, 1968). This proposal is in agreement with Schmidt (1976), who points out that some portion of the movement must be completed before visual feedback information becomes useful. More recently, Carlton (1981a) demonstrated that the withdrawal of visual feedback from the initial portion of aiming responses has little effect on movement outcome. In his experiment, vision was manipulated by moving a metal shield along the apparatus, so that some portion of the initial movement is unsighted. The five vision conditions consisted of the subject seeing the entire movement, including the stylus in the starting position, or having 25%, 50%, 75% or 93% of the initial movement distance unsighted. The results, based on 15 trials per condition, revealed that increases in MTs and error rates only occurred when 75% or more of the initial movement amplitude was unsighted. A speed-accuracy trade-off can not be accepted as a general explanation of the findings, since delaying the opportunity to use visual feedback resulted in both longer MTs and higher error rates. The results might be explained in terms of differences in visual acuity due to the position of the hand, or by considering the nature of the responses. Firstly, assuming that the subjects fixed their vision on the target, the acuity with which the hand was seen changed as the hand approached the target. More precise visual error information would be available as the hand moved toward the target and the foveal point of the eye. The relatively low information content in terms of visual discrimination during the early stages of the movement suggested that vision of the initial portion of the response had little effect on response outcome. Secondly, the results might also be explained by considering the control process used in the production of discrete aiming responses. In attempting to make these movements, visual feedback of the hand position, on the initial portion of the movement, seem to give little information of the 'inbuilt' error at the completion of the aiming response. It would seem more likely that the initial submovement toward the target would be assessed as to its accuracy, and with regard to the correction needed to complete the task when the hand is near the target.

Bard et al. (1985) criticized Carlton's (1981a) experimental conditions and conclusions. According to them, a default argument was used to disprove the role of vision during the initial part of the movement. In Carlton's experiment, vision of the initial phase was either absent or used simultaneously with vision of the terminal phase. These experimental conditions may have led to a trade-off in favor of terminal (central) vision. A question which arises when one considers how subjects focus their attention on the target is related to the type of vision involved in the control of aiming responses. If the eyes are fixed on the target, the aiming hand crosses the visual field from the periphery to the center. In the final phase of the movement, central vision is especially involved in the acquisition of the target, while the initial phase depends on peripheral vision. Therefore, one might consider the possibility that some very rapid corrections occur under the control of peripheral vision in the early phase of the movement (Bard et al., 1985). This would take much less time than corrections made in the final phase, since peripheral vision is known to involve faster processing mechanisms (Paillard & Amblard, 1984). The authors suggested that peripheral vision can be used to extract visual error information for the control of the movement during the acceleration phase. However, the use of this ability demands a task with requirements that are very well adapted to the parameters susceptible for being regulated in the initial movement part. A directional task, where the visual information is provided by the initial part of the movement, will be different for both the imposed requirements on the subject and the performance measurement, from a pointing task where the feedback information is supplied by the acquisition phase. Bard et al. (1985) further explain that if such a peripheral control exists, it cannot carry out all the corrections of all the movement parameters which have been inaccurately specified. In essence, both visual systems, the positional control and the kinetic peripheral, appear under certain conditions to make specific and complementary contributions to the visual control of movement; the prevalence between the two depending on task requirements (Bard et al., 1985).

Recently, Elliott and Allard (1985) have supported the notion that corrections do appear in the first part of the movement, although, it must be noted that the authors included an additional factor in their experiment. Through the use of prisms, they found the visual system to be particularly sensitive to movement errors early in the movement trajectory. This early error detection allows subjects more time to complete a correction before the movement ends. The authors argued that the prism creates a situation in which early error detection is large enough to be useful, indicating that not only the speed of the movement but also the amount of deviation from the "ideal" pointing trajectory and the precision of the movement required are important. Considering the fact that the subject's perception is deformed from the starting position, it can be accepted that the subject tries to use all the visual information he/she can get to eliminate error during the movement.

Another way to examine if visual feedback is really used for movement control, is to investigate whether the withdrawal of vision affects the accuracy of an aiming task which has been learned in the presence of vision. This will be the main aspect of the next section.

Visual guidance in the acquisition of movement

" To see what you are doing " seems to be crucial in manual skills where the hand or an extension of the hand has to be moved to some target (Whiting & Cockerill, 1974). However, visually guided movements give rise to both visual and kinesthetic sensations, because as a movement is carried out, sensory receptors in the body provide information about the movements that are occurring (Klein & Posner, 1974).

If the subject views his hand as it moves through a pattern, he will have information from two modalities upon which to base a reproduction: he can move through the felt or the seen pattern. How the visual and kinesthetic information combines or coordinates in the acquisition of skilled movement is not exactly known (Klein & Posner, 1974). This is because the extent to which feedback is used by the subject may depend to a large degree on the nature of the task, and the type of error confronting the performer (Schmidt, 1976). Therefore, one can postulate an interaction between the feedback channels, as they play out their roles in regulating movement.

An interesting situation arises when information from two or more modalities derives from the same object or event. Will the sources of feedback be coordinated so that perception is unitary, and performance is influenced by all relevant modalities? Or is our limited attention committed to one channel at a time? Furthermore, if the answer to the last question is positive, will the same channel be used whatever the level of expertise of the performer?

Findings from a variety of experimental paradigms reveal that human performance tends to be controlled by visual information (Klein, 1977). In movement control, this visual dominance over kinesthesis, has been explained in different ways. Posner, Nissen and Klein (1976) and Klein (1977) hypothesized that in response to the reduced alerting capacity of visual signals, subjects tend to confine their attention to the visual modality. This bias works via a prior entry to allow vision to control the mechanism that subserves conscious reports. Another possible explanation might be the ready availability of the eye-movement system as a response to visual input. If visual signals tend to evoke eye movement automatically, it may be unnecessary to summon attentional systems unless the input is further classified as dangerous or interesting (Posner et al., 1976). A third explanation is tied to the spatial character of visual information (e.g., Rock, 1966). Rock proposed that vision directly yields spatial information, but that touch provides such information only through its learned association with vision. If this view is correct, vision is very important, especially in the learning phase of a novel task. Furthermore, an interesting question is whether or not visual feedback continues to be important late in practice.

The literature examining the use of visual feedback during practice will now be discussed.

The role of visual feedback during learning

Adams et al. (1977) performed an experiment to evaluate the contribution of vision and proprioception in the development of the perceptual trace (Adams, 1971). Their subjects learned a linear positioning movement (D= 20.3 cm). The design was as follows: vision and proprioception were the two independently manipulated feedback channels. The conditions of feedback were either augmented or minimal. More specifically, there was augmented visual feedback when a subject could see the apparatus and his movement, and minimal visual feedback when visual cues were absent. Augmented proprioceptive feedback was given by an increase of the tension of a spring attached to the slide, or minimal proprioceptive feedback when the spring tension was removed from the slide, or combinations of these four conditions. There were two types of groups for drawing inferences about the potency of the feedback channels. Each had 15 or 150 acquisition trials with KR. These trials were followed by 50 test trials without KR. One group had neither, one, or both of the feedback channels augmented, and the designated channel remained unchanged throughout the acquisition and KR withdrawal trials. The other group had both feedback channels augmented in acquisition, but one or both channels minimized in the KR withdrawal trials. From the present study's point of view, three sets of results were particularly interesting.

Firstly, whatever the number of practice trials, the subjects who performed with vision always had a better performance than those who performed without it. Secondly, subjects who had to perform (no KR-trials) without vision, had a better performance if they trained (KR-trials) without vision than with vision. This was true for both the 15 KR and 150 KR groups. Thirdly, not having visual feedback after having had it during the acquisition phase was less deteriorative for the group with 150 KR trials than for the group with 15 KR trials.

Taken as a whole, these results clearly showed the power of visual feedback in the control of a slow positioning movement. Furthermore, it was shown that proprioception plays a role in the regulation of movement and its influence increases with training, but that its role remains secondary to vision. However, it must be noted that the definition of minimal visual feedback differs from the definition of minimal proprioceptive feedback. Minimal visual feedback was a total denial of feedback, but total denial cannot be achieved for proprioceptive feedback without "deafferentation". Thus, the two kinds of feedback had both augmented and minimum values, but the amounts were not equated across modalities.

Adams et al.'s (1977) conclusions were extended for a two dimension positioning movement by Saltarelli (1977). The author studied the effect of visual feedback on the learning of the terminal direction and the movement extent of a positioning response. He found that in acquisition with KR, in transfer from terminal acquisition to the initial phase of KR withdrawal, and after transfer in the KR withdrawal phase, subjects with visual feedback performed with less movement extent and terminal direction error than subjects without visual feedback. This indicates that learning movement extent and terminal direction are both a function of visual feedback, even though Christina and Merriman (1977) have shown that each dimension can be learned independently of each other. The positive influence of visual feedback on movement extent (Adams et al., 1977) was thus confirmed.

Christina and Anson (1981) extended Saltorelli's (1977) results. More specifically, they designed an experiment to determine the effect of visual feedback on movement extent and initial direction performance on a slow self-paced positioning response, early as well as later in acquisition, and in a KR withdrawal phase. Visual feedback should have a positive effect on movement extent performance, as Saltarelli (1977) found, if the production of such performance is controlled by a feedback process. Except for the early phase of acquisition, visual feedback should have no effect on initial direction performance, since the initiation of a positioning response in a particular direction is controlled by the memory trace (Adams, 1971) which is a program-based process independent of sensory feedback (Adams, 1971; Keele, 1981; Schmidt, 1980). Visual feedback may have a positive influence early in learning to initiate a positioning response in a criterion direction, if it is used between trials for the development of a programmed-based process controlling response initiation.

Christina and Anson's (1981) experiment had two phases: an acquisition phase of 60 trials with KR, followed by a KR withdrawal phase of 20 trials. Visual feedback and non-visual feedback conditions were manipulated by using transparent and non-transparent goggles, respectively. The results revealed that in the early phase of acquisition, the group with visual feedback performed with less direction and movement extent error. For the latter phase of acquisition, visual feedback had no effect on learning to initiate the positioning response in the criterion direction, but it did enhance the accuracy of learning to move the criterion distance. When KR was withdrawn, vision still had a positive influence on movement extent. This was in agreement with Saltarelli (1977) for a two dimensional response and Adams et al. (1977) for a positioning response in one dimension. No effect was found on initial direction performance. However, the finding that the influence of visual feedback disappeared after the first KR withdrawal block was new.

The experiments presented so far revealed that there is a positive influence of visual feedback on movement extent for slow self-paced positioning responses in one as well as two dimensions. These results can be expected because movement extent in a slow positioning movement is believed to be governed by a feedback-based process. With a slow positioning response, there is more than enough time during the actual response for the subjects to use the visual feedback for the ongoing control of the distance they want to move. Now, it can be asked, how will visual feedback influence the performance of more rapidly executed aimed or aim-like movements?

Smyth's (1977) subjects were required to learn to depress a bar using concurrent visual feedback. Pressing the bar induced the upward movement of a lighting dot on a cathode ray tube. The bar movement/dot movement ratio was of 1 to 15, which means that a slight depression of the bar had a considerable effect on the dot displacement. Smyth's rationale was that when the movement made is small and the observable consequence (dot displacement) is large, there is a discrepancy between the visual and kinesthetic feedback. As vision dominates in such a situation (Posner et al., 1976), subjects perceive the movement to be larger than it actually is, so that after learning the task with vision available, overshoots are to be expected when visual feedback is removed. The amount by which the movement is overestimated would therefore reflect the amount by which the movement is controlled by a perceptual trace relying on visual feedback, which misinforms the subject about the size of the movement. Moreover, if subjects depend on visual feedback after extended practice, it is expected that they will be less accurate, and overestimate even more than individuals who have received fewer practice trials. This would be because subjects would then rely on a more developed perceptual trace.

Smyth (1977) investigated the roles of visual guidance with very little practice and visual guidance with a moderate amount of practice. Four experimental conditions were used, two conditions with little practice (two and five trials) and two conditions of moderate practice (50 and 400 trials). The subjects were told that their task was to learn to exert a certain pressure on the bar, and that the light spot was there to guide them. Subjects in the 50 and 400 trial conditions were warned before the end of practice that the light spot was about to be removed. Two control groups were also used. They received either no practice or 50 practice trials without visual feedback but with verbal qualitative terminal KR. Following practice, there were two test blocks of 10 trials. The first block followed immediately after the last practice trials, while the second block was performed after a 10 min rest interval. In both cases, subjects performed without vision or KR. Smyth's (1977) results revealed that subjects who trained with visual guidance learned something about the task, since the distorting effect of visual feedback decreased with training. However, as errors remained overshoots even after 400 trials, it is clear that the perceptual trace is based primarily on visual information and still exerts an influence.

The relationship between vision and kinesthesis, in the perceptual trace, is an interesting one. Vision dominates, and this is not because it codes position more effectively than kinesthesis, since subjects did not receive any information about the position of the hand. Furthermore, the visual cue informed the subject that the movement was a large one, and the subjects used this information rather than the conflicting kinesthetic information (Smyth, 1977).

Smyth (1977) used a guidance situation in which the visually presented movement was larger than that actually made, so that vision and kinesthesis were incongruent. If visual distance information is used less after extended practice rather than more, accurate practice with visual guidance might lead to accurate performance without guidance, if the visual cue does not distort the subject's memory for the purposes of the task. From Smyth's (1977) results, it may be proposed that visual information may distract attention from kinesthesis (Klein et al., 1974), or that the use of guidance may prevent subjects from setting up an accurate referent in that they do not need to select the end position before the movement is begun (Kelso & Stelmach, 1976). The comparison of visually guided movements with constrained movements allows analysis of the effect of guiding, response-produced feedback, separate from that of errorless practice (Smyth, 1978).

Smyth's (1978) experiment was designed to make this comparison, and in addition allowed some subjects to train with both a stop and a visual cue. The performance of the group with neither the stop nor vision could be like that of the stop only condition, unless vision claims attention and prevents learning even when it is not necessary for accurate performance. There were six conditions, three in which movement was made to a stop and three in which there was no stop. One group of the stop and no-stop conditions received concurrent visual information (visual guidance for the no-stop group), one received terminal visual information (terminal KR for the no-stop group) and one was given no relevant visual feedback at all (no training for the no-stop group). All subjects performed 30 practice and 5 test trials (stop was removed, visual guidance and KR were no longer given). The main result of the study was that visual information about the distance to reach the target prevented the subjects from paying attention to kinesthetic distance and position cues, even though the latter were quite informative when movement had been terminated by a stop. Smyth (1978) argued that visual guidance apparently prevented the development of a stop instruction in a stored trace or program, and by dominating kinesthesis, also prevented subjects from using kinesthetic information to estimate the accuracy of the movement. This occurred even when the visual information was irrelevant.

The results presented so far in this section, may be taken as evidence that vision dominates kinesthesis, and is used to control an ongoing movement even after moderate training. Smyth and Marriott (1982) argued that this was probably because proprioceptive information does not specify hand position adequately. Since felt position of the hand is not accurately maintained if vision is not available, it is possible that the calibration of the proprioceptive system requires constant visual updating. Recalibration of the articular proprioceptive system is not a new idea (Howarth, 1978; Lee, 1978). Howarth (1978) speculated that loosening the muscles in the warming up of athletes may also serve to recalibrate the proprioceptive system. Active strategies of this kind may remove the need for visual information about position, and could explain the repetitive and stereotyped patterns of hand movements performed by some athletes, for whom accuracy of hand positioning is very important. Fishman and Schneider (1985) argued that skill level may be an important aspect in the use of proprioceptive feedback for the specification of limb position. That is, due to practice, one develops the ability to use the proprioceptive information accurately in order to specify limb position.

Knowledge of the spatial location of the limbs is necessary for the performance of skilled acts. This information can be provided by proprioception, but if this is not sufficient enough to allow accurate performance, it is possible that there are many other situations in which vision plays an important, but often unnoticed, role (Lee, 1978; Smyth & Marriott, 1982). Support for this statement comes from two recent studies. Firstly, Carlton (1981b) showed that, in an aiming task, an individual needs to see his hand in order to maintain accuracy. Secondly, Proteau and Girouard (note 3) showed that this was the case even after 2 000 practice trials.

Carlton (1981b) examined the contribution of various sources of visual information used in the control of discrete aiming movements (ID= 4.58). Responses were carried out in five vision-manipulation conditions which allowed the subjects complete vision, no vision, vision of only the target or stylus, and a combination of stylus and target. The subjects were instructed to produce the aiming movement in a specified MT (MT= 330 ms), and a total of 50 trials had to be completed within the criterion MT bandwith for each of the vision condition. KR concerning the subjects MT was available after each response. The results revealed that there was a decrement in performance when the movements were completed in the absence of visual information, or when only the target was visible during the response. The stylus and the target plus stylus visual conditions led to response accuracy which was comparable to movements produced with complete vision. These results suggest that the critical visual information for aiming accuracy is that of the stylus. These results do not support the hypothesis, as laid out by Stubbs (1976), that the position of the hand is adequately known from proprioceptive and kinesthetic receptors. This is not to say that kinesthetic information is not important for the control of aiming responses, but it does suggest that when response requirements are stringent, terminal accuracy is largely dependent on visual error information.

Carlton (1981b) showed that in an aiming task, accuracy depends on visual availability of both the hand and the target. However, the amount of training that had been given to the subjects was relatively low, and it can be argued that with training the need to see the performing hand does not persist. This would be if as proposed by Schmidt (1975), performance is centrally monitored late in training, for example by a motor schema. The goal of the study of Proteau and Girouard (note 3) was to investigate if Carlton's results could be replicated even after extensive training of an aiming task.

Subjects were trained for 200 trials (on a single day) or 2 000 trials (400 trials a day for five consecutive days), either with or without vision of the performing arm, to move a stylus to a target located in front of them (D= 80 cm, MT= 550 ms). The target was visible at all times by all subjects. The subjects received KR after every trial (in ms and mm) about their accuracy on MT and the X and Y axes. The last 20 trials were considered to indicate the level of proficiency attained by the subjects. Following a two-min rest interval, the subjects completed 20 more trials where neither KR, nor visual feedback about arm displacement, were available. However, the target was still visually available for all subjects. The experimental design had the amount of training (200 vs 2 000 trials) and availability of visual feedback during training (yes or no) as between-subjects variables, and pre vs post-KR withdrawal performance as a within-subject variable. The results revealed that MT was more accurate and less variable after 2 000 than after 200 trials of practice. Furthermore, the subjects were less accurate after visual feedback withdrawal if they had been trained with visual feedback. Moreover, the performance at the post-test deteriorated even more as the training with visual feedback increased. These results support and extend Carlton's conclusion that in an aiming task, visual feedback about the hand and the target are both required to maintain a high level of accuracy. They also may be taken as an indication that with training, the human being continues to rely heavily on visual feedback.

Statement of the Problem

Given the optimized initial-impulse model, an aimed movement consists of either one or two discrete submovements, regardless of target width and distance. This proposition is consistent with the kinematic results of Carlton (1979, 1980) and Langolf et al. (1976) who typically found one or two discrete submovements in subjects' overall movements toward a target. The first submovement accounts for Fitts' law through a force-pulse generator that optimally programs the initial ballistic impulse. If necessary, a secondary corrective submovement based on visual feedback is executed , after the initial impulse to eliminate error. The occurrence of the latter phase will primarily depend on the level of accuracy required for successful completion of the task. In other words, in low ID conditions the movement is based on a programmed process and can be completed without response adjustments. However, under more stringent conditions, it becomes difficult to produce an accurate response without some type of visual correction taking place.

It should be mentioned that the optimized initial-impulse model was originally proposed for spatially constrained tasks. Although it has been reported that Fitts' law is violated when subjects have to make aiming responses with precisely determined durations as well as accurate endpoints, it does not mean that the optimized initial-impulse model is not appropriate for temporally constrained tasks. Furthermore, the aspects of the present model are probably still relevant even when Fitts' law does break down. More specifically, it has never been shown that the movements realized in a temporally constrained task were made without involvement of visual feedback. This suggestion comes from two lines of evidence.

Firstly, Proteau and Girouard (note 3) used a temporally constrained task, and showed that subjects were less accurate, after visual feedback withdrawl, if they had practiced 2 000 trials rather than 200 trials with visual feedback available. Secondly, many researchers (Carlton, 1981a;

Hay & Beaubaton, 1985, 1986; Smith & Bowen, 1980; Zelaznik et al., 1983) have shown that visual feedback is quite fast (100 to 135 ms). Therefore, at least one rapid correction during the execution of a temporally constrained movement can be made effectively based on visual feedback.

The results of Proteau and Girouard (note 3) may be taken as evidence that the mode of control of an aiming task is modified with training. Early in training, it is possible that an individual tries an open-loop system similar to the one proposed by Schmidt et al. (1979) and Meyer et al. (1982). This would be the case if early in learning, the first submovement is very variable and the individual has a lot of difficulty to make and use effectively a correction based on visual feedback. However, as training increases, the variability of the first impulse may decrease. It is thus possible that this enables the subject to predict where and when a correction might be needed and realized. This possibility would be verified if it can be shown that (a) early in learning the aiming movement is made without corrections and is very variable and (b) late in learning, the aiming movement is characterized by a corrective submovement whilst the first submovement is significantly less variable.

An alternative possibility is that the time to process visual feedback and to use this information to select an appropriate corrective response decreases with training. It does not seem unreasonable to suppose that the time to process visual feedback shortens with training. This would be the case if the subject becomes more effective in using the visual feedback information, that is, the discrepancy between his hand's position and the target (Carlton, 1981b). As a consequence, in a single correction situation, the corrective phase occurs closer to the target while the size of the initial programmed submovement increases without being more variable. This second proposition would be supported if it can be demonstrated that a corrective submovement appears in most of the movements and if this phase is initiated closer to the target as training increases.

CHAPTER III

Method

Subjects

The subjects were 6 right-handed female volunteers from the Université du Québec à Trois-Rivières, who had no previous experience with the experimental task. The subjects were paid $ 4.00 an hour for their services.

Task

The subjects had to reach a target located approximately 80 cm in front of them. The movement was made in the vertical plane and started with the arm in full extension making a 30 degrees angle with the body. The movement was made forward around the humero-glenoidalis joint.

Apparatus

The apparatus is shown in Figure 1. It consisted of four elements: (a) a defined start position, (b) a poly-articulated arm, (c) the target to be reached, and (d) a micro-computer . The starting position was defined by a microswitch in which a stylus, attached to the end of the poly-articulated arm, could be placed. It was constructed to the left side of the subjects' chair. The poly-articulated arm was made to receive the left arm of the subject in the supination position. Several adjustments of the poly-articulated arm permitted a perfect correspondance between the articulations of the mechanical arm and the articulations thus enabling movements of the shoulder (1df; frontal), elbow (1 df; flexion), wrist (1df;

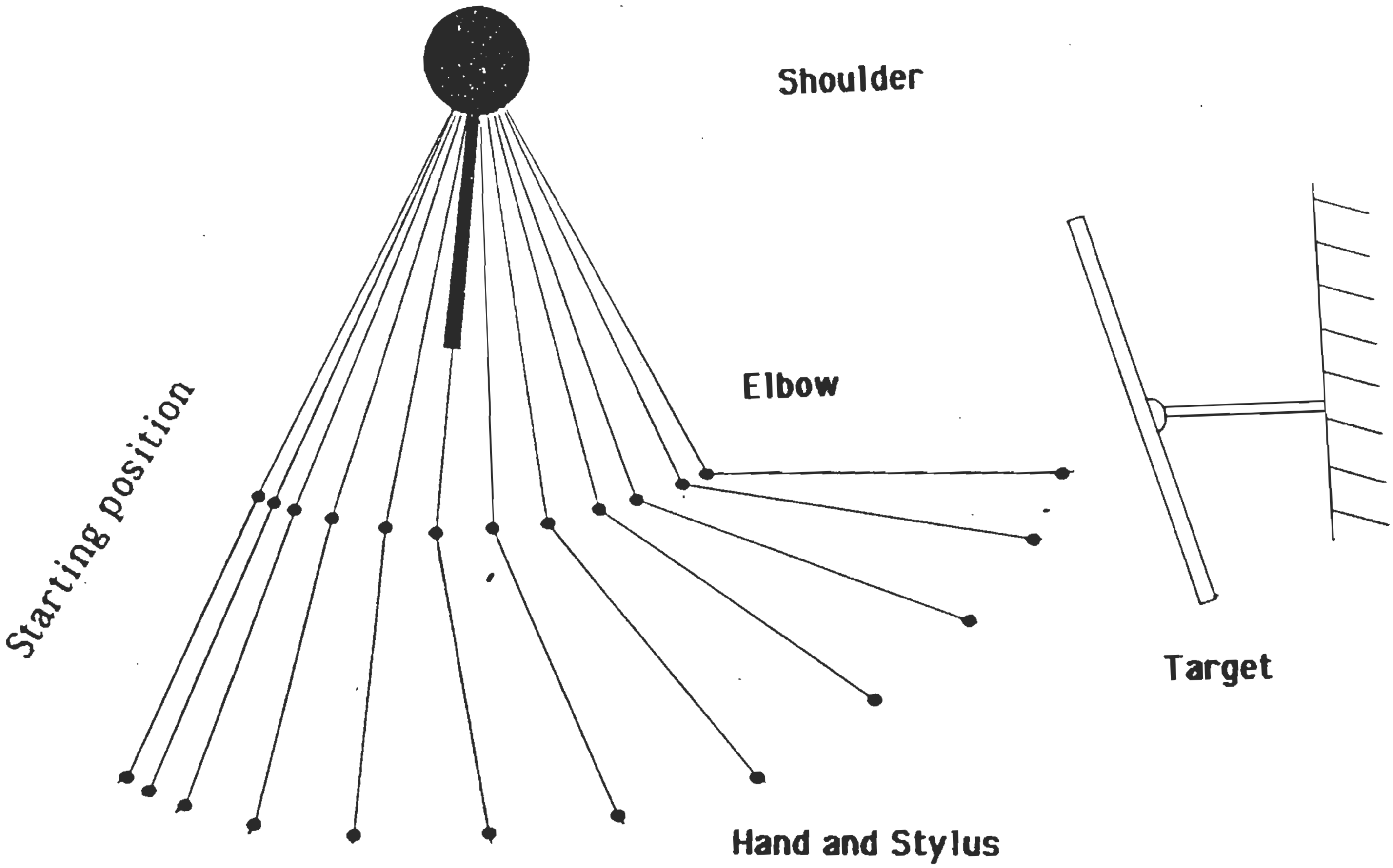

Figure 1. Apparatus.

flexion). A potentiometer was attached to each of the rotation points of the mechanical arm so that it was possible to follow the displacement of each articulation. The target to be reached was indicated by a light emitting diode (diameter= 0.5 mm) and located at the center of a vertically-positionned plate (26 x 26 cm) which was slightly inclined toward the subject (38 degrees). The plate was covered with Teledeltos Recording Paper (Western Union Telegraph, model 1-62s, silver only). This paper permitted the registration, to the nearest millimeter (via an eight-bit analog to digital converter), of the points on the X and Y axes where the stylus touched the target or surrounding area. An Apple 2 E micro-computer controlled the system and permitted the recording of MT, response accuracy on X and Y and of the above mentioned potentiometers.

Data collection and treatment

Two kinds of data were examined, the behavioral and the kinematic parameters. The behavioral measurements included MT and spatial error (X and Y). The raw kinematic data were collected from the potentiometers aligned with each of the above mentioned articulations at a sampling rate of 200 Hz. These data after having been smoothed and differentiated permitted to evaluate the time to peak acceleration and velocity for the shoulder, the elbow and wrist. Although the movement is temporally constrained, the reponses have slightly different movement times. Therefore, it is necessary to normalize the functions in time. The normalized data are then smoothed using a fourth order recursive Butterworth low pass digital filter with a 7 Hz cut-off frequency. The smoothed data are then differentiated using the method of "finite difference" (Winter, 1979) in order to obtain the velocity function (first differentiation) and the acceleration function (second differentiation). Furthermore, since the length of each segment of the poly-articulated arm was measured and because the angular displacement of each segment was recorded from the potentiometers attached to each joint, the same dependent variables were also computed for the tip of the stylus for both the vertical and horizontal coordinates through geometric evaluation.

The acceleration patterns of the stylus were used to locate the point in time where the initial movement appeared to change supposedly (Carlton, 1981) as a result of feedback information. Thus the movement was theoretically composed of at least two phases. The first phase, hereafter called the programmed submovement was defined as the portion of the movement comprised between the initiation of the movement and the end of the first decerelative phase and/or as an abrupt change in the accerelative impulse.[9] The second part of the movement was called the corrective submovement. It begun with the end of the first decerelative phase and was composed of zero, one, two or more corrections. It was determined that a correction took place when the programmed submovement was followed by a second pattern of acceleration and

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[9] In the latter case, a change was abrupt, if and only if, it was followed by a decelerative peak.

deceleration or when an abrupt change was observable in the shape of the accelerative impulse.

Procedures

The subject was seated on a chair and strapped to it to ensure that her position was stable throughout the experimental session. In the starting position, the arm was in complete extension and approximately 30 degrees behind the body. In this position, the stylus rested on the microswitch. The position of the chair was determined so that there existed a fixed distance (80 cm) between the starting position of the tip of the stylus and the center of the target.

The illumination of a red diode, in front of the subject, indicated that she could start the movement. The subject was instructed to produce a left-handed aiming response to the target in the vertical plane, in a MT of 550 ± 90 ms. If the MT was > 640 ms or < 460 ms, the trial was automatically rejected by the system. Furthermore, the subject was reminded of the fact that the MT requirements had to be met. Given this restriction in MT, responses were to be completed as accurately as possible. The aiming movements were executed in two vision manipulation conditions: (a) complete vision, when the lights in the experimental room remained on so that the subject could see her movement and (b) no-vision , when the lights were extinguished before the session started, so that the subject carried her movement out in the dark. Even after the completion of a response, the lights stayed off while the subject moved the stylus back to the starting base. The target was visually available for all the subjects at all times. After each trial, the subjects received KR about accuracy on MT (in ms), X and Y axes (in mm).

In the experiment, subjects performed 20 blocks of 20 trials a day fo three consecutive days. Each day, a ten minute break was given to the subjects after they had performed 200 trials. The sequence of blocks was identical for all three days, hereafter called sessions . The first block of trials was performed in the acquisition-vision condition. That is, vision of both the target and the limb environment was permitted and verbal KR about spatial (both axes in mm) and temporal accuracy (in ms) was given after each very single trial. The second block of trials was performed under the performance-vision condition. For that block, vision of both the target and the limb and environment was permitted, however, KR was not given. The third block of trials was performed under the performance no-vision condition. In that condition vision of the performing limb and environment was not permitted and KR was not given. From the fourth block till the eighteenth block, the subjects were again submitted to the acquisition-vision condition. Finally, the nineteenth and twentieth blocks replicated the second and third blocks respectively.

CHAPTER IV

Results: Behavioral data

Acquisition effect

The behavioral measurements included MT and spatial accuracy. Error scores (absolute error, constant error, variable error and root mean square error) were analyzed.

In order to examine the effects of learning, the different results were submitted to a 3 (session) x 16 (blocks) with visual feedback and KR (block 1 and blocks 4 till 18) within-subject factorial design. When appropriate, post-hoc comparisons were made using the Newman-Keuls technique ($p < .05$).

Movement time

The outcome of the F-test for the absolute error (AE) scores due to the factor session was found to be significant, $F(2, 10) = 4.21$, $p < .05$. Post-hoc comparisons revealed that session 2 ($\bar{X} = 33.5$ ms) was significantly different from session 3 ($\bar{X} = 26.0$ ms). However, session 1 ($\bar{X} = 33.0$ ms) was not different from session 2 and 3.

For the constant error (CE) variable, no main effects or interaction were found to be significant ($p > .05$).

The experimental data for the variable error (VE) scores showed a highly significant effect for session, $F(2,10) = 52.1$, $p < .05$. Post-hoc comparisons revealed that session 1 ($\bar{X}$ = 35.6 ms), session 2 ($\bar{X}$ = 29.1 ms) and session 3 ($\bar{X}$ = 25.8 ms) had significantly different values from one another. That is, the VE scores decreased as practice increased.

The ANOVA conducted on the root mean square error (RMSE) scores revealed a significant effect for session, $\underline{F}$ (2,10) = 4.34 , $\underline{p} < .05$. Post-hoc comparison showed that session 1 ($\bar{X}$ = 39.8 ms) and session 2 ($\bar{X}$ = 40.5 ms) were significantly different from session 3 ($\bar{X}$ = 32.2 ms).

Spatial accuracy on the X-axis

For the AE scores, the main effect due to the factor session was observed to be significant, $\underline{F}$ (2,10) = 6.85 , $\underline{p} < .05$. Post-hoc analysis showed that session 1 ($\bar{X}$ = 6.8 mm) was no different from session 2 ($\bar{X}$ = 6.4 mm); however, session 1 was found to be significantly different from session 3 ($\bar{X}$ = 5.3 mm).

For the CE variable, neither the main effects or interaction were found to be significant ($\underline{p} > .05$).

For the VE scores, the main effect due to the factor session was found to be significant, $\underline{F}$ (2,10) = 6.46, $\underline{p} < .05$. Post-hoc analysis showed that session 1 ($\bar{X}$ = 7.6 mm) was not different from session 2 ($\bar{X}$ = 6.7 mm), however, session 1 was found to be significantly different from session 3 ($\bar{X}$ = 5.8 mm).

A significant main effect for the RMSE scores, due to the factor session was observed, $\underline{F}$ (2,10) = 6.81, $\underline{p} < .05$. Post-hoc comparisons showed that the error values during session 1 ($\bar{X}$ = 8.7 mm) were not different from session 2 ($\bar{X}$ = 8.0 mm); however, session1 was observed to have higher scores than session 3 ($\bar{X}$ = 6.8 mm).

Spatial accuracy on the Y-axis

For the AE and CE variable, neither the main effects or interaction were found to be significant (p > .05).

The ANOVA conducted on the VE rates revealed a significant effect for session, F (2,10) = 9.88 , p < .05. Post-hoc comparisons showed that the error scores during session 1 ($\bar{X}$ = 13.9 mm) were no different from those obtained during session 2 ($\bar{X}$ = 12.6 mm); however, session 1 was found to have higher values than session 3 ($\bar{X}$ = 12.2 mm).

A significant main effect for the RMSE scores due to the factor block was observed, F (2,10) = 1.84, p < .05. Polynomial regression showed a significant cubic component (p < .05) that accounted for 59% of the total variation.

In conclusion, practice data revealed that training produced an increase in accuracy on the X-axis and a reduced variability of the timing errors. Somewhat surprisingly, the effect of practice on spatial accuracy on the Y-axis was not so evident. However, subjects were able to perform more consistently on the Y-axis as training increased. Furthermore, error scores on the X-axis were always much smaller on the X-axis than on the Y-axis. Both observations can perhaps be explained by the particular movement which was executed in the vertical plane.

Visual feedback withdrawl effect

In order to evaluate the consequence of not permitting the vision of the performing limb and environment, the performance of the subjects was compared for the performance-vision and performance no-vision blocks. It should be noted that KR was not provided in these two conditions. These data were analyzed using a completely within-subject factorial design. A 3 (session) x 2 (moment - beginning; blocks 2 and 3 versus end; blocks 19 and 20 of a session) x 2 (performance - vision versus performance no-vision) factorial design was used in order to examine the effect of the experimental manipulations.

Movement time

No main effects or interactions for the AE, and CE variables were found to be significant ($\underline{p} > .05$).

The VE scores were influenced by two main factors. Firstly, the main effect due to the factor session was observed to be significant, $\underline{F}(2,10) = 6.29$, $\underline{p} < .05$. Post-hoc comparisons revealed that session 1 ($\bar{X}$ = 31.7 ms) was no different from session 2 ($\bar{X}$ = 30.0 ms), however, session 1 was found to have higher values than session 3 ($\bar{X}$ = 24.6 ms). Secondly, the main effect due to the moment factor was observed to be significant, $\underline{F}(1,5) = 31.7$, $\underline{p} < .05$. This observation means that consistency in the MT performance increased from the beginning ($\bar{X}$ =

31.6 ms) to the end ($\bar{X}$ = 27.9 ms) of a practice session. See Table 3 in Appendix B.

RMSE values were affected by the factor session, F (2,10) = 6.54, $p < .05$. Post-hoc analysis revealed that session 1 ($\bar{X}$ = 42.3 ms) and session 3 ($\bar{X}$ = 36.6 ms) were significantly different from session 2 ($\bar{X}$ = 50.3 ms). See Table 4 in Appendix B.

The mean values for the respective variables (AE, CE, VE and RMSE) in the visual (block 2 and 19) and no-visual (block 3 and 20) condition are shown from Table 1 to 4 in Appendix B.

Spatial accuracy on the X-axis

The F-ratio for the AE scores revealed a significant main effect due to the factor condition, F (1,5) = 29.3 , $p < .05$. These results show that the accuracy on the X-axis differed during the experimental visual manipulation (vision = 6.6 mm; non-vision = 12.5 mm). See Table 5 in Appendix B.

For the CE variable, the session x moment x performance interaction was found to be statistically significant, F (2,10) = 8.2 , $p < .05$. This interaction represents the particular effects attributable to the combination of the three factors. Post-hoc comparisons revealed that at the beginning of the session 1, the performance deteriorated a great deal when performing in the dark ($\bar{X}$ = -10.3 mm) compared to performing with vision availability ($\bar{X}$ = -2.3 mm), in contrast to the end of that session where the difference was very small (no-vision $\bar{X}$ = -1.0 mm and vision $\bar{X}$ = -0.7 mm). For the beginning of session 2, there was a small difference for both conditions (no-vision $\bar{X}$ = -3.7 mm and vision $\bar{X}$ = -3.5 mm). However at the end of that session, performing in the dark ($\bar{X}$ = -9.3 mm) worsened the execution compared to the visual performance ($\bar{X}$ = -0.2 mm). For session 3, there were only small differences in the visual conditions between the beginning (no-vision $\bar{X}$ =-1.5 mm and vision $\bar{X}$ = -2.0 mm) and end (no-vision $\bar{X}$ = -1.8 mm and vision $\bar{X}$ = -1.3 mm) of the last experimental session. See Table 6 in Appendix B.

A significant main effect for the RMSE variable, due to the factor condition, was observed, $F(1,5) = 33.9$, $p < .05$. This means that the total amount of spread of the responses around the target on the X-axis increased during the lights-off trials ($\bar{X}$ = 14.9 mm) compared to the lights-on trials ($\bar{X}$ = 8.1 mm). See Table 8 in Appendix B.

The mean data for the respective variables (AE, CE, VE and RMSE) in the visual and no-visual condition are presented from Table 5 to 8 in Appendix B.

Spatial accuracy on the Y-axis

A significant main effect for the AE scores, due to the factor condition, was observed, $F(1,5) = 61.6$, $p < .05$. These results suggest that the accuracy on the Y-axis decreased during the no-vision trials ($\bar{X}$ = 24.0 mm) compared to the trials with visual feedback ($\bar{X}$ = 11.8 mm). See Table 9 in Appendix B.

For the CE variable, a session x moment interaction was observed, F (1,5) = 5.97, $p < .05$. Post-hoc comparisons revealed that for session 1 the performance improved a great deal at the end ($\bar{X}$ = -2.3 mm) compared to the beginning ($\bar{X}$ = -8.3 mm) of that session. For sessions 2 and 3, the performance deteriorated at the end (session 2 ; $\bar{X}$ = -8.2 mm and session 3; $\bar{X}$ = -8.7 mm) compared to the beginning (session 2 ; $\bar{X}$ = -1.7 mm and session 3; $\bar{X}$ = -0.4 mm) of these particular sessions. See Table 10 in Appendix B.

The outcome of the F-test for the VE scores due to the factor condition was found to be significant, F (1,5) = 33.5 , $p < .05$. This implies that the variability on the Y-axis increased during the no-vision trials ($\bar{X}$ = 19.3 mm) compared to the trials with vision availability ($\bar{X}$ = 13.0 mm). See Table 11 in Appendix B.

RMSE values were also strongly affected by the factor condition, F (1,5) = 54.9 , $p < .05$. This means that the total amount of spread of the trials around the target on the Y-axis increased with lights-off ($\bar{X}$ = 27.7 mm) compared to the lights-on ($\bar{X}$ =14.7 mm) condition. See Table 12 in Appendix B.

The mean values for the respective variables (AE, CE, VE and RMSE) in the visual and no-visual condition are demonstrated from Table 9 to 12 in Appendix B.

In conclusion, the visual experimental manipulation did not affect the MT performance. It seems that a lights-on or lights-off situation does not influence the subjects target time performance (Proteau and Girouard, note 3; Proteau, Marteniuk, Girouard & Dugas, 1987). In contrast, spatial accuracy was strongly affected by the visual manipulations. Since the aimed movement was mainly executed on the vertical plane, it can be accepted that the effect was stronger on the Y-axis. The difference in results in the vision condition over the no-vision condition led us to conclude that the incorporation of visual information is necessary and important in order to execute the discrete movement with a high degree of precision.

Results: Kinematic data

Acquisition effect

The kinematic measurements included time to peak acceleration and peak velocity. In order to examine the effect of practice, a 3 (session) x 2 (moment ; beginning - block 2 or end - block 19 of a session) within-subject factorial design was used.

Stylus

The movement patterns were analyzed in the vertical and horizontal planes. Here, it is the tangential displacement of the stylus that is considered in both planes.

For the vertical dimension, a typical acceleration pattern for the beginning of session 1 is presented in Figure 2. The profile, which showed little inter-subject variability, was characterized by an initial acceleration and deceleration phase as the movement progressed, with peak acceleration and velocity occuring at mean times of 103 ± 35 ms and 145 ± 37 ms respectively. Following the deceleration segment, a re-acceleration was noted, near the end of the movement, with peak value arriving at a mean time of 470 ± 46 ms. This re-acceleration feature was determined to be initiated at approximately 364 ± 38 ms; that is, when 66% of the target time was completed.

With training, the acceleration profile underwent only minor changes, despite variation in the location and especially the standard deviation of the time to the second peak acceleration. Tables 13,14 and 15 of Appendix B show respectively time to peak acceleration 1, initiation of the second acceleration phase and peak acceleration 2 with corresponding standard deviations, for three subjects[10] during the beginning (block 2) and end (block 19) of the three practice sessions.

A representative example of an acceleration profile at the end of session 3 is shown in Figure 3. The acceleration pattern keeps its basic form, with peak acceleration and velocity occurring at mean times of 109 ± 39 ms and 148 ± 39 ms respectively . The second acceleration near the target continues to be a characteristic of the movement profile, peak value arriving at a mean time of 526 ± 2 ms. The re-acceleration was determined to start at approximately 402 ± 20 ms; that is at 73 % of the target time. A significant main effect for the time to the second acceleration peak value due to the factor moment was observed, $\underline{F}$ (1,4) = 15.06 $\underline{p} < .05$. This observation suggests that peak acceleration 2 occurred later in time at the end of a session ($\bar{X}_2 = 526$ ms) compared to the beginning of a session ($\bar{X}_1 = 501$ ms).

Although the time to peak acceleration 1, velocity and re-acceleration for the stylus in the vertical dimension occurred somewhat later in time with practice, the ANOVA's conducted on these time locations were not found to be significant ($\underline{p} > .05$). For demonstration

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[10] Individual variability scores for the kinematic data were only obtained for the three last subjects (subjects 4, 5 and 6). The raw data of the first three subjects were lost due to a computer failure, only the mean results were thus available for these subjects.

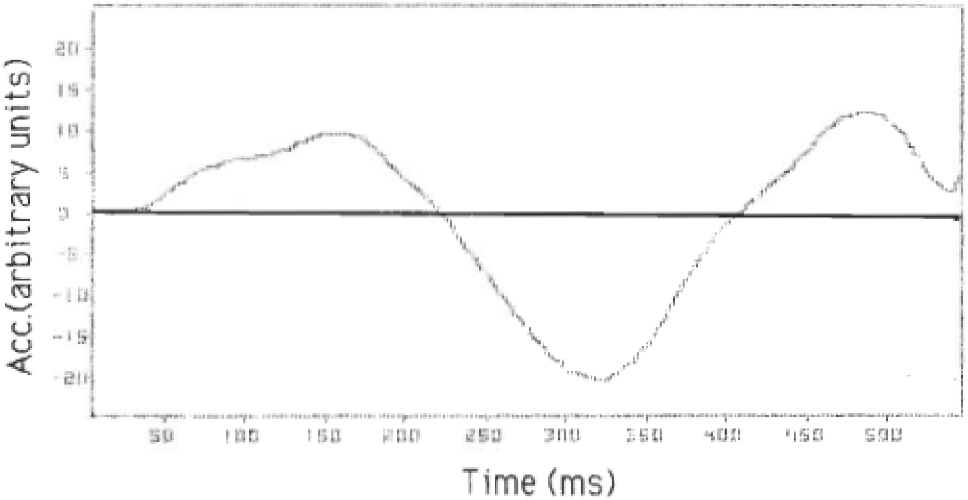

Figure 2. A typical acceleration pattern of the stylus in the vertical dimension at the beginning of session 1 in the visual condition

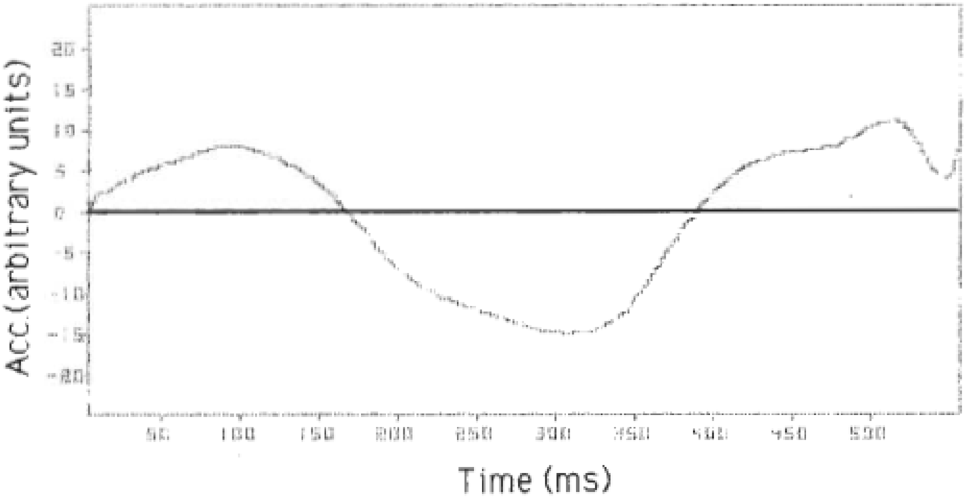

Figure 3. A typical acceleration pattern of the stylus in the vertical dimension at the end of session 3 in the visual condition

purpose, the small time differences between the beginning of session 1 ($\bar{X}_1$) and the end of session 3 ($\bar{X}_2$) support this observation; time to peak acceleration 1 ($\bar{X}_1$ = 103 ms, $\bar{X}_2$ = 109 ms), velocity ($\bar{X}_1$ = 145 ms, $\bar{X}_2$ = 148 ms) and re-acceleration ($\bar{X}_1$ = 364 ms, $\bar{X}_2$ = 402 ms).

Concerning the horizontal dimension, acceleration profiles for the beginning of session 1 are shown in Figure 4 . The acceleration pattern reveals an acceleration phase, with peak acceleration and velocity occurring at mean times of 153 ± 50 ms and 242 ± 52 ms respectively, followed by the corresponding deceleration segment. The shape of this latter segment was subject dependent. That is, 74% of the responses were marked by a distinct change during the deceleration phase occurring at a mean time of 478 ± 34 ms (Figure 4a), 16% of the responses had a smooth approach to the target (Figure 4b) and 10% of the responses were characterized by a second acceleration arriving at approximately 440 ms (Figure 4c).

Practice did bring some changes to the individual variations of the acceleration profile as shown in Figure 5. The acceleration pattern, at the end of session 3, demonstrates the initial acceleration phase with peak acceleration and velocity arriving at mean times of 144 ± 49 ms and 273 ± 29 ms respectively. Following is the deceleration segment which is characterized by a smooth approach to the target (66% of the responses, see Figure 5a) or by an abrupt change in this sequence (34 % of the responses, see Figure 5b) arriving at a mean time of 485 ± 7 ms.

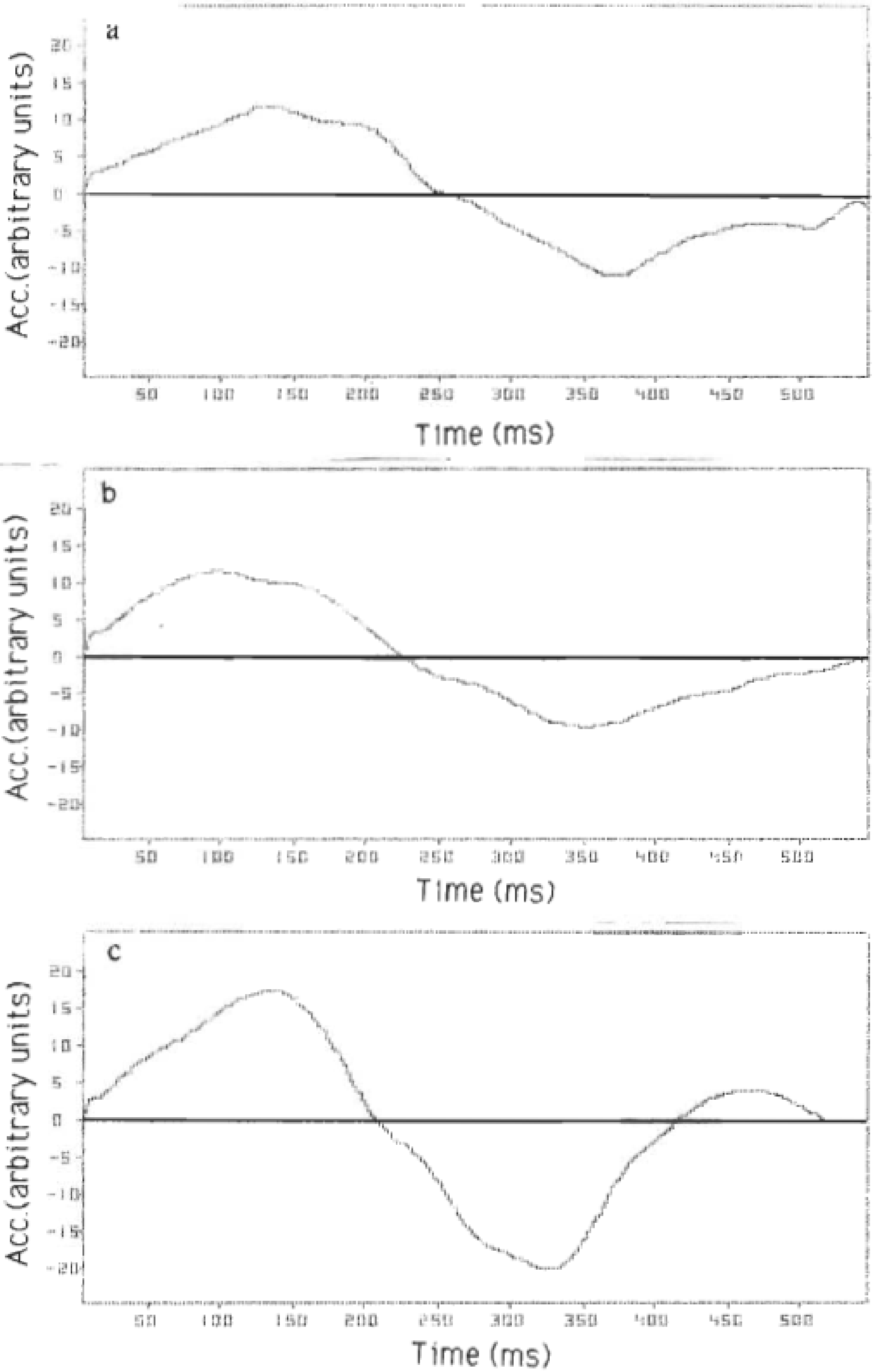

Figure 4. An acceleration pattern of the stylus in the horizontal dimension with irregular deceleration (a), smooth deceleration (b), and re- acceleration (c) at the beginning of session 1 in the visual condition

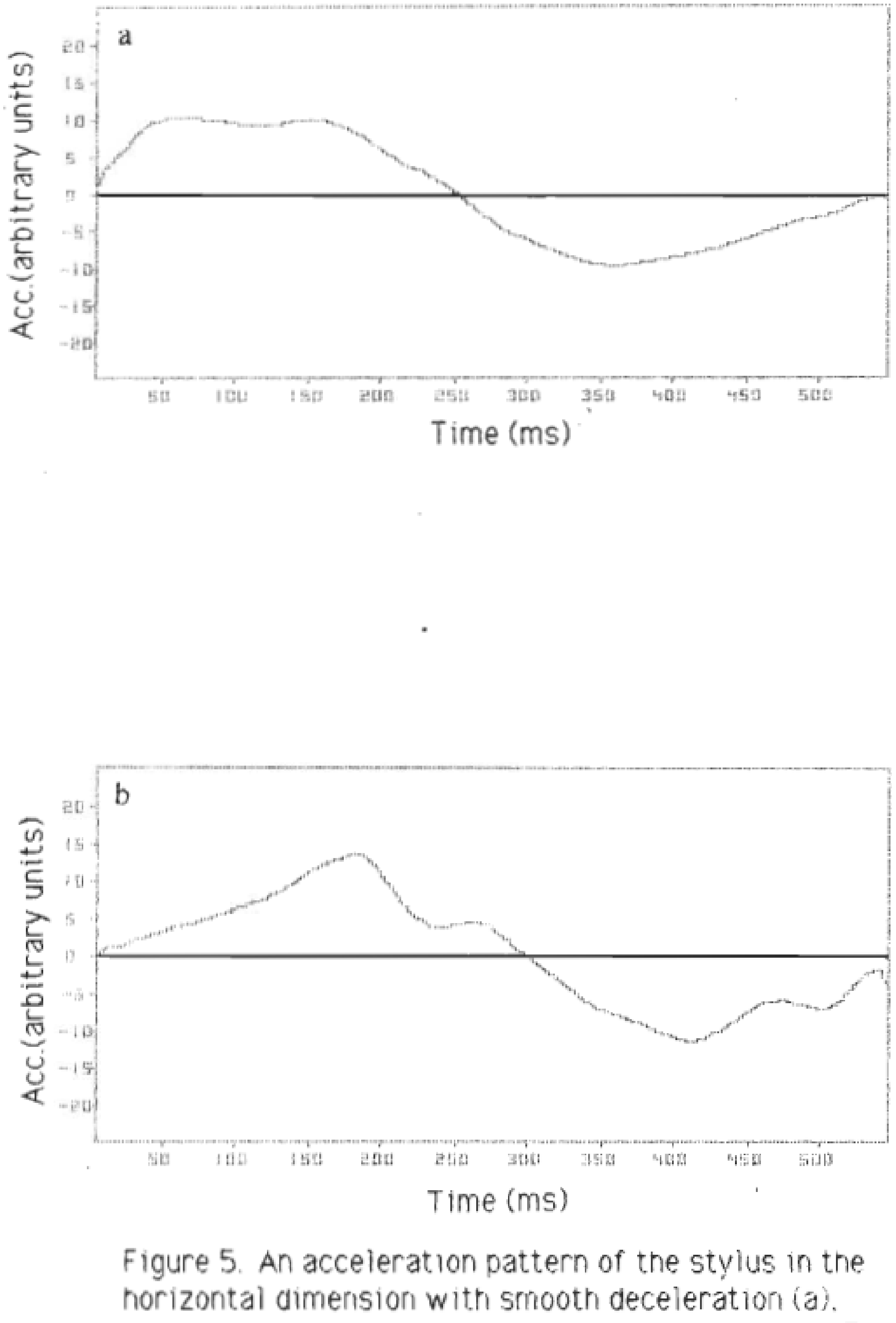

Figure 5. An acceleration pattern of the stylus in the horizontal dimension with smooth deceleration (a), and irregular deceleration (b) at the end of session 3 in the visual condition

Although the time location values for the stylus in the horizontal dimension changed with practice, no main effects or interactions reached the level of significance ($\underline{p} > .05$). For demonstration purpose, the small time location differences between the beginning of session 1 ($\bar{X}_1$) and the end of session 3 ($\bar{X}_2$) support this observation; time to peak acceleration ($\bar{X}_1 = 153$ ms, $\bar{X}_2 = 144$ ms) and velocity ($\bar{X}_1 = 242$ ms, $\bar{X}_2 = 273$ ms).

In conclusion, examining the movement pattern of the stylus in the horizontal and vertical dimension gives reliable information about the two basic components of the aiming response. For the horizontal dimension, there was a remarkable change, throughout practice, in the movement pattern. That is, at the beginning of learning most of the responses (74%) were characterized by an abrupt change in the deceleration phase, whereas at the end of practice most of the responses (66%) were marked by a smooth approach to the target. This observation can perhaps be explained by the fact that this dimension is almost fully controlled by a motor program. Since the movement is performed in the vertical dimension, this component can be considered as being the determining one. The movement pattern of the stylus in the vertical plane was marked by a characteristic feature. That is, after the initial acceleration and deceleration phase, a re-increase in acceleration occurred, early in practice, when 66% of the movement time was completed. Late in pratice, this re-acceleration shifted to 73% of the target time. As a result of practice sessions, a trend was observed for the peak value of this re- acceleration to occur later in time. Furthermore, the associated standard deviation to this latter value diminshed a great deal as training progressed, having a minimal value at the end of session 3.

The re-acceleration, on the one hand, can be attributed to a corrective impulse which is initiated when the stylus is near the target (e.g. Carlton, 1981 b). However, since it appears so consistently it may also be that the re-acceleration is also a feature of a motor program. Clearly, more research is needed to clear up that particular point. Since the complete arm action involves the motions of the shoulder, elbow and wrist, it is relevant to find out which articulation(s) were responsible for this particular feature during the execution of the discrete movement. It should be noted that for the articulations, the angular movement patterns were analyzed.

Shoulder

A representative acceleration profile for the beginning of session 1 is illustrated in Figure 6. The acceleration phase is characterized by an acceleration phase, as the movement is initiated, with peak acceleration and velocity appearing at mean times of 91 ± 31 ms and 222 ± 22 ms respectively. Following is the corresponding irregular deceleration portion.

Practice did not cause much change to the general trajectory of the movement pattern. As shown in Figure 7, the acceleration pattern at the end of session 3 still revealed its initial acceleration and deceleration segment. Peak acceleration arrived at almost the same time compared to early training, that is at a mean time of 97 ± 23 ms, in contrast to peak velocity which occurred much later, with practice, that is at a mean time of 301 ± 80 ms. The ANOVA conducted on this latter time value revealed a significant main effect due to the factor session, $\underline{F}$ (2,10) = 4.38 , $\underline{p} < .05$. Post-hoc comparisons showed that the time to peak velocity attained during session 1 ($\bar{X}$ = 229 ms) arrived significantly earlier than during session 2 ($\bar{X}$ = 268 ms) and session 3 ($\bar{X}$ = 294 ms)[11] however, session 2 and 3 were not significantly different from each other ($\underline{p} > .05$).

The spatial variability of the shoulders' displacement trajectory was analyzed as a function of training. Keeping in mind that the displacement of the stylus in the vertical dimension was characterized by a re-acceleration near the target, the movement could thus be divided into two different parts: an initial and a corrective phase. The first phase began with the initiation of the displacement and ended at the end of the first decelerative phase. Considering Carltons' proposition, this phase can be associated with the motor program planned before the movement initiation. This first phase is hereafter referred to as the

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[11] It should be noted that this latter score is the mean value for session 3 (blocks 2 and 19 combined).

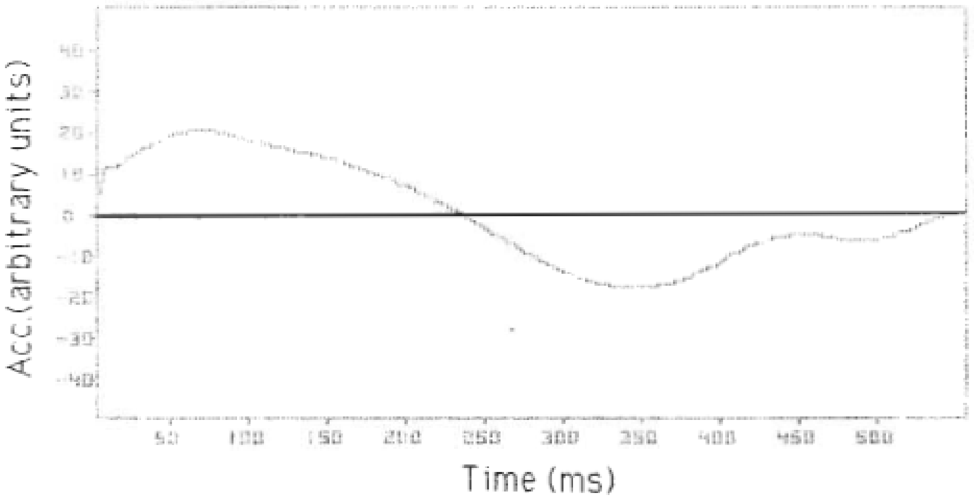

Figure 6. A typical acceleration pattern of the shoulder at the beginning of session 1 in the visual condition

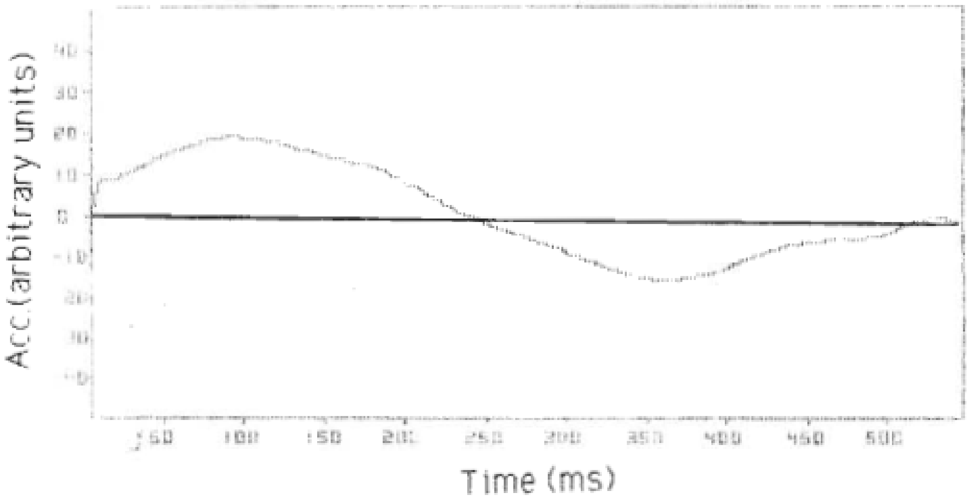

Figure 7. A typical acceleration pattern of the shoulder at the end of session 3 in the visual condition

'initial phase' of the movement. The second phase began with the second impulse for acceleration. This phase, seems to be related to some error detection and correction mechanism and is therefore referred to as the corrective phase of the movement. In order to gain some insight on the nature of the corrective phase observed for the stylus , the displacement data obtained for the shoulder, the elbow and wrist were also broken down into two phases. Each of these phases was considered to begin and end at the same time as those found for the vertical dimension of the stylus.

In order to examine the effect of practice, a 2 (moment; beginning - end of practice) x 2 (phase; initial - corrective phase) within-subject factorial design was computed on the mean variability observed for each phase of the movement. No significant main effects ($\underline{p} > .05$) were observed. However, the moment x phase interaction was shown to be significant, $\underline{F}(1,2) = 2326.17$, $\underline{p} < .05$.

This interaction suggests that at the beginning of learning, there is only a small difference in dispersion values for both phases (initial phase; $\bar{X} = 3.8$ and corrective phase; $\bar{X} = 3.7$ in arbitrary units). However, at the end of practice, the variability of the corrective phase ($\bar{X} = 3.6$, arbitrary units) was found to be smaller compared to the dispersion of the initial impulse ($\bar{X} = 4.0$,arbitrary units). Figure 8 demonstrates a representative mean trajectory of the beginning of practice (session 1 - block 2) and end of training (session 3 - block 19). Figure 9 shows the individual paths of these mean trajectories.

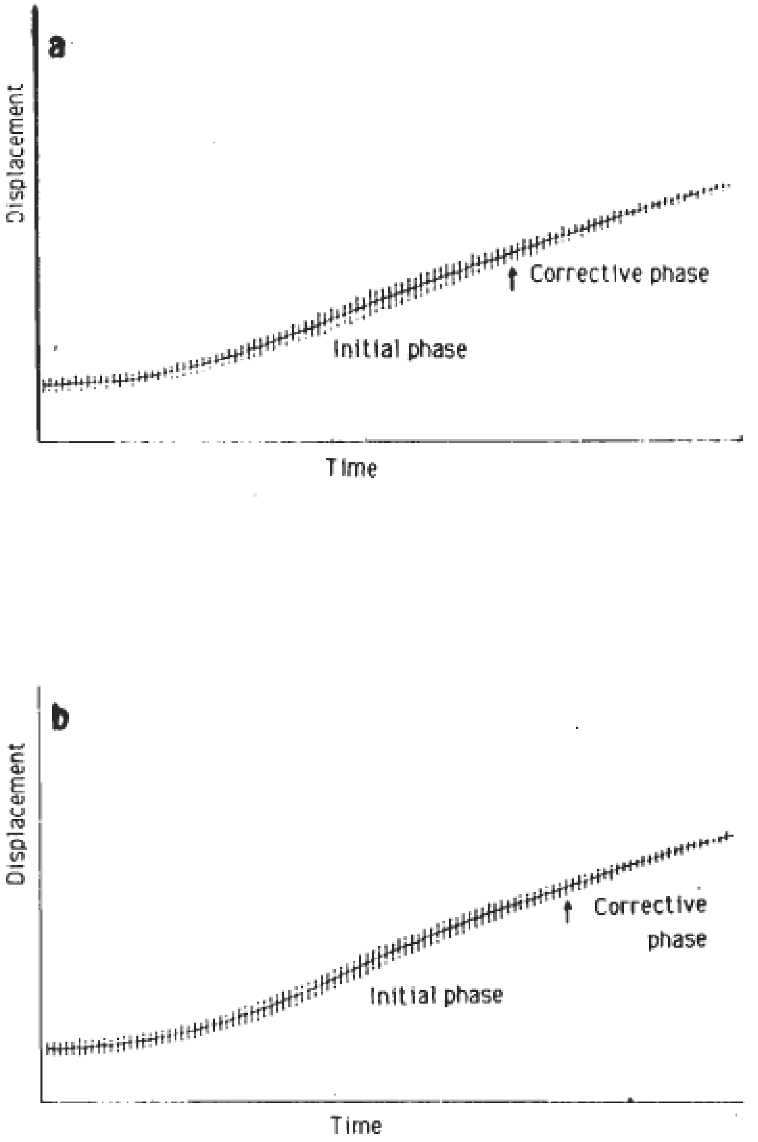

Figure 8. A representative mean displacement trajectory with dispersion of the shoulder at the beginning ofsession 1(a) and the end of session 3 (b) in the visual condition

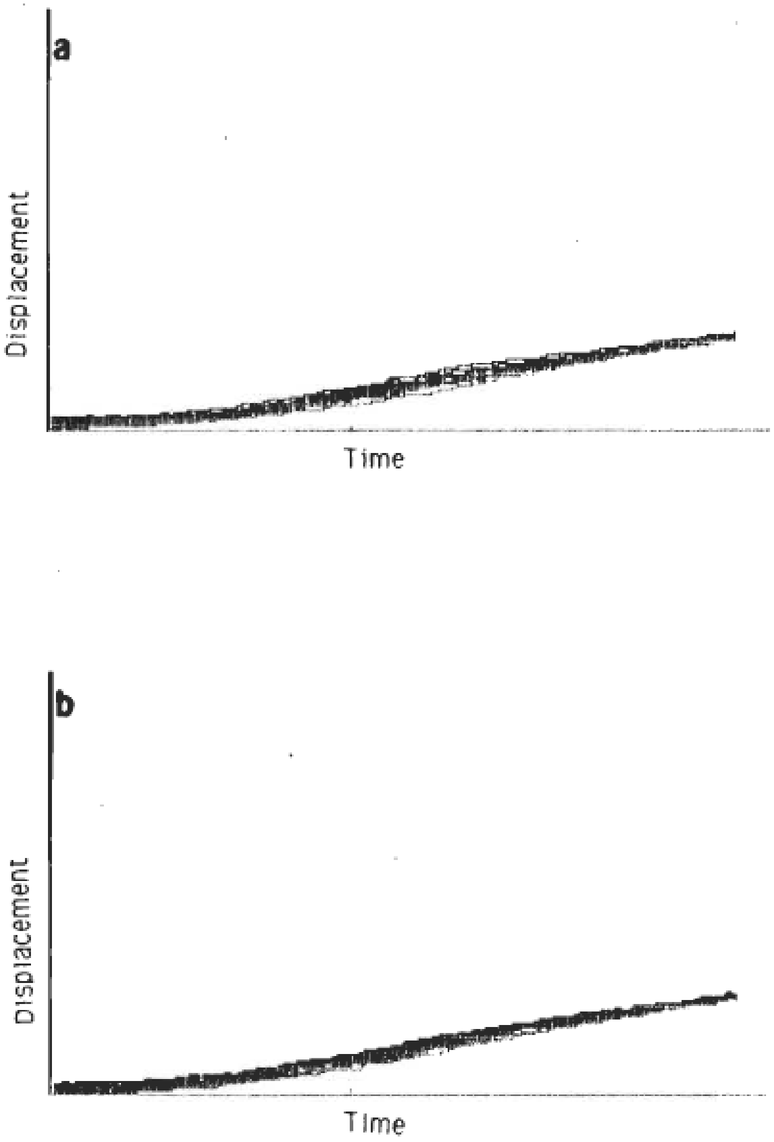

Figure 9. The individual paths attributing to the mean displacement trajectory of the shoulder at the beginning of session1 (a) and the end of session 3 (b) in the visual condition

Elbow

A typical example of an acceleration pattern for the beginning of the first session is demonstrated in Figure 10. The acceleration profile reveals a long irregular acceleration phase; peak acceleration and velocity arriving at mean times of repectively 235 ± 72 ms and 333 ± 31 ms followed by the corresponding deceleration sequence.

With training, the non-symmetric curvature will vary little in shape, as shown in Figure 11. As can be seen in that Figure, the acceleration pattern at the end of session 3 still reveals a long acceleration; peak acceleration and velocity being attained at mean times of respectively 226 ± 45 ms and 350 ± 42 ms, followed by the deceleration portion.

Although for the elbow articulation, peak acceleration and velocity differed somewhat during training, no main effects or interactions reached the level of significance ($\underline{p} > .05$). For illustration purpose, the rather small differences in values for the beginning of session 1 ($\bar{X}_1$) and end of session 3 ($\bar{X}_2$) support this observation; time to peak acceleration ($\bar{X}_1$ = 235 ms, $\bar{X}_2$ = 226) and velocity ($\bar{X}_1$ = 333 ms, $\bar{X}_2$ = 350 ms).

As for the shoulder, the spatial variability of the elbow displacement was also observed as a function of the initial and corrective phase of the stylus displacement and practice. An ANOVA, similar to the one computed for the corresponding shoulders'

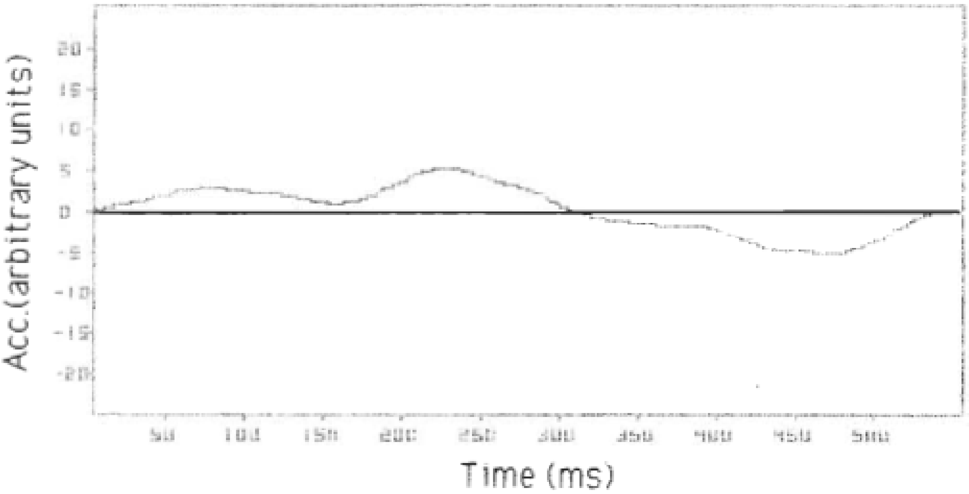

Figure 10. A typical acceleration pattern of the elbow at the beginning of of session 1 in the visual condition

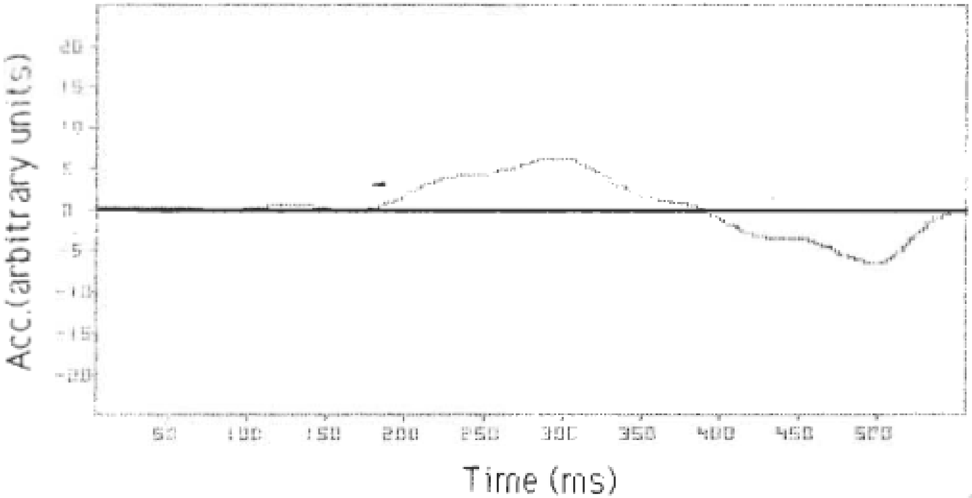

Figure 11. A typical acceleration pattern of the elbow at the end of session 3 in the visual condition

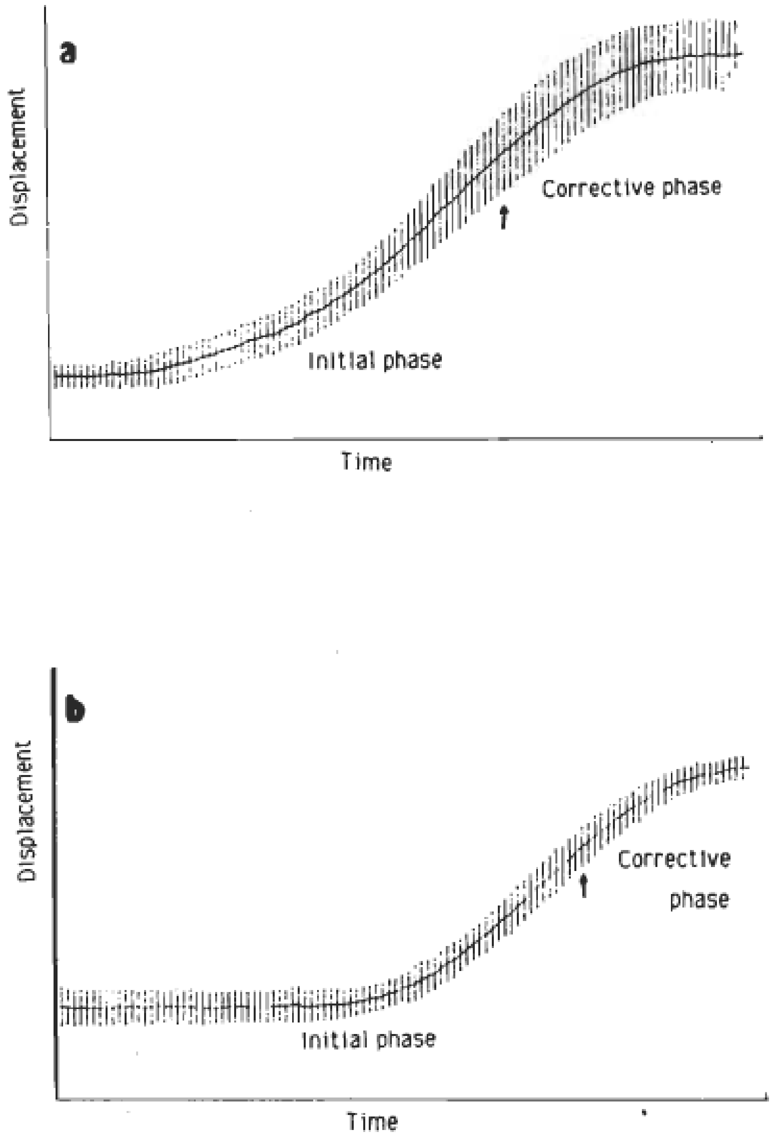

Figure 12. A representative mean displacement trajectory with dispersion of the elbow at the beginning of session 1(a) and the end of session 3 (b) in the visual condition

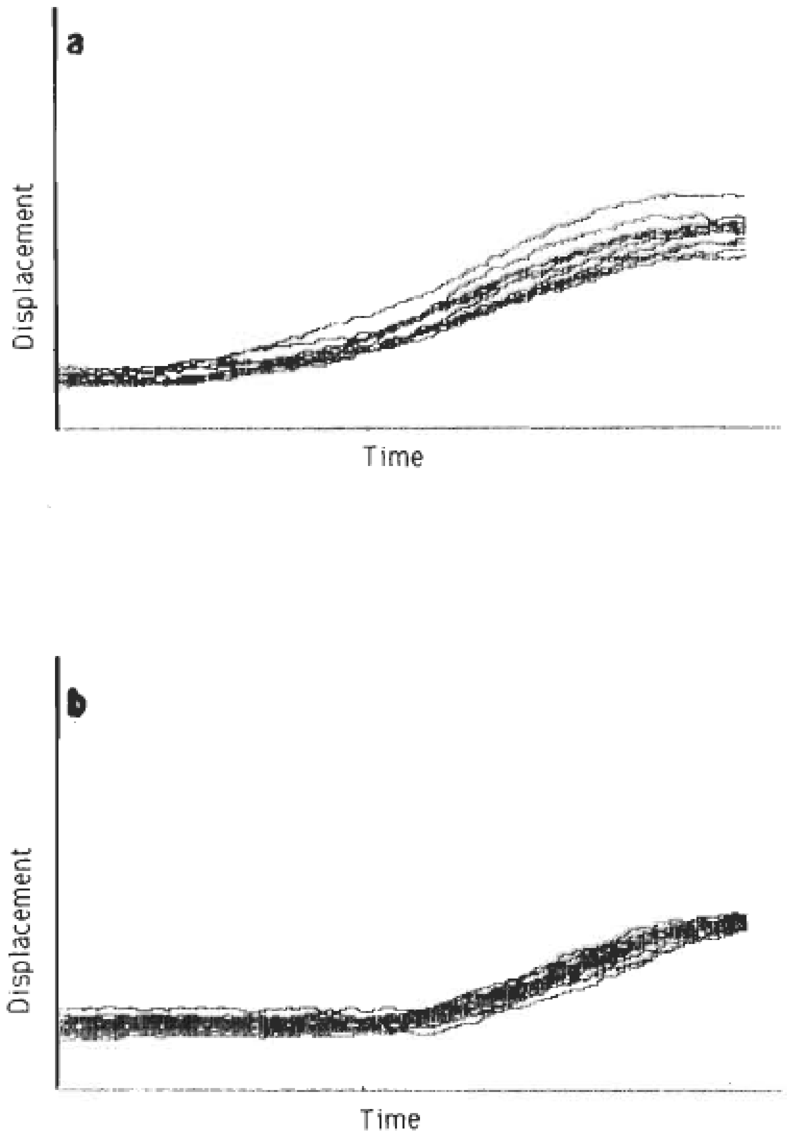

Figure 13. The individual paths attributing to the mean displacement trajectory of the elbow at the beginning of session 1(a), and at the end of session 3 (b) in the visual condition

displacement data, was conducted on the mean variability values of the elbow displacement. This analysis revealed a significant effect for the factor peak, $\underline{F}$ (1,2) = 109.68, $\underline{p}$ < .05. These results show that the variability of the initial phase ($\bar{X}$ = 3.7, arbitrary units) is significantly smaller than the dispersion of the corrective phase ($\bar{X}$ = 4.2, arbitrary units). Figure 12 shows a typical mean displacement trajectory with dispersion for the beginning (session 1 - block 2) and end of learning (session 3 - block 19). Figure 13 demonstrates the individual trials attributing to these mean paths.

Wrist

Because of the rather large inter-subject variability in the beginning of session 1, the mean acceleration pattern of all subjects are demonstrated in Figures 14 and 15. The basic form of the profile reveals an acceleration and deceleration phase, peak acceleration and velocity arriving at respectively 124 ± 57 ms and 218 ± 76 ms. However, both sections are marked by inflections and valleys. In particular the deceleration portion is characterized by several abrupt changes.

With training, the individual differences disappeared and the movement profiles became more consistent between subjects. Also, common features were observed compared to early practice in session 1. As shown in Figure 16, the mean acceleration pattern at the end of session 3 demonstrates an acceleration and deceleration phase early in movement, where peak acceleration and velocity arrived at mean times of 102 ± 57 ms and 171 ± 42 ms respectively. At approximately 300 ms,

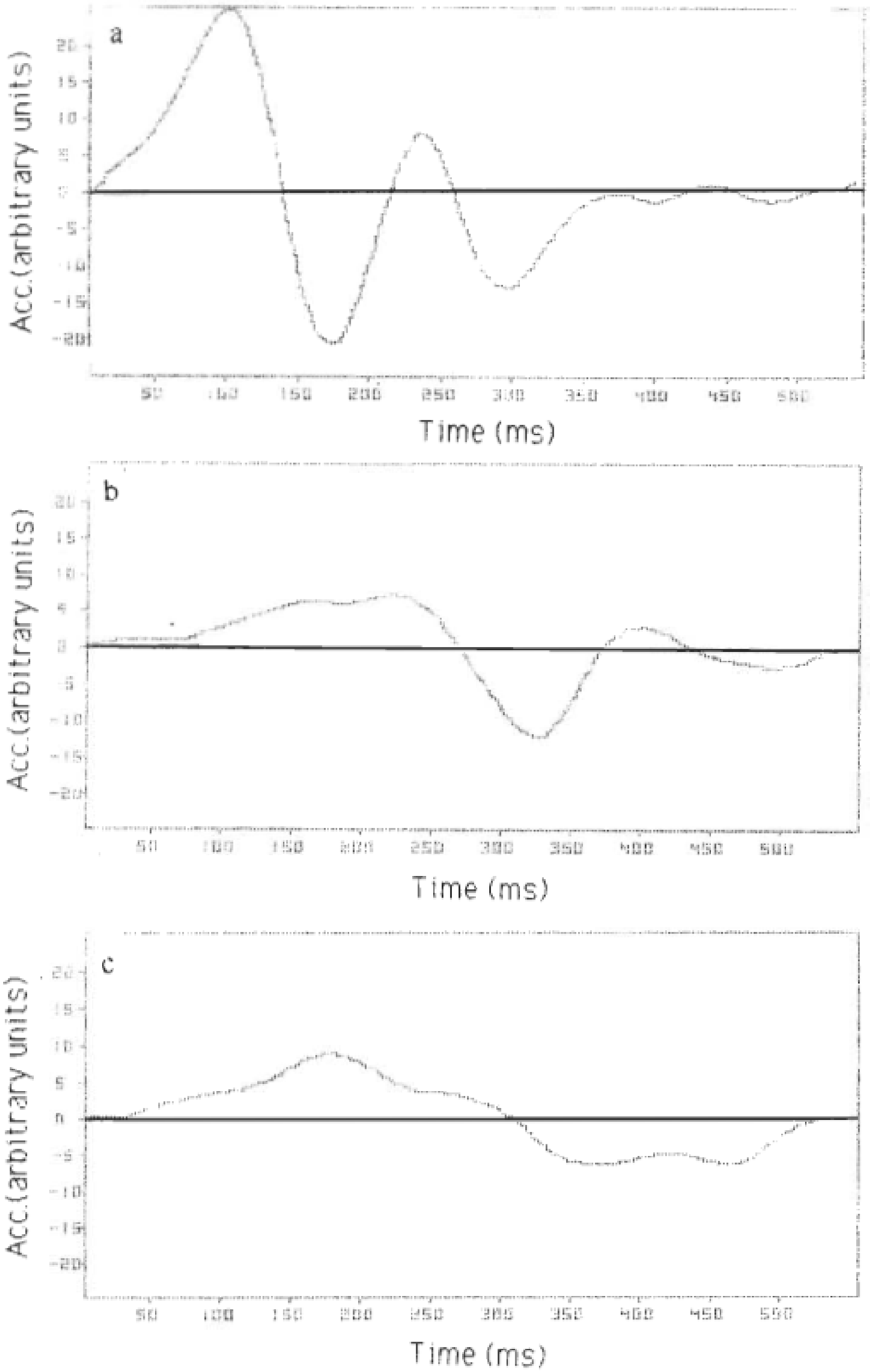

Figure 14. The acceleration pattern of the wrist for subject 1(a), subject 2 (b) and subject 3 (c) at the beginning of session 1 in the visual condition

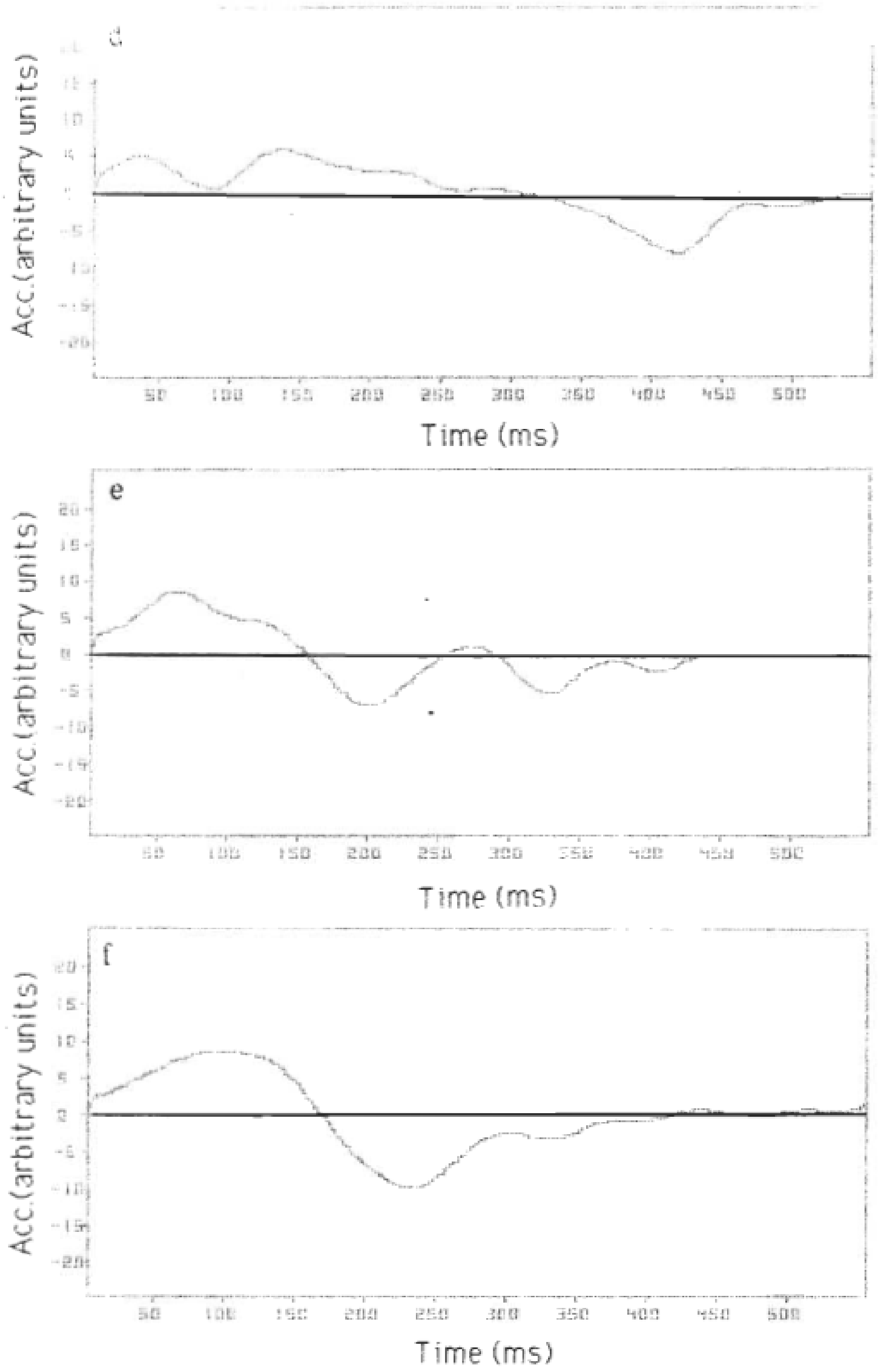

Figure 15. The acceleration pattern of the wrist for subject 4 (d),subject 5 (e) and subject 6 (f) at the beginning of session 1 in the visual condition

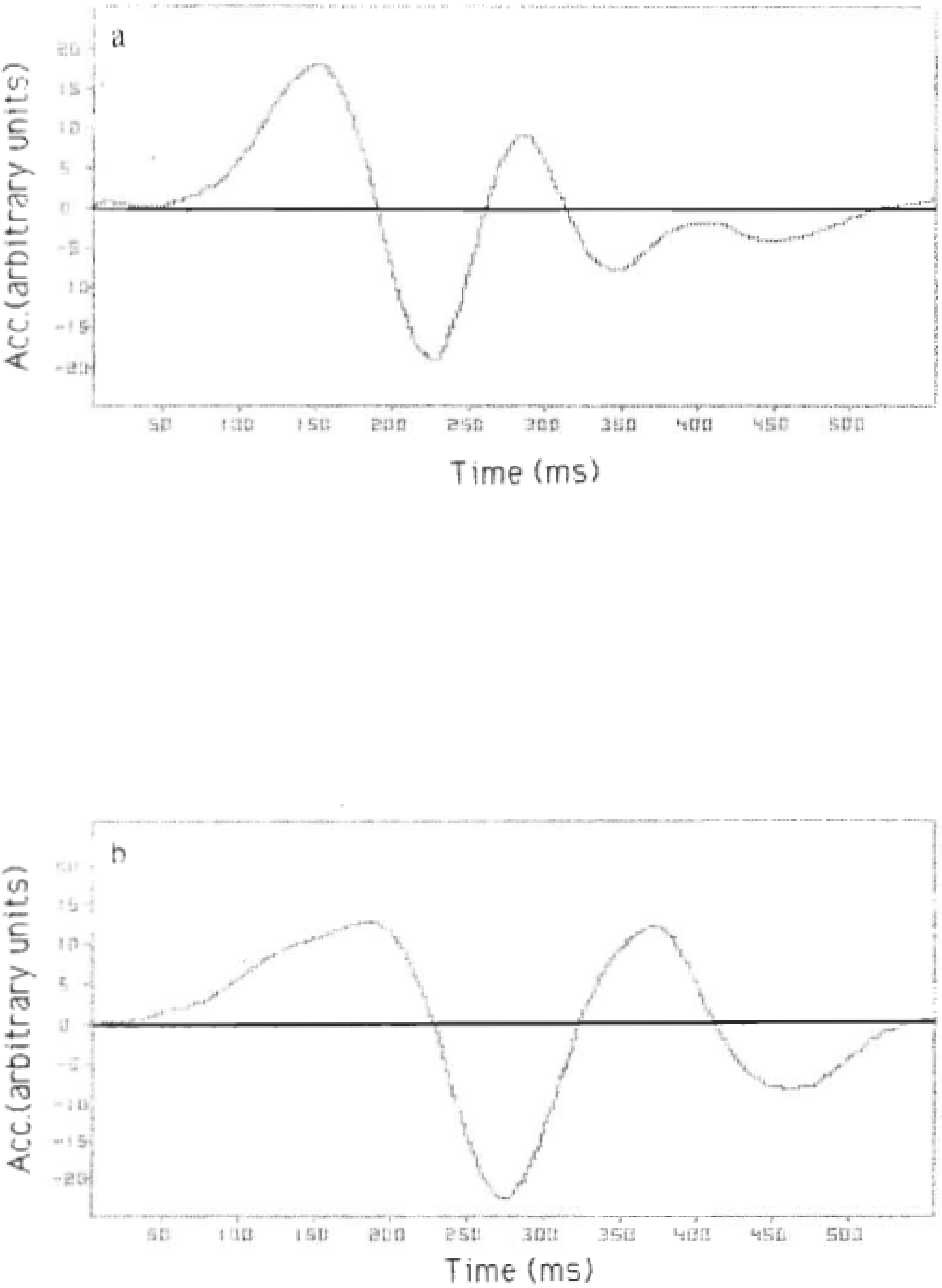

Figure 16. An acceleration pattern of the wrist with no smooth approach (a) and smooth approach (b) at the end of session 3 in the visual condition

there was a second acceleration followed by a deceleration segment that did not (Figure 16a) or did (Figure 16b) show a smooth approach to the target.

Although for the wrist articulation peak acceleration and velocity differed throughout training, no main effects or interactions were observed to be significant ($\underline{p} > .05$). For illustration purpose, the small time differences between the beginning of session 1 ($\bar{X}_1$) and the end of session 3 ($\bar{X}_2$) support this observation; time to peak acceleration ($\bar{X}_1$ = 124 ms, $\bar{X}_2$ = 102 ms) and velocity ($\bar{X}_1$ = 218 ms, $\bar{X}_2$ = 171 ms).

As for the shoulder and elbow, the spatial dispersion of the wrist displacement was also observed as a function of the initial and corrective phase of the stylus displacement and practice. The variability of the wrist was the highest of the articulations, and was to decrease the most during training. However, for one subject the variability was observed to be increased after training. An ANOVA, similar to the one computed for the corresponding shoulder and elbow displacement data, was conducted on the mean spatial variability values of the wrist displacement. No significant main effects or interactions were observed ($\underline{p} > .05$). Figure 17 demonstrates a representative mean displacement trajectory for the two 'normal' subjects at the beginning (session 1 - block 2) and end of training (session 3 - block 19). Figure 18 presents the individual paths leading to these mean trajectories.

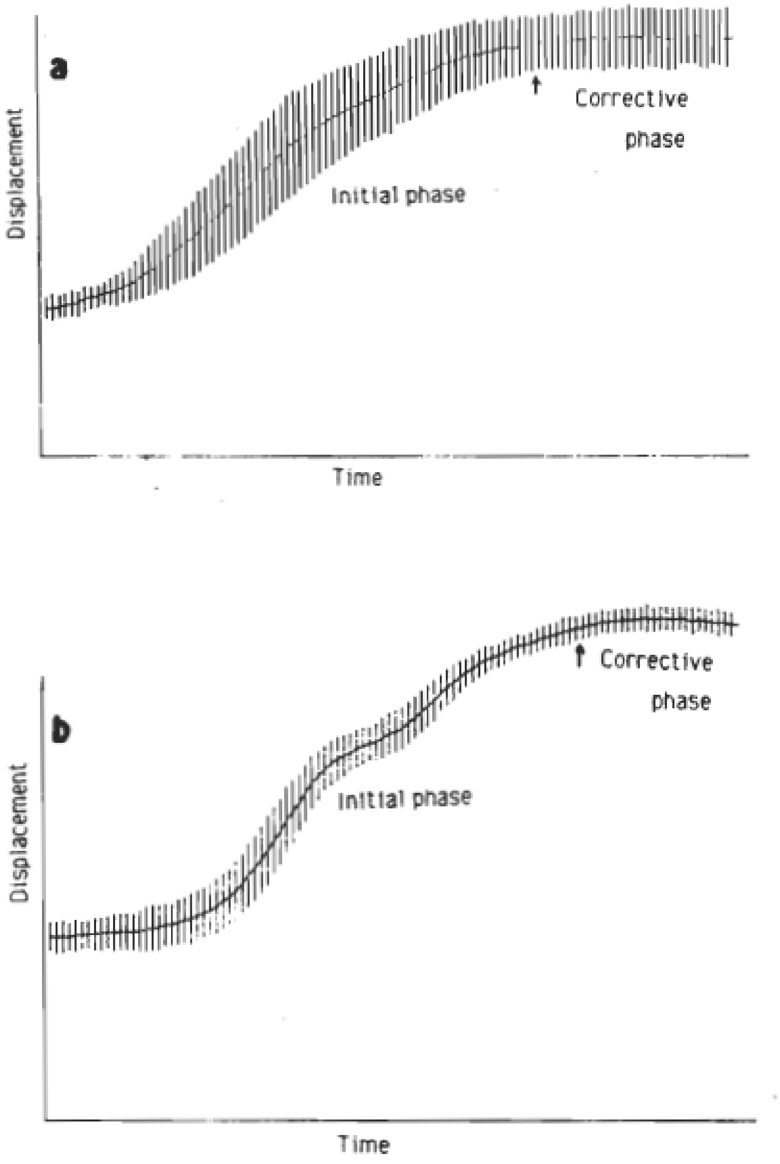

Figure 17. A representative mean displacement trajectory with dispersion of the wrist at the beginning of session 1(a) and at the end of session 3 (b) in the visual condition

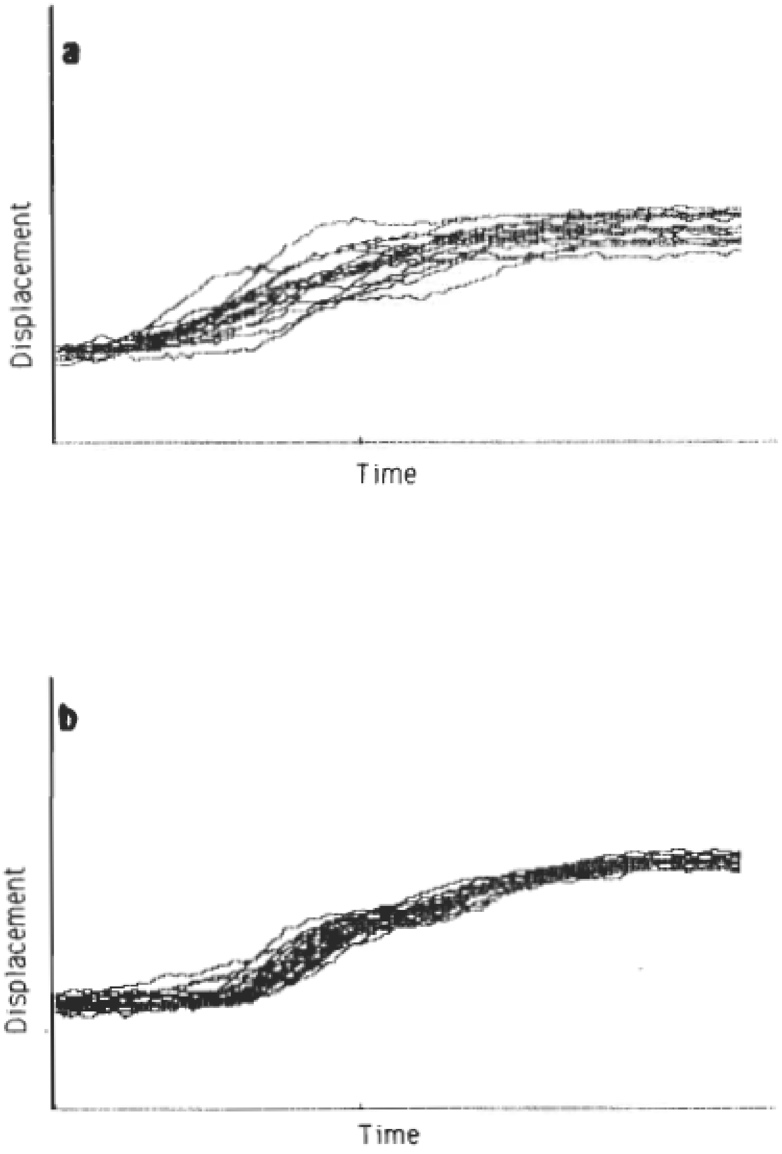

Figure 18. The individual paths attributing to the mean displacement trajectory of the wrist at the beginning of session 1(a) and at the end of session 3 (b) in the visual condition

As a complementary analysis, within-subject correlations were computed between the angle taken by the elbow and the wrist when the stylus touched the target or surrounding area. The mean value observed for each articulation for each of the 15 blocks of practice (blocks 4 to 18) were used to compute this analysis. Furthermore, the same analysis was computed for each session. As shown in Table 16 of Appendix B, rather high negative correlations, except for one subject, were attained, expressing the reactive nature of both segments. This means that some compensation must take place between the articulations in order to obtain the observed typical pattern of the stylus.

In conclusion, in contrast to the same general profile of the stylus, the movement patterns of the articulations showed individual differences. With practice, only the reponse profile of the wrist articulation reached a typical trajectory. That is, an initial acceleration and deceleration phase followed by a smaller acceleration and regular or irregular deceleration sequence. Within-subject correlations between elbow and wrist on the spatial endposition showed a relationship between the two articulations. The high negative correlation that was observed reflects the intensity of this functional interaction. For these latter articulations, no significant effects were observed for the time to peak acceleration and velocity, suggesting that from the beginning of training, some optimal time values were attained. However, these values showed a tendency to change during training, probably to optimize even more the cooperation of the articulations.

Visual feedback withdrawal effect

The data were subjected to a 3 (session) x 2 (condition - with or without visual feedback) completely within-subject factorial design, in order to investigate the effect of the visual manipulation. The movement patterns will be discussed for the beginning of practice (session 1 - block 3) and end of training (session 3 - block 20).

Stylus

Concerning the stylus in the vertical plane, a typical acceleration profile for the beginning of session1 in the no-vision condition is displayed in Figure 19. The movement patterns when aiming in the dark, look remarkably similar to the acceleration pattern when aiming with lights-on in session 1 - block 2 (see Figure 2). Here again, the acceleration profile marks an initial acceleration phase, with peak acceleration and velocity arriving at mean times of respectively 112 ± 35 ms and 153 ± 31 ms, followed by the deceleration segment of the curvature. A second acceleration was initiated at a mean time of 361 ± 25 ms, that is when 66% of the movement time was completed. The re-acceleration had its peak value at a mean time of 464 ± 37 ms.

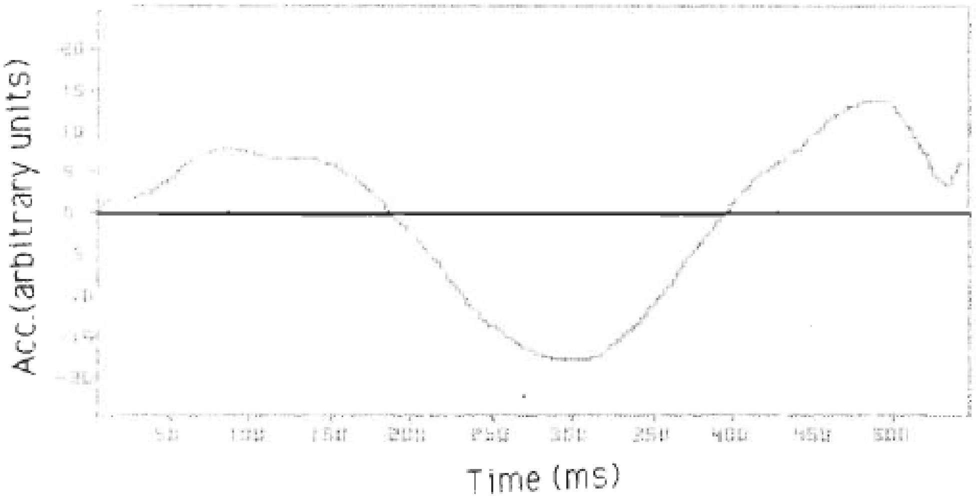

Figure 19. A typical acceleration pattern of the stylus in the vertical dimension at the beginning of session 1 in the no- visual condition

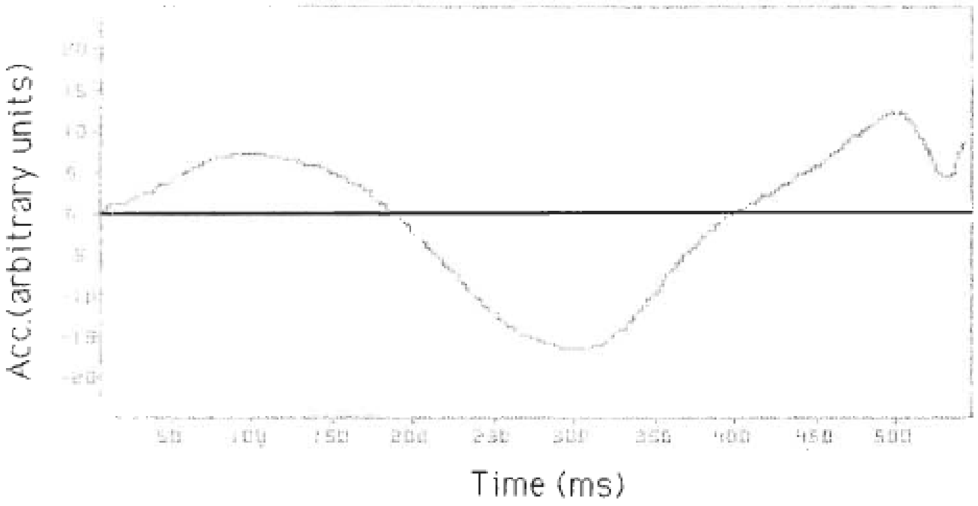

Figure 20. A typical acceleration pattern for the stylus in the vertical dimension at the end of session 3 in the no- visual condition

When aiming in the dark, training with visual feedback left the general form of the movement pattern practically intact. Tables 13, 14 and 15 of Appendix B demonstrate time to peak acceleration 1, re-acceleration and peak acceleration 2 with associated standard deviations for three subjects during the beginning (block 3) and end (block 20) of the practice sessions in the no-visual condition.

As shown in Figure 20, the acceleration profile at the end of session 3 in the lights-off situation revealed the initial sequence, peak acceleration and velocity arriving at a somewhat faster time compared to early practice in session 1, that is at mean times of 92 ± 14 ms and 151 ± 27 ms respectively. The re-acceleration near the target was initiated later in time compared to the beginning of session 1, that is at a mean time of 404 ± 24 ms, or when 73% of the target time being completed. Peak acceleration also arrived at a later mean time , compared to early in learning, that is at a mean time of 526 ± 3 ms.

The ANOVA's conducted on all the relevant time locations did not reveal any significant main effects or interactions (p > .05) suggesting that training does not significantly affect the time values of the stylus in the vertical dimension. Furthermore, the movement pattern is left unchanged even if vision of the performing arm is not permitted.

Concerning the stylus in the horizontal dimension, the acceleration profiles for the beginning of session 1 in the no-vision condition are demonstrated in Figure 21. As with the profile in the vertical dimension,

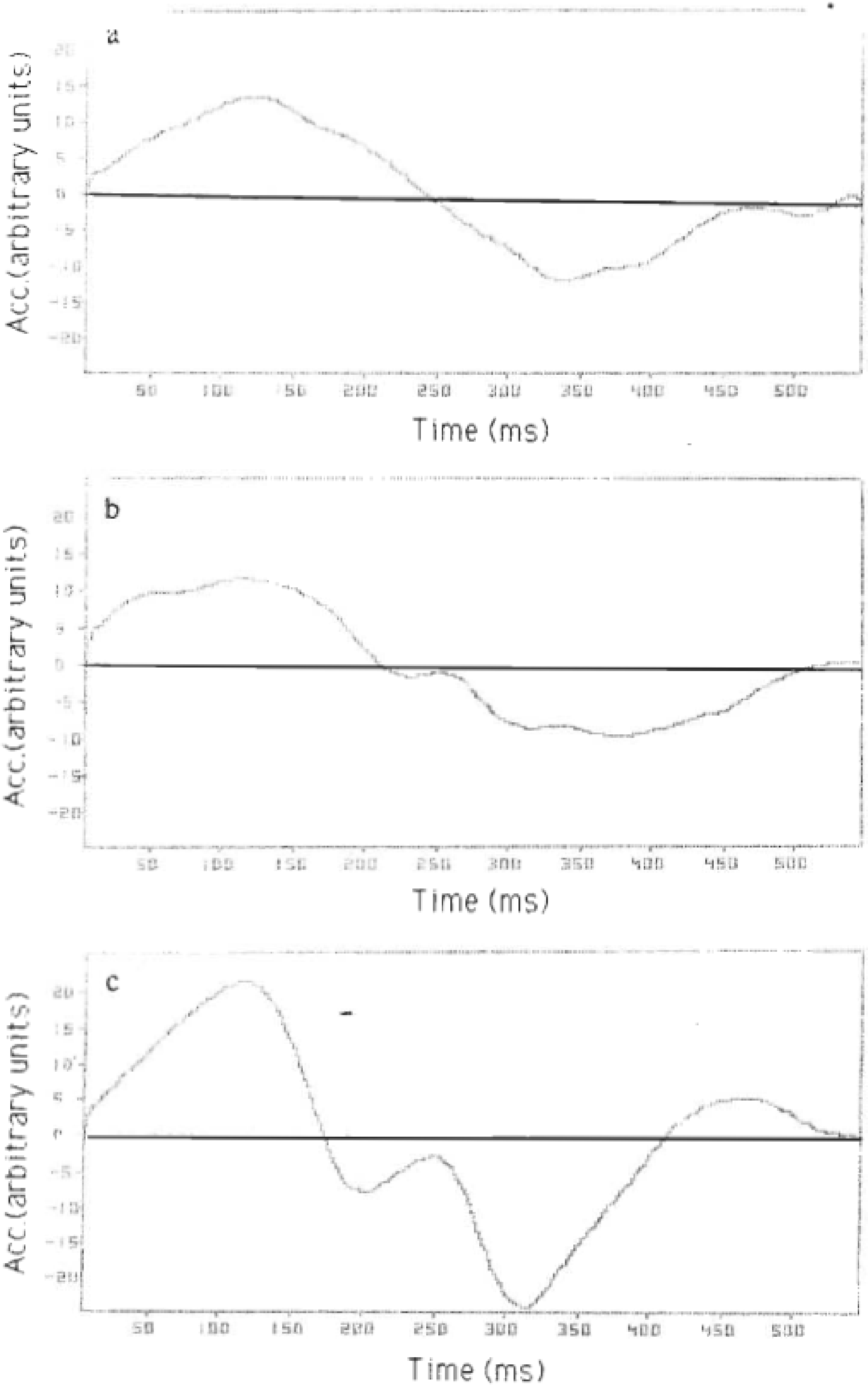

Figure 21. An acceleration pattern of the stylus in the horizontal dimension with irregular deceleration (a), smooth deceleration(b) and re-acceleration (c) at the beginning of session 1 in the no-visual condition

the form of the acceleration pattern in the no-vision condition in session 1 - block 3 (Figure 21) is very like the one in the vision condition in session 1 - block 2 (see Figure 4). The acceleration pattern shows an acceleration portion, peak acceleration and velocity occurring at mean times of respectively 157 ± 46 ms and 258 ± 38 ms. The deceleration phase was characterized by a distinct change in its curvature (74% of the responses, see Figure 21a) occurring at a mean time of 497 ± 9 ms, a smooth approach to the target (12% of the responses, see Figure 21b) or a second acceleration (14% of the responses, see Figure 21c) arriving at approximately 445 ms followed the deceleration segment.

Practice with visual feedback available from the moving arm, did not show much difference from the movement pattern of performing in the dark during the blocks 3 and 20 of each session. The acceleration pattern, at the end of session 3 in the no-vision situation demonstrates the acceleration phase, with peak acceleration and velocity arriving at mean times of respectively 158 ± 28 ms and 279 ± 40 ms. Following this, as shown in Figure 22, is the deceleration portion marked by a smooth approach to the target (83% of the responses, see Figure 22a) or a distinct change (17% of the responses, see Figure 22b) occurring at approximately 495 ms characterized this segment.

The analysis of variance carried out on the kinematic measurements revealed no significant effects or interactions ($\underline{p} > .05$), suggesting that the experimental manipulations did not significantly affect the time to peak acceleration and velocity for the stylus in the horizontal dimension.

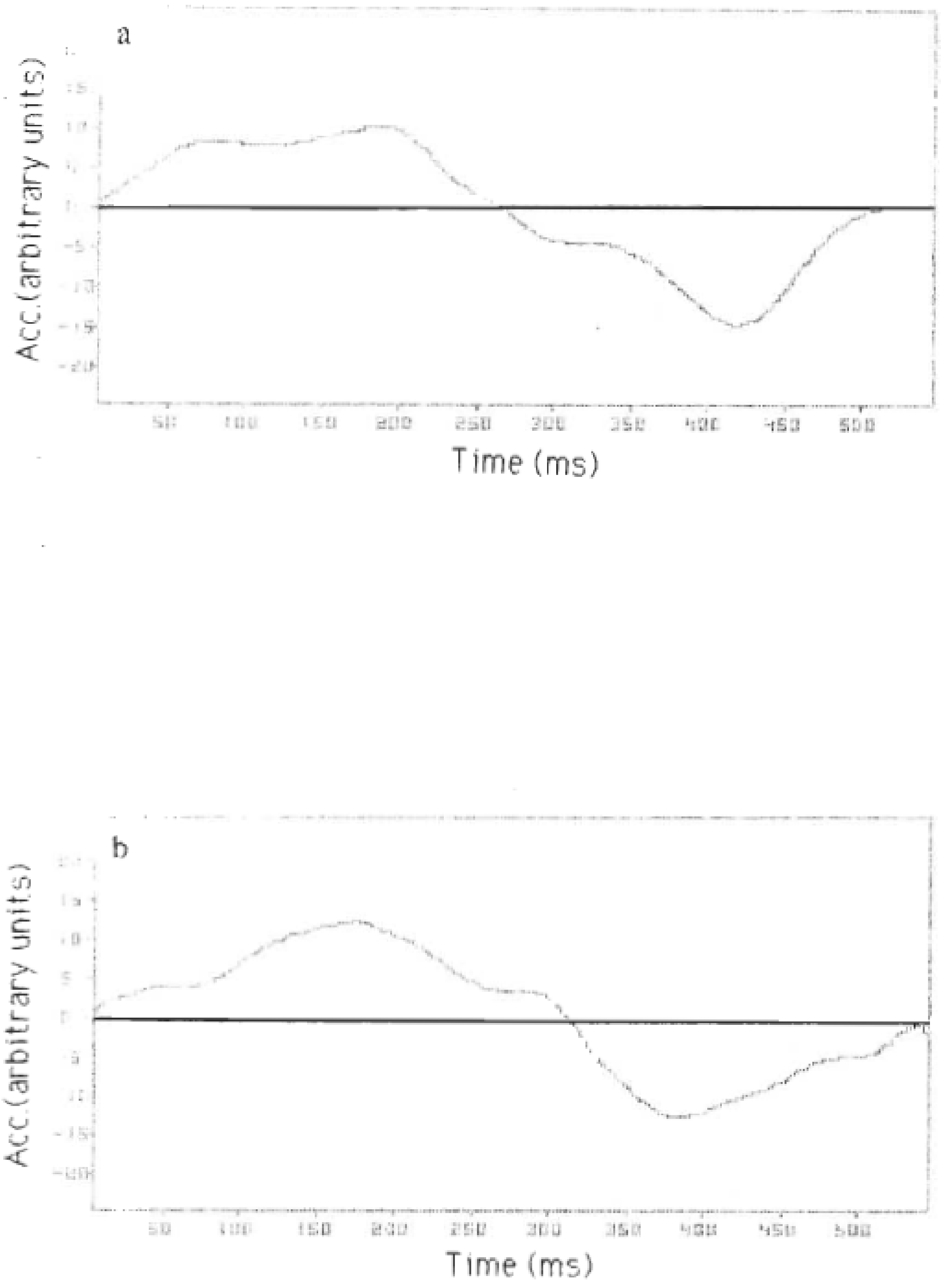

Figure 22. An acceleration pattern of the stylus in the horizontal dimension with smooth deceleration (a) and irregular deceleration (b) at the end of session 3 in the no-visual condition

In conclusion, executing the discrete movement in the dark revealed the same training effect for the movement pattern of the stylus on the horizontal place, as when performing with vision available from the moving arm. That is, at the beginning of learning most of the responses (74%) were marked by an abrupt change in the deceleration phase, where with practice most of the responses (83%), were characterized by a smooth approach to the visible target. For the movement pattern of the stylus in the vertical plane, the same characteristics were observed as when executing the movement with visual feedback available. Firstly, after the initial acceleration and deceleration phase, a re-acceleration occurred towards the target. Secondly, with practice, the initiation of this re-acceleration shifted in time from 66% to 73% of the elapsed time. Thirdly, with training, the peak value of this re-acceleration arrived later in time, and the standard deviation associated with this value diminished a great deal as learning progressed. The withdrawal of vision does not seem to affect the action of the stylus, since we observed the same response profiles in the no-vision and vision condition. Nor were the time locations (time to peak acceleration 1, re-acceleration and peak acceleration 2) significantly affected. Now, it can be asked how aiming in the dark will influence the reponse profiles of the articulations. The results of the examination of that particular issue follow.

Shoulder

A typical profile, for the beginning of session 1 in the lights-off condition, is presented in Figure 23. Comparing the movement pattern of performing with lights- on or off, respectively block 2 (see Figure 6) and 3 of session 1 (Figure 23), we observe that the general movement pattern persists when aiming in the dark. The acceleration profile reveals the acceleration, peak acceleration and velocity arriving at mean times of 82 ± 17 ms and 229 ± 21 ms respectively, followed by the irregular deceleration phase.

Practice with visual feedback did very little to change the typical form of the movement profile. As shown in Figure 24, at the end of session 3 in the no-vision situation, acceleration and velocity attain their maximal values at respective mean times of 102 ± 45 ms and 304 ± 93 ms.

Although for the shoulder articulation, peak acceleration and velocity differed during practice and visual conditions, no significant main effects or interactions were observed ($p > .05$).

Spatial variability was also observed in the no-vision condition. A 2 (moment; beginning or end of practice) x 2 (phase; initial or corrective phase) x 2 (condition; with or without visual feedback) experimental design was conducted. No main effects or interactions were found to be significant, ($p > .05$). Figure 25 demonstrates a representative mean displacement trajectory with dispersion at the beginning of session 1

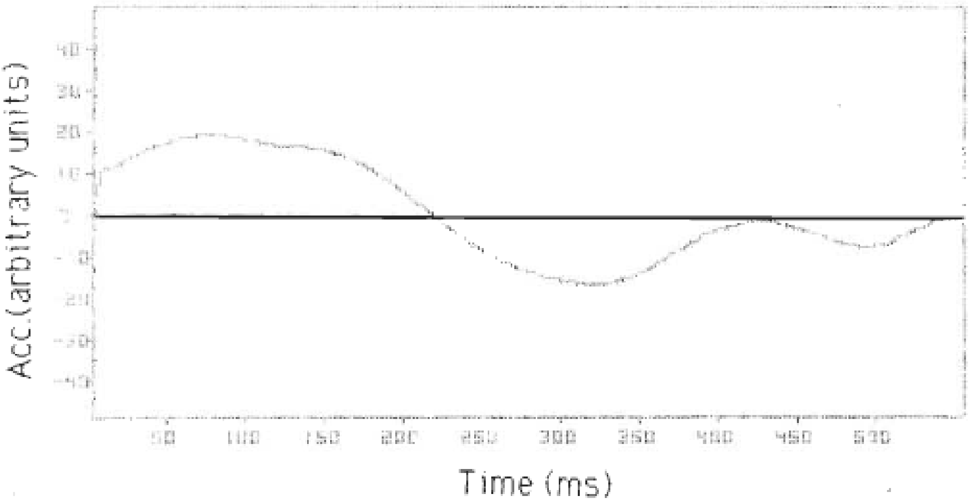

Figure 23. A typical acceleration pattern of the shoulder at the beginning of session 1 in the no-visual condition

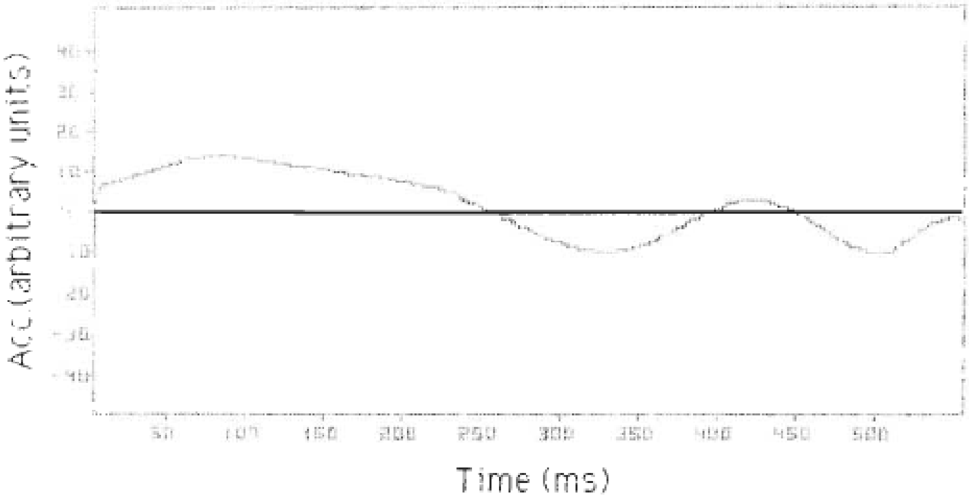

Figure 24. A typical acceleration pattern of the shoulder at the end of session 3 in the no-visual condition

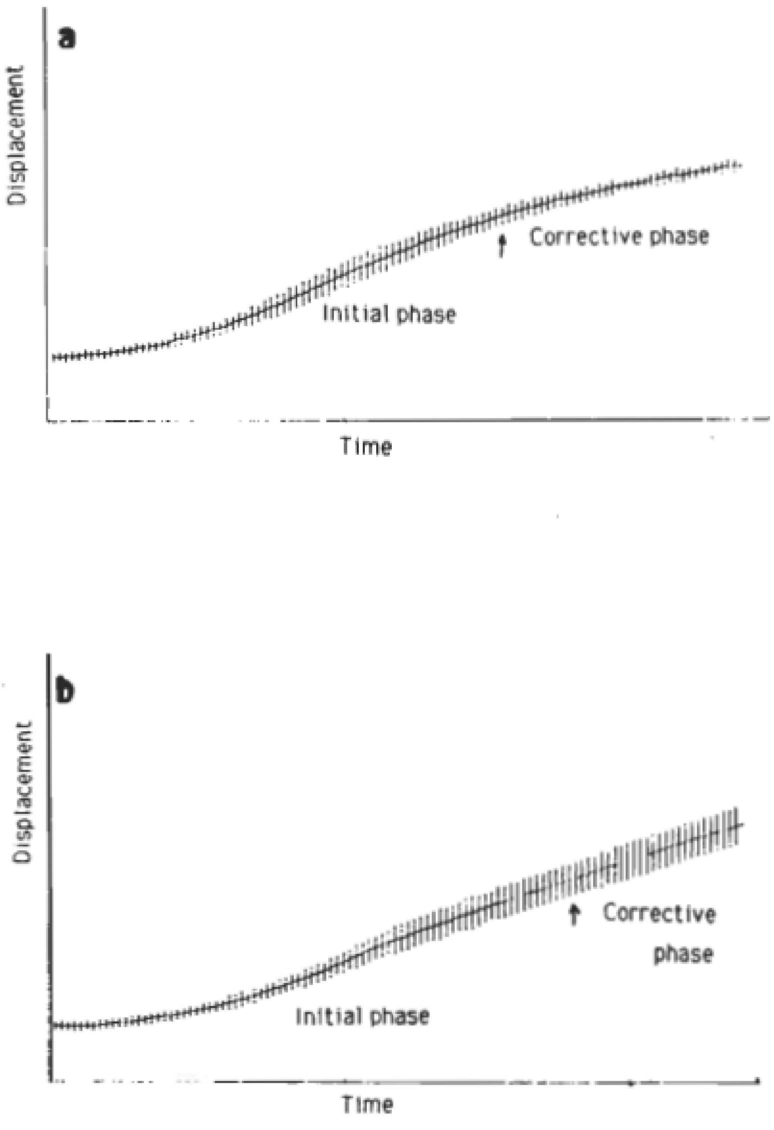

Figure 25. A representative mean displacement trajectory with dispersion of the shoulder at the beginning of session 1(a) and at the end of session 3 (b) in the no-visual condition

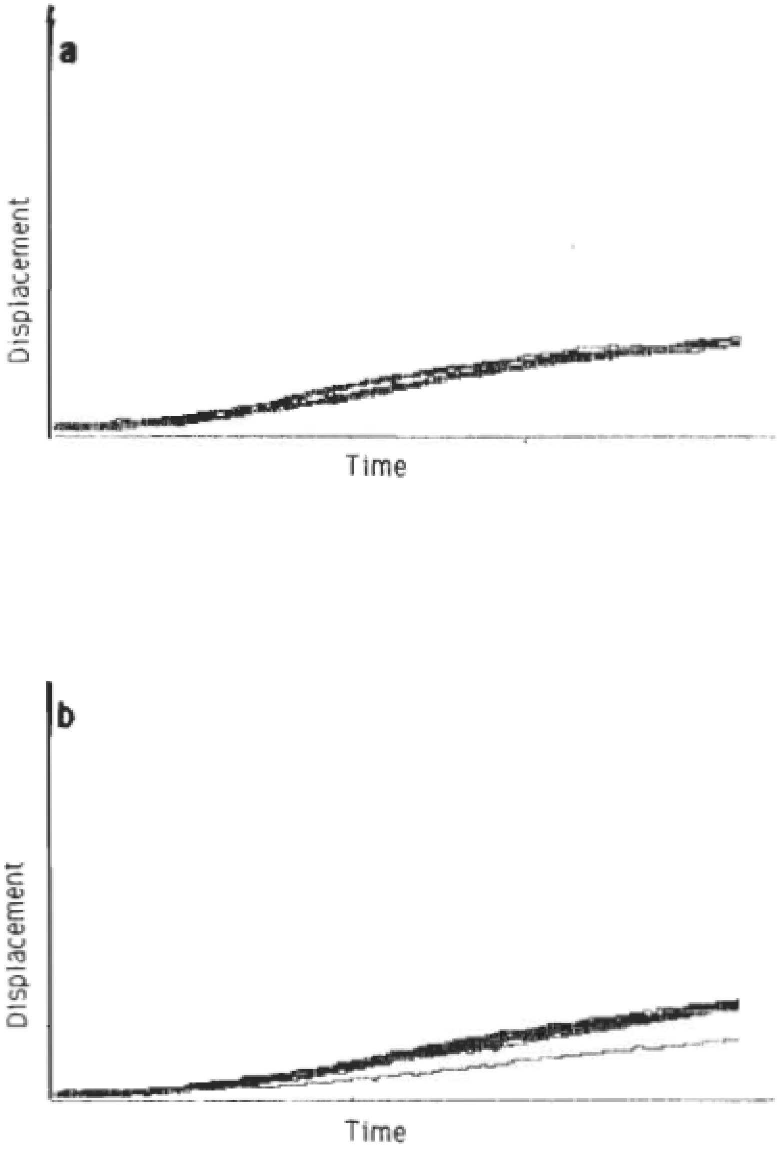

Figure 26. The individual paths attributing to the mean displacement trajectory of the shoulder at the beginning of session 1(a) and at the end of session 3 (b) in the no-visual condition

(block 3) and the end of session 3 (block 20). Figure 26 presents the individual paths of these mean trajectories.

Elbow

A representative example of the acceleration pattern, at the beginning of session 1 in the no visual feedback condition, is shown in Figure 27. Comparing the kinematic variables of aiming in the visual (see Figure 10) and no-visual conditions (Figure 27), we observe that the profiles are almost alike in their behavior. The acceleration profile in the no-vision condition reveals an acceleration phase, peak acceleration and velocity arriving at mean times of 224 ± 68 ms and 342 ± 18 ms respectively. Following is the corresponding deceleration sequence.

Trials with visual feedback availability did not change the acceleration pattern very much. As shown in Figure 28, at the end of session 3 in the lights-off condition, the long acceleration phase had its peak value and velocity arriving at mean times of 231 ± 70 ms and 358 ± 34 ms respectively. Following was the deceleration segment.

Although for the elbow articulation, the time to peak acceleration and velocity had small differences throughout training, depending upon the visual condition, no significant effects or interactions attained the level of significance ($\underline{p} > .05$).

The spatial variability of the elbow's displacement was examined. No significant main effects or interactions reached the level of significance ($\underline{p} > .05$). Figure 29 displays a representative example of a

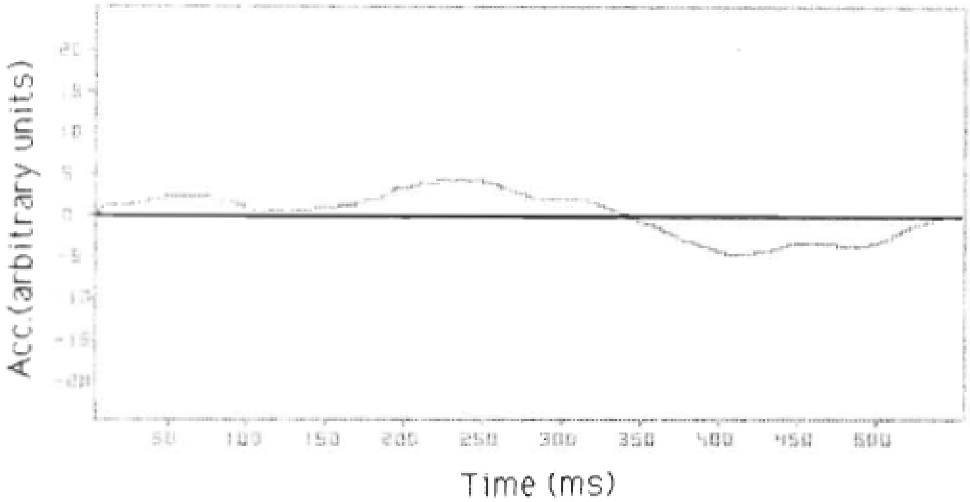

Figure 27. A typical acceleration pattern of the elbow at the beginning of session 1 in the no-visual condition

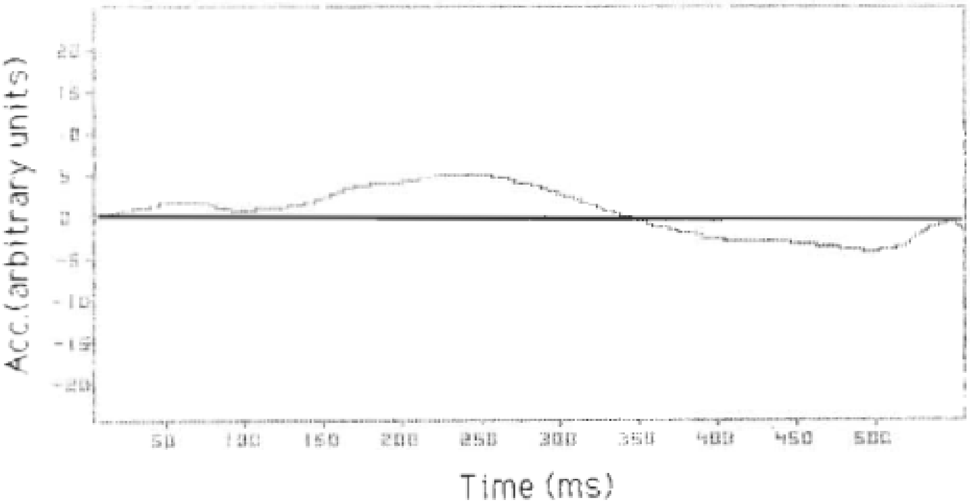

Figure 28. A typical acceleration pattern of the elbow at the end of session 3 in the no-visual condition

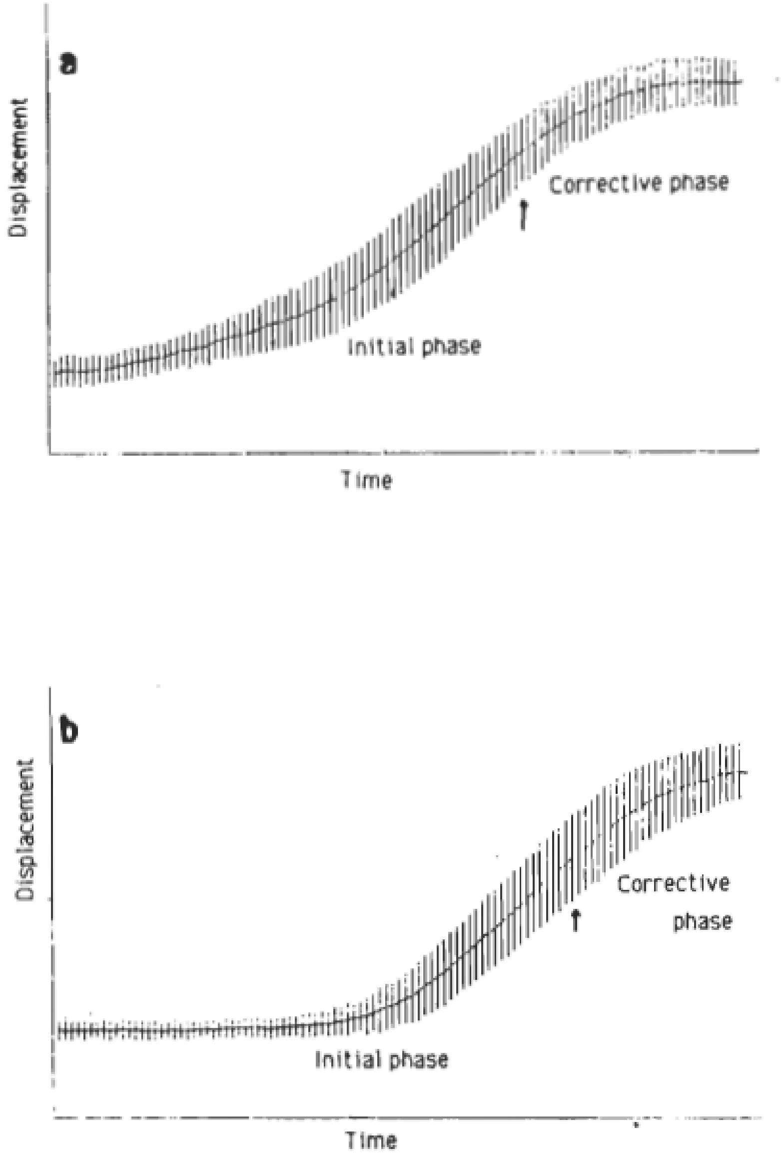

Figure 29. A representative mean displacement trajectory with dispersion of the elbow at the beginning of session 1 (a) and at the end of session 3 (b) in the no visual condition

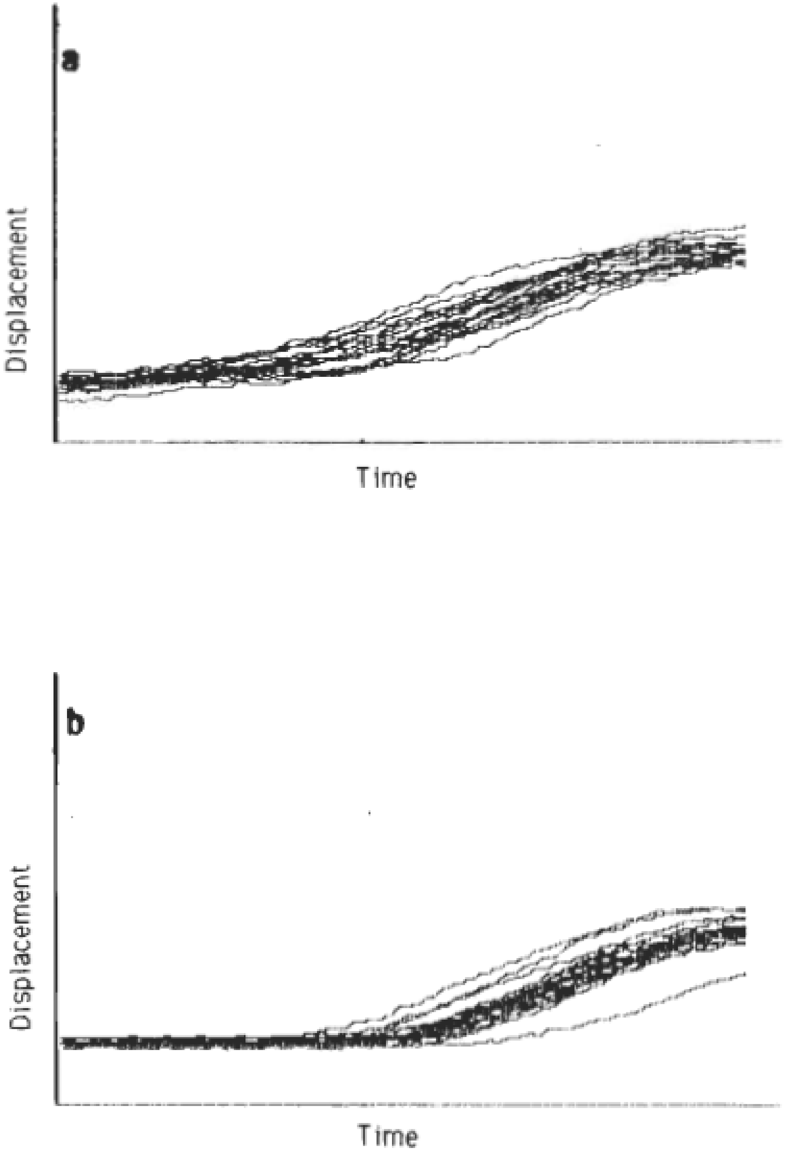

Figure 30. The individual paths attributing to the mean displacement trajectory of the elbow at the beginning of session 1(a) and at the end of session 3 (b) in the no-visual condition

mean displacement trajectory with dispersion for the beginning of session 1 (block 3) and end of session 3 (block 20). Figure 30 demonstrates the individual trials attributing to these mean patterns.

Wrist

As when aiming with lights-on (see Figures 14 and 15), executing the discrete movement in the no-vision condition means that there are a lot of inter-subject variations for the motion of the wrist. The acceleration pattern of the wrist for all the subjects, in the beginning of session 1 in the no-vision condition, is demonstrated in Figure 31 and 32. The movement pattern reveals irregular features during the acceleration and especially the deceleration portion of the path. Peak acceleration and velocity occurred at mean times of 123 ± 54 ms and 200 ± 57 ms respectively.

Training with visual feedback availability brought some changes to the movement profiles, so that the kinematic behavior could be divided into two groups. These two distinct features are well presented in the acceleration patterns, as shown in Figure 33. At the end of session 3 in the visual feedback withdrawal condition, the movement pattern reveals an initial acceleration, peak acceleration and velocity occurring at mean times of 116 ± 41 ms and 198 ± 55 ms respectively. Following is an irregular deceleration phase (Figure 33a), or a second acceleration (Figure 33b) at approximately 300 ms, with a smooth approach to the target taking place after this latter sequence.

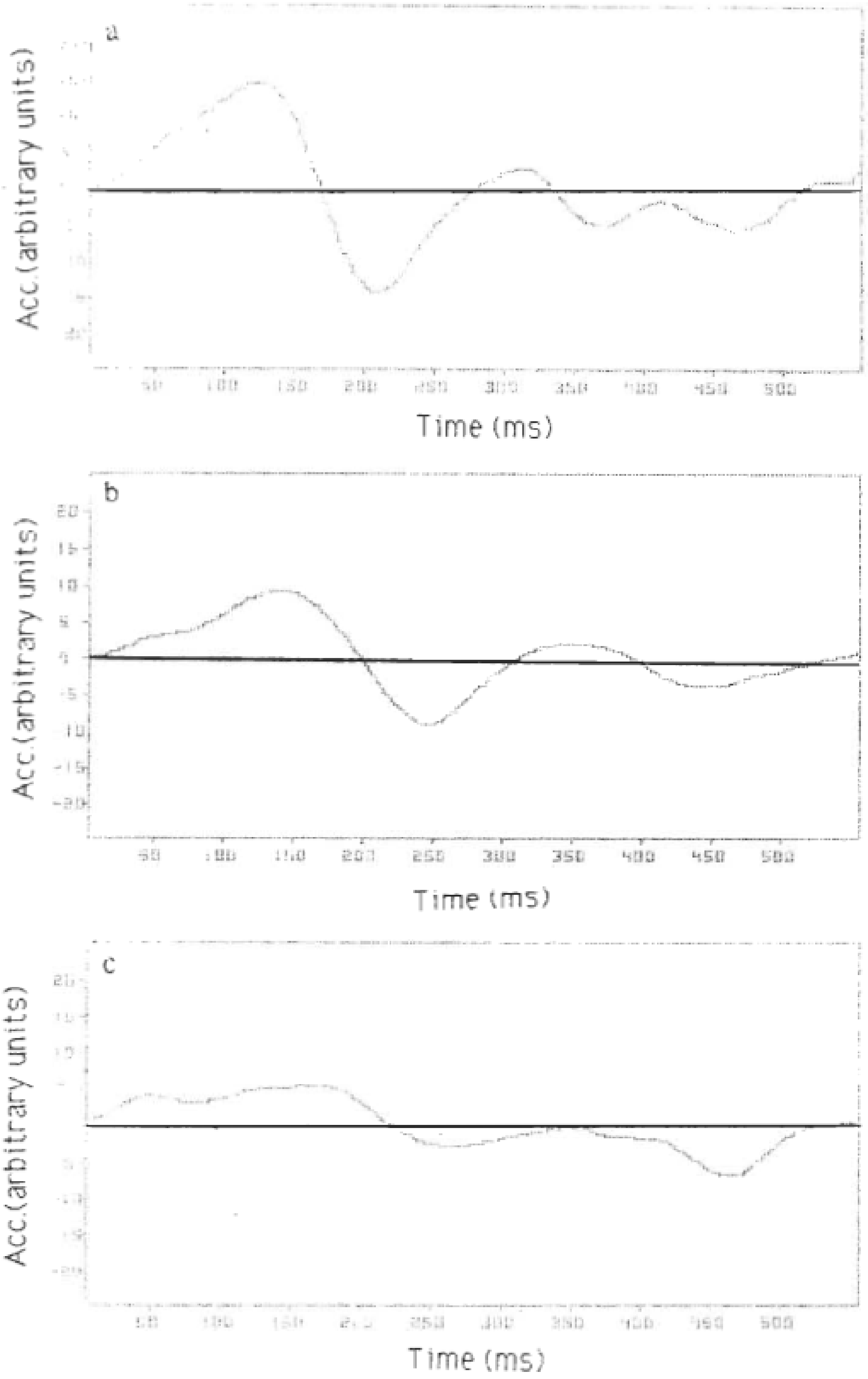

Figure 31. The acceleration pattern of the wrist for subject 1(a), subject 2 (b) and subject 3 (c) at the beginning of session 1 in the no-visual condition

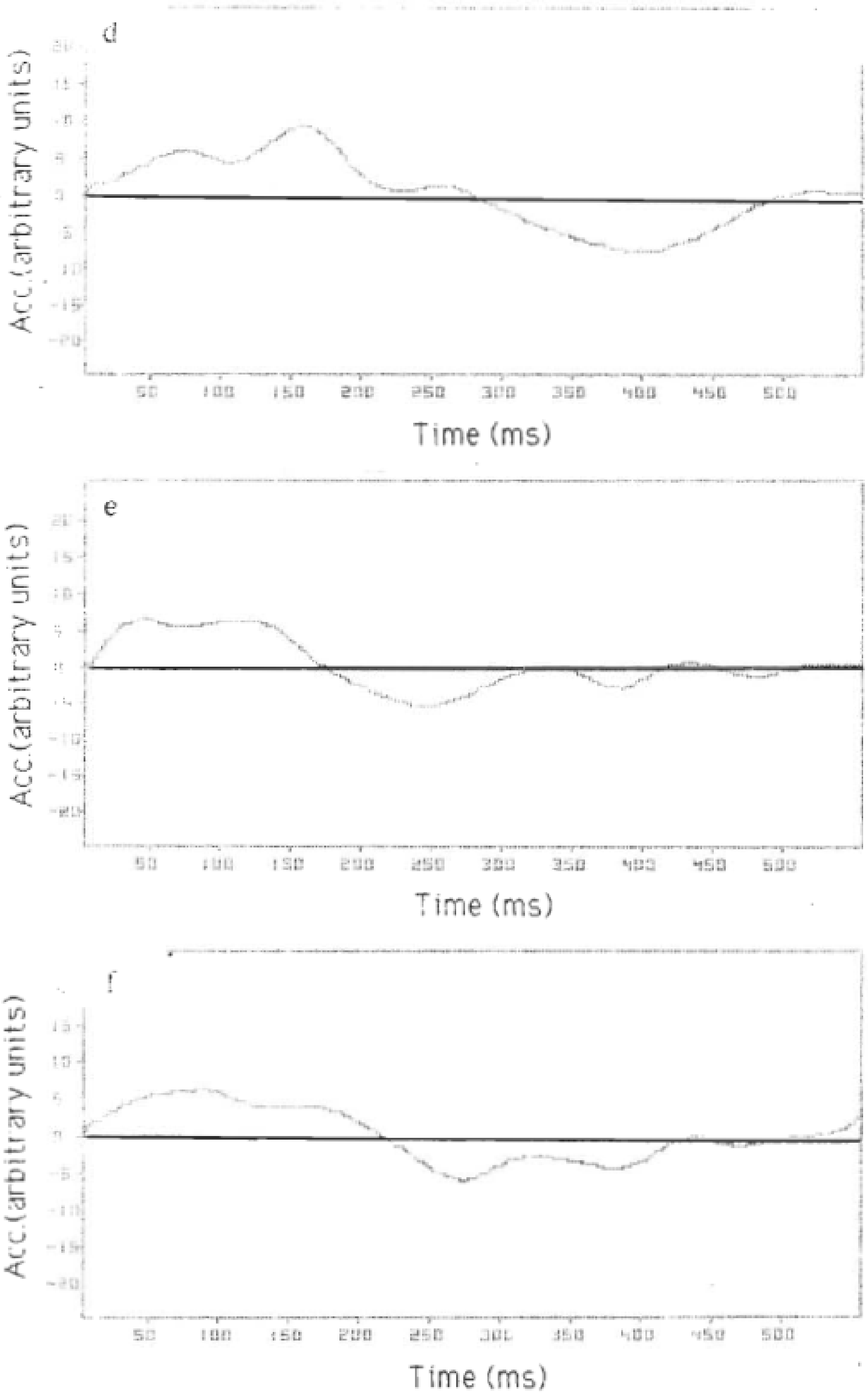

Figure 32. The acceleration pattern of the wrist for subject 4 (d), subject 5 (e) and subject 6 (f) at the beginning of session 1 in the no-visual condition

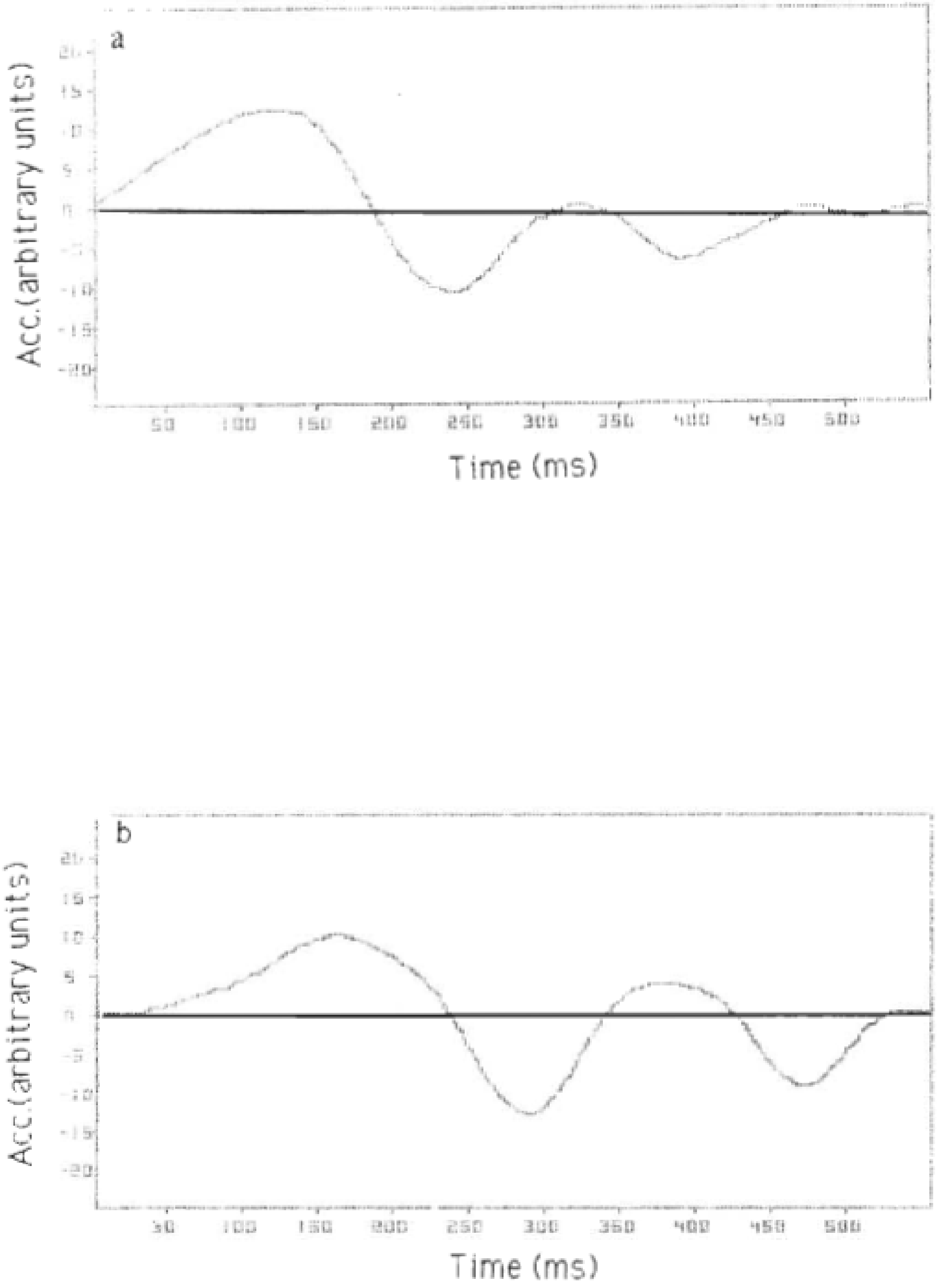

Figure 33. An acceleration pattern of the wrist with irregular deceleration (a) and re-acceleration (b) at the end of session 3 in the no-visual condition

For the wrist articulation, practice and the no-visiual condition brought some differences in the time to reach the maximum value of acceleration and velocity. However, no significant main effects or interactions were observed ($\underline{p} > .05$).

Spatial variability was also investigated for the wrist articulation. No main effects or interactions reached the level of significance ($\underline{p} > .05$). Figure 34 represents a mean displacement trajectory with variability for three subjects at the beginning of training (session 1 - block 3) and end of practice (session 3 - block 20). Figure 35 demonstrates the individual trials associated with these mean trajectories.

As a complementary analysis, within-subject correlations were computed between the angle taken by the elbow and the wrist when the stylus touched the target or surrounding area in the no-vision condition (block 3 and 20 of each session) and compared to the vision condition (block 2 and 19 of each session). As shown in Table 17 of Appendix B, the elbow-wrist correlations in the lights-off condition are also negative (except subject 1), and smaller compared to the visual condition. A t-test on the correlation coefficient (excluding subject 1) revealed that a significant effect, $\underline{t} = - 5.5$ ($\underline{p} < .05$, one -tailed). This means that the reactive nature of the elbow and wrist will be smaller in the no-visual condition.

As in the visual condition, inter-subject variations persist in the trajectories of the articulations. With training, only the profile of

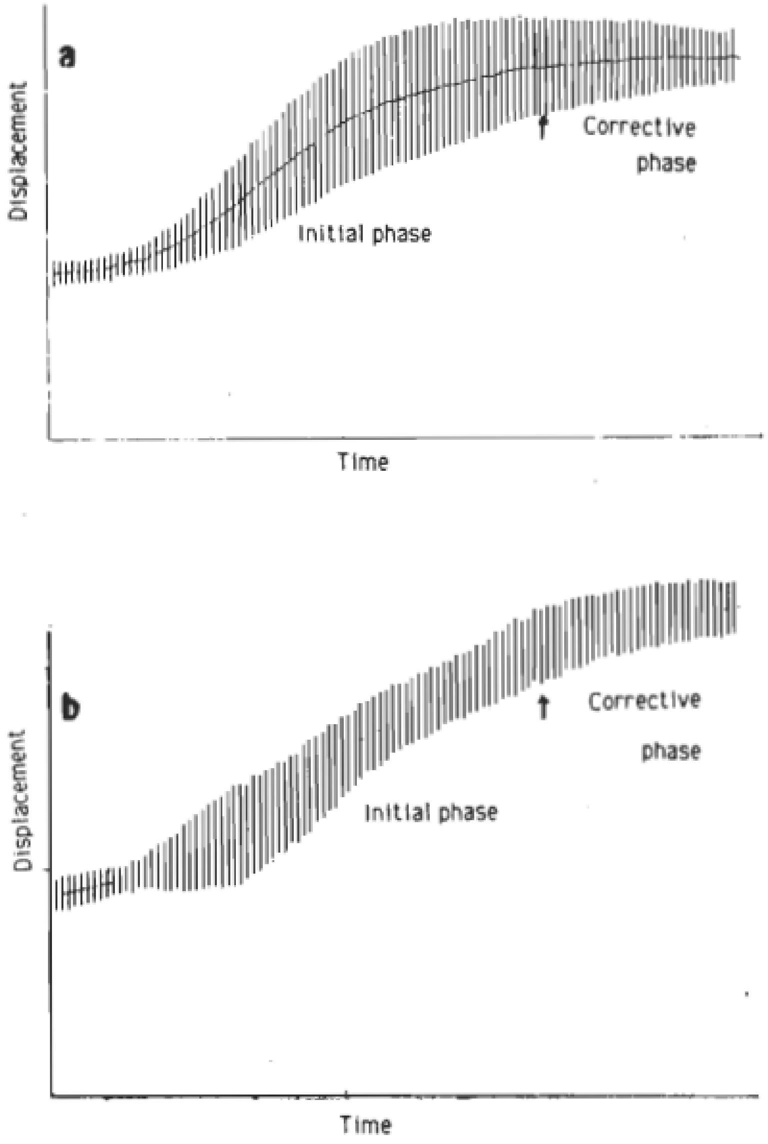

Figure 34. A representative mean displacement trajectory with dispersion of the wrist at the beginning of session 1(a) and the end of session 3 (b) in the no-visual condition

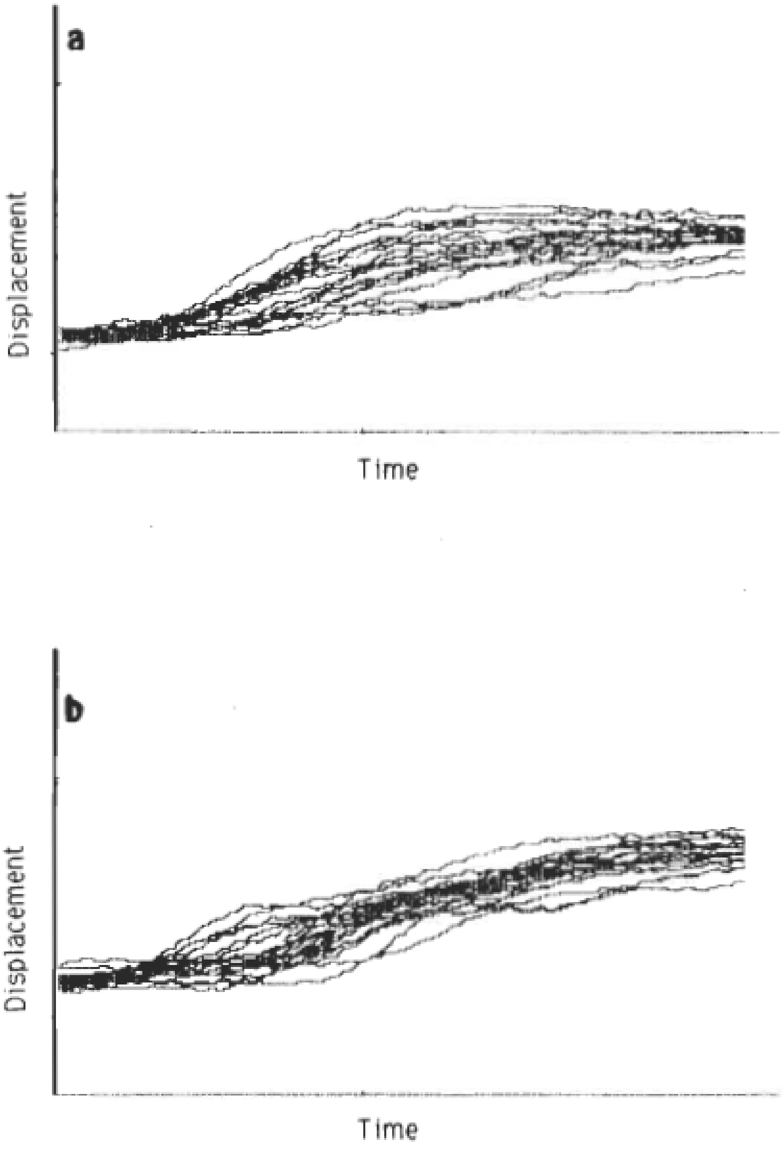

Figure 35. The individual paths attributing to the mean displacement trajectory of the wrist at the beginning of session 1(a) and at the end of session 3 (b) in the no-visual condition

the wrist will outline a more typical path. That is, an initial acceleration is followed by an irregular deceleration, or else a re-acceleration appears at the end of the movements' execution. No significant effects were noted in terms of the visual manipulation, suggesting that wether or not there is visual feedback from the moving arm, this does not affect the time locations for the articulations or stylus during the execution of the aiming movement. However, smaller within-subject correlations were observed in the no-visual condition suggesting that visual information is a main contributor to the cooperative correlation found between elbow and wrist.

CHAPTER V

Discussion

The main feature of our approach was to combine the behavioral measures of the aiming movements' outcome with a kinematic analysis of the movement patterns, in order to gain greater insight into how the central nervous system plans and controls a discrete movement.

Our major interest was to examine whether modifications in the mode of control, during the execution of an aiming task, occurred as practice increased. Two possibilities were proposed. Firstly, it was proposed that early in learning , the initial impulse is very variable, and as a result the subject has a lot of difficulty in making a visually based correction. However, as training increases, the variability of the first impulse may decrease. This would enable the individual to predict where and when a correction might be needed and realized. This proposition would be supported if (a) early in training, the aiming response is executed without corrections and is very variable and (b)_ late in practice, a correction is made whilst the first submovement remains "constant". An alternative possibility would be that the visual processing time decreases with training. That is, the subject becomes more efficient in using the visual feedback information. As a consequence, as practice increases, the corrective phase shifts closer to the target whilst the initial impulse increases without being more variable. This second proposition would be supported if it could be demonstrated that a corrective phase occurs, even in early practice, and if this sequence is initiated closer to the target as training progresses.

Our results support the second proposition, since a corrective phase was observed for the stylus even in the beginning of learning. As practice increased, there was a trend for this latter phase to occur later in time, so that a correction based on available feedback was made when the stylus was in close proximity to the target. Furthermore, it was shown that the variability of the first submovement does not change with training, suggesting that the correction was made more efficiently with practice. The latter point was well supported by the fact that the accuracy improved as training increased.

Spatial and temporal aspects of a motor program

The concept that motor programs contain both invariant and variant features is a central aspect of the motor program hypothesis (e.g. Pew,1974; Schmidt,1975,1982). These authors have proposed that phasing (temporal relationships) of a movement is an invariant property of the movement pattern, and hence an invariant feature of motor programs. In other words, MT is generated by a central pattern (except reflexes) and this pattern remains uninfluenced by feedback control.

The results obtained in this thesis confirm the lack of influence of visual feedback on movement duration, and its importance for spatial accuracy. Once again, this difference may be brought forward by separating the aspects of a discrete movement which are dependent upon visual feedback information from those which are not. Performing a discrete movement to a defined target, without the access of visual information from the moving arm, means that the action must be highly programmed. That is, movement requirements must be translated into a (precise) movement pattern which can not be modified on course based on visual feedback. Certainly, some programmed details can be accurately retained throughout the movement performed in the dark, but a limit must exist in the translation mechanism (Jeannerod, 1981). One important point of interest in the arrangement at the programming level is that the temporal aspects are kept independent from the spatial parameters of the movement (e.g. Bernstein,1967; Arbib,1980). This leads to the suggestion that timing is not affected by the withdrawal of visual feedback. However, the data from the present experiment demonstrate that visual information needs to be incorporated during the trajectory in order to improve precision. Even after a lot of practice, reproducing a movement pattern based on proprioception deteriorates response accuracy. This observation contradicts Stubbs (1976) assumption that the position of the hand is well known from the proprioceptive and kinesthetic receptors. It supports, however, the results from Carlton (1981) that for the terminal accuracy of discrete aiming movements, it is important to visually determine the position of the stylus and the hand.

Control process used in the visual and no-visual condition

Woodworth (1899) formulated several conclusions about the nature of the control process used during the execution of an aimed movement. He suggested that a discrete response consisted of two distinct components: an initial ballistic submovement followed by a control phase. This latter control phase, in contrast to the initial programmed segment, occurs late in movement and corrects errors in order to optimize the terminal accuracy. Woodworth speculated on the contribution of visual feedback to the correction process from a deterioration of movement performance when aiming in the dark.

We have come a long way since Woodworth's observations. However, the intial statements of this pioneer about the important role of vision in movement control are still generally accepted and have been more fully developped throughout the years. Crossman and Goodeve (1963/1983) and Keele (1968) have proposed that an aimed movement is composed of a series of submovements, each of about the same duration and relative accuracy, serving to correct errors until the desired precision is attained. Carlton (1979, 1980,1981) examined the discrete corrections theory by analyzing the movement patterns produced in the execution of aiming movements.

Movement displacement, velocity and acceleration were observed in order to understand more about the control processes employed in those movements. A discrete visual corrections theory was supported since the response profiles were discontinuous in nature. That is, movements were made up of an initial sequence having an acceleration, as the stylus left the starting position, and a deceleration as the stylus approached the target. This latter phase was followed a re-acceleration, or a distinct change in the deceleration pattern, towards the target. Carlton claimed that the visual information, processed near the end of the initial response, was used to make one or more discrete corrections if the accuracy demands were stringent. The observed re-acceleration at the end of a discrete movement has been attributed to a corrective impulse based on visual feedback information. Our results do not support this statement, or that for prehension movements (Jeannerod, 1981), since the correction was also observed in the absence of vision of the hand. This correction-control system is in agreement with Prablanc, Pélisson and Goodale (1986), Pélisson, Prablanc, Goodale and Jeannerod (1986), and Goodale, Pélisson and Prablanc (submitted for publication) who hypothesized that during aiming movements in the dark, with the target visible, corrections are being made during its execution. These authors proposed that the visual feedback available from the target (by an internal representation) is compared with non-visual information from the moving arm-hand, and this error information is used to control and correct the movement during its execution. However, as shown in the present thesis, the effectiveness of these corrections is inferior to those realized on the basis of visual information about the moving limb.

The suggestion that re-acceleration at the end of the hand trajectory is a corrective phase has been proposed based on comparison with the control mechanism of eye responses. For saccadic eye movements, the initial saccade is followed by a corrective second saccade to eliminate error due to the inaccuracy of the main response. Since there exists a tight coupling between the eye and arm, it can be suggested that a triggered command system releases a centrally patterned sequence of eye-head-arm movements which utilizes the same retinal error information (Herman, Herman & Manlucci,1981), leading to the assumption that there exists a common control mechanism for eye and hand movements (Carlton, 1981; Fisk & Goodale, 1985; Mather & Fisk,1985). Generating the commands for the different moving segments in parallel may have an important implication for the eye-hand coordination. In this context, several authors (e.g. Fisk & Goodale, 1985; Paillard, 1982; Prablanc et al.,1979) have demonstrated that the accuracy of an aiming movement with the target visible improves when one may move the head and eyes towards the target, meaning that foveal fixation of the visible target can provide important cues for the guidance of the arm. This proposition is well supported by the kinematic data, showing that vision only of the target enables the subject to correct the ongoing movement.

It should be noted that this common control mechanism does not mean that there are no functional differences between the oculo-motor and manual system. Although eye and hand latencies are correlated, (Biguer, Jeannerod & Prablanc, 1982; Prablanc et al.,1979), Gielen, Van der Heuvel and Van Gisbergen (1984) and Mather (1985) have shown that different timing mechanisms are involved for both movements. This difference in timing mechanism is in contrast to the spatial mechanism which was postulated to be similar for both systems.

Both types of movement show the same spatial characteristics. That is, an initial sequence (initial acceleration and deceleration) that falls short of the target is followed by a correction. It thus seems that the initial command, and a check on the trajectory of the aiming movement, are both pre-programmed (as already proposed for saccades; Becher and Fuchs, 1969). More specifically, the main response is pre-set to end short of the target. Information coming from this initial submovement is used to make a first approximation of the landing point. This information will be used with concurrent feedback to plan a corrective impulse. The efficiency of this correction will depend upon the availability of feedback sources. Since we predominantly rely on visual feedback while neglecting kinesthetic cues, it seems that under conditions where there is sufficient time to process visual feedback, visual information will be incorporated into the corrective phase, in order to improve precision. If no visual cues are available to guide the final phase, the corrective sequence may depend upon the kinesthetic modality as an alternate compensatory feedback channel in order to realize the final adjustments. However, proprioceptive information does not seem to update the initial centrally-determined movement with the same efficiency as do visual cues.

Visual feedback processing time and practice

Earlier in this discussion, it was mentioned that if their is enough time to process visual feedback, this information will be incorporated and analyzed in the terminal phase, to optimize terminal accuracy. This processing time aspect has long overshadowed the role of vision in the control of our motions, since it was postulated that the time for a visual feedback loop is much too long for this kind of information to be used effectively (e.g. Keele and Posner,1968; Woodworth, 1899). However, recent vision manipulation studies (Bard et al. 1985; Carlton, 1981a; Elliott & Allard, 1985; Hay & Beaubaton, 1985, 1986; Smith & Bowen, 1980; Zelaznik et al., 1983) have shown evidence that visual feedback can be used quite quickly, even early in practice, to make corrective responses. Now, it can be asked how practice will affect the visual processing time. Our results tend to support the suggestion that the time for a visual feedback loop diminishes with training. In agreement with Smyth (1977), it was shown that the break-point, where the corrective phase was initiated, shifted closer to the target as training progressed. That is, the turning-point increased from 66 to 73% of the elapsed time, thus increasing the initial programmed part of the movement. However, the shift in time can not be attributed to a process specific to the visual condition, since the same time increase was also observed in the non-visual condition. At the present time, our interpretation is that a motor program is developed taking into consideration the different sources of information that are available. As practice increases, the initial program is modified to reach some optimal characteristics. If the visually used information is for any reason not available, the motor program retains its characteristics. To better understand the role of the different feedback sources, it would be useful to check whether a motor program having different features would have been developed if the training had taken place without vision of the performing limb. . However, this was beyond the scope of the present thesis.

A mean time of 402 ms for the corrective phase to be initiated was observed, leaving about 150 ms or less for a visual feedback loop to be processed, assuming that this information really is analyzed. This can be accepted, since performances with vision of the moving arm were always more accurate than those not having this information. These results support the notion that the visual processing time is much faster than originally thought. As a consequence, considering the short latency associated with the analysis of the information of this superior modality, it is not surprising that the visual cues were still used, late in training, to correct the ongoing movement.

Coordinative structures

The execution of the aimed response in our experiment required the joint regulation of the shoulder, elbow and wrist articulation. It can be proposed (Leroux, 1986) that it is the shoulder that directs the arm in the desired direction and location. This is supported by the low variability values found on the displacement curves of that articulation. Furthermore, the action of the elbow and wrist only become important as the movement progresses, with the interplay between these two articulations determining the spatial precision.

Concerning this latter point, it must be noted that since there are many independent and alternative ways of executing a specific discrete action, the components involved must be highy controlled and coordinated in order to obtain a level of accuracy, since different spatial and temporal constraints are imposed on each component. However, controlling each component separately with the specification of each complex movement detail, does not seem to be an efficient control process and would probably provoke an overload situation for the central nervous system. Rather, a coupling process of the individual components attributing to the movement is organized (e.g. Turvey, 1977). The idea that the central nervous system determines a functional grouping or coordinative structures to attain a specific objective stems originally from Bernstein (1967). The creation of the coordinative structures for attaining a goal would further be responsible for specifying the details of the movement so that the complete action is well coordinated. In this way, the movement elements function temporally as a single component, with the advantage that the many degrees of freedom that a multi-joint action can have are reduced by the motor system. Such an interactive system, where the movement outcome is dependent upon the blending of the individual segments, permits a high degree of flexibility and efficiency. That is, to accomplish a certain functional goal, the coordinative structure establishes the coordination of the different articulations. This coordination is produced in such a way that a possible variation in a particular segment is counterbalanced by a variation in the opposite direction in one or more components, so that the resulting motion, leading to the accomplishment of the movement, is highly controlled. Since the discrete reponse in our experiment involved the shoulder, elbow and wrist articulations, and if the components are organized into an interactive system, then there must be some sign of a covariance contribution of each segment. As shown earlier, a high negative correlation was found between the spatial endposition of the elbow and the wrist. This means that deviations of the elbow are paired with opposite but almost equal deviations of the wrist; that is, a negative compensatory phenomenon took place between these two segments. Finally, the fact that the correlation was significantly higher in the visual condition gives a clear indication that visual information was used effectively and permitted a better accuracy performance.

General conclusion

In conclusion, the results support the notion that in an aiming task a corrective process takes place at the end of the initial impulse (e.g. Carlton, 1979, 1980,1981b). To update the first submovement,which is centrally monitored, a peripheral control process is incorporated in order to optimize the execution of the movement. This latter control mechanism will use new information that becomes available at the end of the main saccade (Pélisson et al., 1986) reflecting the visual (vision of the moving arm) or non-visual (no vision of the moving arm) information processing that must go on between the hands' position when it is in proximity to the target and the target position. The available information will then be used to issue a command deciding the resultant function of the path to follow. This decision will be made rather than a command for a specific trajectory or/and end-position for each component of the movement.

With training, the corrective phase will shift closer to the target, thereby increasing the initial programmed part of the movement, and consequently permitting a better computation of the resultant function to be used. It thus appears, as in a previous experiment using the same apparatus (Leroux, 1986) that the shoulder was primarily used to reach some specific end-position whilst the elbow and wrist acted as a coordinative structure. That is, an overestimation of the distance to be travelled by an articulation is compensated by diminishing the distance travelled by the other.

The concept of motor programs and coordinative structures has been opposed in the literature. Our contention is that a mixture of both ideas may be more useful than each of these views taken separately. More specifically, in an aiming task and other like tasks, a motor program may be issued to control the first impulse. Then, the error of this initial part is detected and a corrective impulse is initiated based on the available information. The movement resulting from that second impulse will be programmed, not on the basis of the path to be followed by each component, but rather towards a resultant function. Why would the system behave in such a way ? A possible explanation is that the movement can no longer be corrected via voluntary feedback loops, and as a consequence, "programming" the resultant function is in such circumstances the most efficient way to reach the target.

Appendix A

Problems with the impulse-variability models

Schmidt et al. (1978,1979) found that a linear relationship accounted for 85% to 98% of the variance, between We and D/MT. However, this relation was not found to be proportional as predicted by equation 1. The nature of the motor processes that created the non-zero intercept is far from clear and a number of explanations exists as layed out by Schmidt et al. (1979). First, there is the possibility that errors in measurement caused the non-zero intercept, by adding a constant to all of the data points. However, the intercept was rather large to be entirely associated with measurement errors. Second, it is also possible that the lack of proportionality is caused by noise in the motor system, that is not related to the nature of the movement. Tremor is one such source of variability contributing to the non-zero intercept. Third, there may be relatively larger variations in the early portion of the impulse while the force is building up to a peak. This latter possibility has been ruled out by Wright (note 2) who showed that variability was linearly related to movement speed at: (a) the point of maximal velocity, (b) zero velocity and (c) the target acquisition point.

Although, mentioning these possible causes, the source of the intercept still produces some interesting speculation. An alternative possibility can be the use of visual feedback, especially considering the appearance of increased slope and intercept with decreasing MT, as shown by the results of Schmidt et al. (1978,1979). This may suggest a tendency for error correction. Support for this interpretation comes from the study of Zelaznik, Shapiro and McColsky (1981). The subjects had to perform a concurrent (probe-reaction) task during the execution of an aiming response (MT= 500 ms). The rational was that the attentional demand imposed by the secondary probe task would not permit to attend to visual feedback for controlling the aiming movement. If visual feedback was effectively used in the studies of Schmidt et al. (1978, 1979), the slope of the We-average velocity function would be greater. This was confirmed by the results which showed that the slope increased for the probe trial condition, compared to the no-probe trial condition. Based on this observation, Zelaznik et al. (1981) concluded that visual feedback was used to correct the 500 ms movements in the no-probe condition, but not in the probe condition.

Various difficulties with the impulse-variability models (error measurement - noise in the motor system - impulse variability changes during the movement), either in their critical or in their failures to predict certain empirical facts, have been outlined by Schmidt et al. (1986). Some of the most troublesome problems will now be discussed. First, both models fail to consider the complex three-dimensional nature of aiming movements. This nature includes three observations. A first one considers the fact that the impact forces do play a role in the deceleration phase. An experiment by Teasdale (note 4) revealed that the impact force with the target is a linear function of D/MT. This suggests that the subject 'saves' some muscular activity by hitting the target rather than landing softly on it. These results show that not only it is incorrect to assume that all of the forces acting to stop the limb are muscular, but also that additional impact forces vary systematically with D and MT. In this context, MacKenzie, Marteniuk, Dugas, Liske and Eickmeier (submitted for publication) argues that subjects will modify their strategy in function of the precision demands imposed by the task. That is, when accuracy is not stringent, the target will be used to decelerate the hand (high impact velocity) and when accuracy demands are high, the hand will be precisely decelerated (low impact velocity) toward the target. A second observation is that the variability in time to drop, and in other temporal aspects of the vertical trajectory, are probably nearly proportional to MT. So the movement's endpoint is determined not only by movement in the horizontal dimension (which the models treat) but also by movement in the vertical dimension (which the models do not treat). A third observation is that where the stylus lands will be related to when the stylus is brought to the plane of the target. A late downward component should lead to a movement which is spatially too long. Both models neglect the variability in the temporal aspects of the vertical component.

A second critical finding that both models must be able to predict, is the linear relation between We and D/MT. A problem for the Schmidt et al.'s model, as pointed out by Meyer et al. (1982) is the failure to predict this relationship. Meyer et al. (1982) directly assumes the empirical relationship and then derives the mathematical acceleration-time function that produces it. One feature of these functions is the mirror-image symmetry, so that the accelerative and decelerative impulses, after one of them is inverted and reversed, would be congruent. However, Zelaznik and Schmidt (1983) have provided evidences that this symmetry assumption does not hold in aiming movements, with the impulse for acceleration having a considerably longer duration and smaller peak amplitude than the impulse for deceleration. Also, probably associated with these asymmetries, the spatial trajectories of the movements are not symmetrical, with a gradual rise in the hand to a point considerably past the movement midpoint, and then a rather abrupt drop toward the target. MacKenzie et al. (submitted for publication) argue that the skewness feature will be determined by the accuracy demands imposed by the task So contrary to the Meyer et al. (1982) model, but not to the Schmidt et al.'s (1978, 1979) model, these results provide evidence against the symmetry aspects of the impulses and movement trajectory.

A third critical point considers the shape-constancy assumption. The notion that the distance travelled by the time the impulse has stopped acting, is directly proportional to the impulse size multiplied by the time over which it acts, provided that the shape or mathematical form of the force-time function does not change as the impulse size (D or MT) does. The assumption demands that with the accelerations plotted in relative time, the various temporal aspects (e.g., peak acceleration, time to zero acceleration...) should line up nearly perfectly. However, recent studies (Schmidt & Gielen, note 5; Zelaznik & Schmidt, 1983) have shown that there is a marked shift in relative time of appearance of the peak acceleration, with the peak acceleration occurring later in relative time as the MT decreases. Similarly, the peak deceleration occurs relatively earlier as the MT decreases. Furthermore, the results revealed that on the one hand, the initial portions of the acceleration and final portions of the deceleration do not scale with MT (they are essentially constant) so that the shape constancy assumption was seriously violated. On the other hand, the duration of acceleration and deceleration both scale with MT. Furthermore, the amount of time involved in the deceleration phase is considerably greater than the time in acceleration, so that the acceleration-time function is not symmetrical in time as predicted by Meyer et al. (1982). These data provided strong implications since the impulse-variability models strongly rely on the shape-constancy assumption. So, it appears that future impulse-variability models should not rely on this questionable assumption.

Finally, involving the force variability-force relationship. From a number of experiments, where the forces were rather small, Schmidt et al. (1978) argued that force variability and force are roughly linearly related with the relationship being almost proportional. In modeling, Schmidt et al. (1978, 1979) and later also Meyer et al. (1982) have used, for simplicity reasons, an idealized statement of this relationship with force variability and force regarded as being proportional[12]. Sherwood and Schmidt (1980) examined this relationship with somewhat larger forces,

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[12] However, following Newell et al. (1984), Schmidt and his colleagues claim to have used quick contractions in their experiment; one can not verify the meaning of quick because time to peak force was never reported.

and some even approaching the subject's maximum. Their results revealed an inverted U-relationship. The force variability increased roughly linearly up to about 65% of the subject's maximum but decreased as the force requirements further increased. Schmidt and Sherwood (1982) subsequently modified the motor-output variability predictions to include an inverted U-shaped function; a relation that Schmidt and Sherwood (1982) also showed for movement accuracy.

Not everyone has found the inverted U-effects and this has led to some controversies. Newell, Carlton and Carlton (1982) have shown a generally continuously increasing (negatively accelerated) force variability value as a function of force. It must be noted that the movements used in the latter experiment resulted in only 68% of the subject's maximum, just about where Sherwood and Schmidt (1980) have found the peak in force variability to lie. However, a recent experiment by Newell and Carlton (1985) were subjects produced a range of peak forces between 2.5 to 90% of maximum force, do suggest that within-subject variability increases at a negatively accelerating rate with equal increments of peak force produced.

Newell and Carlton (1983,1985) and Newell et al., (1984) have shown that the form of the force variability-force relationship depends on the rate of rise of force within the contractions[13]. If the subjects increase their time to peak force as the force requirements become very large , then this could explain why force variability decreases past about 65% of the maximum force. This may suggest that the speed-accuracy relationships are based in part on the tendency of the motor system to produce more force inconsistency as force requirements are increased. On this basis, the inverted U-function reported by Sherwood and Schmidt (1980) could be due to subjects lenghtening time to peak force in comparison to the time to peak force generated at the lower peak force levels.

There are a number of experimental factors that could influence estimates of peak force variability as a function of peak force (a) transfer effects (Poulton,1973), (b) insufficient force levels to adequately describe the function, (c) insufficient data points at any force to obtain a veridical estimate of variability (e.g. Fisher 1915), (Newell et al., 1984). Following Newell and Carlton (1985), there is probably a more fundamental reason for the discrepant observations. They argue that in previous isometric force variability studies no force variables in addition to peak force have been reported from recordings of the impulse. It can be

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[13] It should be recognized that peak force is only a consequence of rate and the time that a given contraction rate is maintained (e.g. Kamen, 1983). In attempting to reproduce forces of a given percentage of maximum, subjects may well change the rate with which the peak force is achieved, thus changing time to peak force, the percentage of maximum that the criterion force represents and ultimately the variability function (Newell & carlton, 1985).

suggested that subjects change rate of force production according to the criterion peak force level. The rate adopted at each condition will probably be individual specific and consistent with principles of optimization and efficiency in human motion.

The variability of peak force as a function of peak force has already been claimed to be an increasing square root function (Fullerton & Catell, 1892), a non-proportional but increasing function (e.g. Jenkins, 1947), a linear function (Schmidt et al., 1979; Meyer et al., 1982), an inverted U-shaped function (Sherwood & Schmidt, 1980) and a J-shaped function (Shea, Northam, Beach & Howard, submitted for publication) depending on the constraints imposed upon the subject during response production (Newell et al., 1984). Newell and Carlton (1985) proposed that one could generate any of the force variability functions by shifting time to peak force in relation to the time to peak force upon which estimates of maximum peak force have been generated.

The different observations lead to serious concern about modeling force variability in the way that Schmidt et al. (1978, 1979) and Meyer et al. (1982) did. Probably, a linear relationship between peak force and peak force variability can be attained given a certain set of tasks constraints, however there is not one study published that has demonstrated a linear function across the full range of force production for a given anatomical unit. This suggests that generating a constant time to peak force across the full range of force production is not an optimal strategy for subjects to minimize peak force variability, at least with the task constraints typically imposed in isometric experiments. Also it must be noted that the force variability function can be linked to the physiology of muscular contraction. It is possible that the force variability function will differ according to the muscle group(s) utilized for action (Newell & Carlton, 1985). Both impulse-variability models while conceptually argue that the speed-accuracy trade-offs are caused by variations in movement output rather than limitations in feedback processing, seem inadequate with respect to the more detailed statements about how such variability occurs and how it leads to errors in movement.

Appendix B

Tables

Table 1
Mean AE scores (in ms) on MT in the visual and non-visual condition

Subjects	Block 2	Block 3	Block 19	Block 20
	$\bar{X}$	$\bar{X}$	$\bar{X}$	$\bar{X}$
		session 1		
1	47	52	30	26
2	33	45	33	36
3	22	44	33	44
4	61	29	20	15
5	41	28	33	27
6	23	45	27	47
$\bar{X}$	37.8	40.5	29.3	32.5
		session 2		
1	54	50	35	63
2	37	57	65	67
3	44	45	34	36
4	37	51	57	41
5	21	38	20	25
6	31	33	33	48
$\bar{X}$	37.3	36.1	42.0	46.7
		session 3		
1	60	58	17	48
2	43	19	30	22
3	31	44	29	39
4	27	20	14	23
5	35	18	18	28
6	23	42	20	34
$\bar{X}$	[illegible]	33.5	[illegible]	[illegible]

Table 2
Mean CE scores (in ms) on MT in the visual and non-visual condition

Subjects	Block 2	Block 3	Block 19	Block 20
	$\bar{X}$	$\bar{X}$	$\bar{X}$	$\bar{X}$
		session 1		
1	-14	-26	-23	10
2	24	45	34	32
3	-9	24	29	1
4	64	4	2	-7
5	7	-12	33	8
6	-3	-39	20	47
$\bar{X}$	11.5	-0.7	15.8	15.2
		session 2		
1	-53	-45	-30	-61
2	36	59	68	75
3	-15	-3	12	-27
4	-36	-52	-60	-42
5	-13	-10	15	17
6	0	30	30	49
$\bar{X}$	-13.5	-3.5	5.8	1.8
		session 3		
1	-62	-67	-2	-45
2	44	10	23	-11
3	20	7	-15	-23
4	-24	7	0	7
5	-31	-17	-13	-27
6	17	43	0	29
$\bar{X}$	-6.0	-2.8	-1.2	-11.7

Table 3
Mean VE scores (in ms) on IIT in the visual and no-visual condition

	Block 2	Block 3	Block 19	Block 20
Subjects	$\bar{X}$	$\bar{X}$	$\bar{X}$	$\bar{X}$
		session 1		
1	49	51	29	30
2	32	25	24	34
3	27	45	25	54
4	25	34	28	17
5	46	35	25	35
6	33	30	30	27
$\bar{X}$	35.3	36.7	26.8	32.8
		session 2		
1	28	39	29	30
2	29	31	23	18
3	50	52	39	36
4	25	25	24	30
5	24	43	30	26
6	37	28	29	24
$\bar{X}$	32.2	36.3	29.0	27.3
		session 3		
1	18	24	21	22
2	27	20	29	24
3	31	47	30	37
4	21	23	18	36
5	22	18	18	21
6	24	23	24	30
$\bar{X}$	23.8	25.8	23.3	28.3

Table 4
Mean RMSE scores (in ms) on IIT in the visual and no-visual condition

	Block 2	Block 3	Block 19	Block 20
Subjects	$\bar{X}$	$\bar{X}$	$\bar{X}$	$\bar{X}$
		session 1		
1	51	58	37	32
2	40	52	41	47
3	29	51	38	54
4	68	34	28	18
5	47	37	41	36
6	33	49	36	54
$\bar{X}$	44.7	46.8	37.6	40.2
		session 2		
1	60	59	41	68
2	46	66	72	77
3	52	52	41	45
4	43	57	65	52
5	28	44	34	31
6	37	41	41	55
$\bar{X}$	44.3	53.2	49.0	54.7
		session 3		
1	65	71	22	53
2	52	22	37	26
3	37	48	33	44
4	32	24	18	31
5	39	25	22	35
6	29	48	24	41
$\bar{X}$	42.3	39.7	26.0	38.3

Table 5

Mean AE scores (in mm) on the X-axis in the visual and no-visual condition

	Block 2	Block 3	Block 19	Block 20
Subjects	$\bar{X}$	$\bar{X}$	$\bar{X}$	$\bar{X}$
session 1				
1	14	16	12	14
2	4	16	4	7
3	7	22	7	19
4	6	5	5	12
5	6	17	6	9
6	6	27	6	12
$\bar{X}$	7.2	17.2	6.7	12.2
session 2				
1	12	7	8	7
2	4	7	3	7
3	7	5	11	23
4	5	11	6	7
5	11	13	8	30
6	6	8	5	12
$\bar{X}$	7.5	8.5	6.8	14.3
session 3				
1	9	10	7	21
2	4	13	3	7
3	5	7	9	18
4	4	7	4	7
5	6	9	5	18
6	3	10	8	9
$\bar{X}$	5.2	9.3	6.0	13.3

Table 6

Mean CE scores (in mm) on the X-axis in the visual and no-visual condition

	Block 2	Block 3	Block 19	Block 20
Subjects	$\bar{X}$	$\bar{X}$	$\bar{X}$	$\bar{X}$
session 1				
1	-1	9	-11	9
2	-4	-16	1	1
3	-1	-18	4	-6
4	-5	4	0	9
5	-1	-14	-2	-7
6	-2	-27	4	-12
$\bar{X}$	-2.3	-10.3	-0.7	-1.0
session 2				
1	-10	-5	-8	5
2	0	-6	3	3
3	-1	-2	8	-23
4	1	11	1	1
5	-10	-12	-7	-30
6	-1	-8	2	-12
$\bar{X}$	-3.5	-3.7	-0.2	-9.3
session 3				
1	-9	5	-7	18
2	0	-11	0	-5
3	-1	-4	2	-10
4	0	6	1	2
5	-2	-5	-1	-17
6	0	0	-3	1
$\bar{X}$	-2.0	-1.5	-1.3	-1.8

Table 7

Mean VE scores (in mm) on the X-axis in the visual and no-visual condition

	Block 2	Block 3	Block 19	Block 20
Subjects	$\bar{X}$	$\bar{X}$	$\bar{X}$	$\bar{X}$
session 1				
1	17	19	7	15
2	3	7	4	8
3	8	18	7	21
4	6	7	7	13
5	8	14	7	8
6	9	11	7	7
$\bar{X}$	8.5	12.7	6.5	12.0
session 2				
1	9	8	8	6
2	4	7	3	9
3	12	7	10	14
4	6	7	8	10
5	6	11	10	10
6	8	5	6	6
$\bar{X}$	7.5	7.5	7.5	9.2
session 3				
1	4	14	4	13
2	5	12	5	9
3	7	7	13	17
4	5	6	5	8
5	8	11	6	12
6	4	11	8	10
$\bar{X}$	5.5	10.2	6.8	11.5

Table 8

Mean RMSE scores (in mm) on the X-axis in the visual and no-visual condition

	Block 2	Block 3	Block 19	Block 20
Subjects	$\bar{X}$	$\bar{X}$	$\bar{X}$	$\bar{X}$
session 1				
1	17	21	13	17
2	5	18	4	8
3	8	26	8	22
4	7	8	7	15
5	8	20	7	11
6	9	29	7	14
$\bar{X}$	9.0	20.3	7.7	14.5
session 2				
1	13	9	12	8
2	4	10	4	9
3	12	7	12	27
4	6	13	8	10
5	12	16	12	32
6	8	10	6	14
$\bar{X}$	9.2	10.8	9.0	16.7
session 3				
1	10	14	8	22
2	5	17	5	10
3	7	8	13	20
4	5	8	5	8
5	8	12	6	21
6	4	11	9	10
$\bar{X}$	6.[illegible]	11.7	7.7	15.2

Table 9

Mean AE scores (in mm) on the Y-axis in the visual and no-visual condition

	Block 2	Block 3	Block 19	Block 20
Subjects	$\bar{X}$	$\bar{X}$	$\bar{X}$	$\bar{X}$
session 1				
1	23	27	19	37
2	13	35	7	16
3	10	17	12	30
4	13	16	15	16
5	11	24	10	17
6	11	31	10	34
$\bar{X}$	13.5	25.0	12.2	25.0
session 2				
1	14	28	15	26
2	9	29	8	17
3	12	18	11	22
4	13	28	13	19
5	16	22	13	23
6	12	14	9	38
$\bar{X}$	12.7	23.3	11.5	24.2
session 3				
1	12	41	16	19
2	9	32	11	29
3	7	16	9	22
4	8	21	10	14
5	11	24	16	19
6	12	19	8	21
$\bar{X}$	9.8	25.5	11.2	20.7

Table 10

Mean CE scores (in mm) on the Y-axis in the visual and no-visual condition

	Block 2	Block 3	Block 19	Block 20
Subjects	$\bar{X}$	$\bar{X}$	$\bar{X}$	$\bar{X}$
session 1				
1	5	5	-7	33
2	-8	-35	2	1
3	-8	6	3	-7
4	-11	10	-10	-2
5	-7	-20	-9	7
6	-6	-31	-5	-34
$\bar{X}$	-5.8	-10.8	-4.3	-0.3
session 2				
1	-3	25	-9	23
2	0	-27	-3	-14
3	-8	17	-4	-19
4	-6	25	-6	7
5	-14	-5	-8	-19
6	-10	-14	-8	-38
$\bar{X}$	-6.8	3.5	-6.3	-10.0
session 3				
1	-6	41	-13	-3
2	0	-20	-8	-28
3	-3	-10	-6	-18
4	-2	15	-4	3
5	-7	16	-10	7
6	-11	-9	-4	-20
$\bar{X}$	-4.8	5.5	-7.5	-9.8

Table 11
Mean VE scores (in mm) on the Y-axis in the visual and no-visual condition

	Block 2	Block 3	Block 19	Block 20
Subjects	$\bar{X}$	$\bar{X}$	$\bar{X}$	$\bar{X}$
session 1				
1	30	31	22	23
2	12	8	8	20
3	10	20	14	33
4	15	18	16	18
5	12	29	10	22
6	12	14	11	15
$\bar{X}$	15.2	18.3	13.5	21.8
session 2				
1	17	20	18	20
2	11	16	10	14
3	13	13	12	19
4	15	23	16	21
5	16	26	14	20
6	11	11	8	16
$\bar{X}$	13.8	18.2	13.0	18.3
session 3				
1	15	13	16	24
2	11	29	11	18
3	8	16	9	17
4	11	18	11	19
5	12	23	15	24
6	9	22	9	10
$\bar{X}$	10.8	20.2	11.6	18.7

Table 12
Mean RMSE scores (in mm) on the Y-axis in the visual and no-visual condition

	Block 2	Block 3	Block 19	Block 20
Subjects	$\bar{X}$	$\bar{X}$	$\bar{X}$	$\bar{X}$
session 1				
1	30	31	24	41
2	15	36	8	20
3	13	21	14	34
4	19	21	19	18
5	14	28	14	23
6	13	34	12	37
$\bar{X}$	17.3	28.5	15.2	28.8
session 2				
1	17	32	20	30
2	11	32	10	20
3	16	22	12	27
4	17	34	17	22
5	21	26	16	27
6	15	18	11	41
$\bar{X}$	15.5	27.3	14.3	27.8
session 3				
1	16	43	21	24
2	11	35	14	33
3	8	19	11	25
4	11	25	12	20
5	14	28	15	25
6	14	24	10	23
$\bar{X}$	12.3	28.7	13.8	25.0

Table 13

Mean time to the first peak acceleration (in ms) with standard deviation for three subjects in the visual and non-visual condition

	Block 2		Block 3		Block 19		Block 20	
Subjects	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
session 1								
4	105	30	90	25	100	20	75	20
5	85	25	95	20	105	35	105	40
6	75	15	85	20	90	20	95	30
$\bar{X}$	88.3	23.3	90.0	21.7	98.3	25.0	91.7	30.0
session 2								
4	105	30	100	30	95	30	90	20
5	95	30	105	40	135	40	125	45
6	90	20	95	20	90	20	95	45
$\bar{X}$	96.7	25.0	100.0	30.0	106.7	30.0	103.3	36.7
session 3								
4	110	25	95	25	120	35	120	35
5	115	30	115	30	125	35	125	35
6	75	15	85	20	80	20	80	20
$\bar{X}$	100.0	23.3	98.3	25.0	108.3	30.0	108.3	30.0

Table 14

Mean time to the re-acceleration (in ms) with standard deviation for three subjects in the visual and no-visual condition

	Block 2		Block 3		Block 19		Block 20	
Subjects	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
session 1								
4	385	25	390	25	400	20	410	30
5	370	30	410	40	455	25	450	25
6	395	30	385	25	420	25	435	35
$\bar{X}$	383.3	28.3	395.0	30.0	425.0	23.3	431.7	30.0
session 2								
4	405	20	405	25	415	25	425	25
5	450	20	455	25	450	20	470	20
6	420	20	385	25	410	20	405	35
$\bar{X}$	425.0	20.0	415.0	25.0	425.0	21.7	433.3	26.7
session 3								
4	450	15	395	20	430	20	425	25
5	425	15	435	25	435	20	455	25
6	415	25	410	20	410	25	410	30
$\bar{X}$	430.0	18.3	413.3	21.7	425.0	21.7	430.0	26.7

Table 15
Mean time to the second peak acceleration (in ms) with standard deviation for three subjects in the visual and no-visual condition

	Block 2		Block 3		Block 19		Block 20	
Subjects	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
				session 1				
4	475	35	470	45	515	20	500	35
5	450	55	485	45	525	5	520	15
6	525	15	500	45	525	20	525	10
$\bar{X}$	483.3	35.0	485.0	45.0	521.7	15.0	515.0	20.0
				session 2				
4	490	35	515	20	515	20	515	20
5	525	5	525	5	525	5	525	5
6	520	20	500	30	530	5	515	20
$\bar{X}$	511.7	20.0	513.3	18.3	523.3	10.0	518.3	15.0
				session 3				
4	505	25	515	20	520	15	520	15
5	525	5	525	5	525	5	525	15
6	510	20	520	10	520	20	500	30
$\bar{X}$	513.3	16.7	520.0	11.7	521.7	13.3	515.0	20.0

Table 16

Within-subject correlations on the spatial endposition between elbow and wrist during the practice sessions

Subject	session 1	session 2	session 3
1	-0.07	0.45	0.42
2	-0.98	-0.94	-0.93
3	-0.96	-0.84	-0.88
4	-0.95	-0.98	-0.97
5	-0.78	-0.83	-0.96
6	-0.10	-0.98	-0.95

Table 17

Within-subject correlations on the spatial endposition between elbow and wrist during the visual (blocks 2 and 19) and no-visual (blocks 3 and 20) condition

Subject	with visual feedback	no visual feedback
1	0.22	-0.05
2	-0.56	-0.46
3	-0.80	-0.64
4	-1.00	-0.88
5	-0.99	-0.83
6	-0.73	-0.65

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