

THE EFFECT OF PRACTICE ON THE VISUAL CONTROL OF RAPID
AIMING MOVEMENTS

by

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Abstract

Numerous everyday activities require individuals to make rapid movements to specific locations in space (e.g., pointing, reaching and grasping, catching). Although it is generally accepted that vision plays an important role in both the control and acquisition of goal directed movement, it is still not fully understood how vision is used and in what way its role changes as a function of practice. There were two primary goals of the present research. The first was to examine how the reliance on visual feedback in the control of rapid aiming movements changes with practice. The second was to investigate how participants adapt control strategies to optimize performance under different visual feedback conditions. Three experiments were conducted in which we examined (1) the influence of visual feedback on the centrally planned initial impulse and feedback-based error correction phases during acquisition; and (2) the effect of removing visual feedback at different levels of practice. The results indicated that in both the acquisition trials and transfer tests, vision had a major impact on the spatio-temporal properties of the initial impulse and error correction phases. It is proposed that learning involved a dual process of improved programming and increased efficiency of feedback processing. Within this framework, practice not only acted on programming and feedback processes directly, but also indirectly through a reciprocal interplay between both processes. On one side, improvements in the programming of the initial impulse decreased the frequency of error correction phases and facilitated the efficiency of the correction process. On the other side, the proficiency to utilize sensory information influenced the programming of the initial impulse. When participants had visual feedback, they planned their movements to use this effective source of information. As a result, the reliance on visual feedback processing remained even after extensive levels of practice. When visual feedback was not available, movements were planned to minimize the need for sensory-based error correction.

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CONTRIBUTIONS OF THE AUTHORS

This thesis contains three separate studies that have been undertaken by the candidate, Michael A. Khan, under the supervision of Ian M. Franks (Professor, Human Kinetics). David Goodman is a co-investigator in the first study (see references below). Each study is the primary ownership of the candidate.

The above statement was written by Michael A. Khan and agreed upon by the undersigned.

Ian M. Franks

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1. Introduction

Numerous everyday activities require individuals to make rapid movements to specific locations in space. Indeed, it has been said that aiming movements 'constitute the basic building blocks of numerous everyday activities (e.g., pointing, reaching, touching, grasping, walking, looking, talking)' (Meyer, Abrams, Kornblum, Wright & Smith, 1988, p. 340). Research involving aiming movements has considerably enhanced our understanding of underlying processes in motor control. Topics such as impulse variability (Schmidt, Zelaznik, Hawkins, Frank & Quinn, 1979), the speed of feedback processing (Carlton, 1981; Carlton, 1992; Keele & Posner, 1968), the relative importance of visual versus proprioceptive feedback (Adams, Gopher & Lintern, 1977), feedback and feedforward control (Beaubaton & Hay, 1986), and speed-accuracy trade-off functions (Fitts, 1954; Wright & Meyer, 1983) have been among the many issues that have been extensively investigated. Research has now shown that significant changes occur in the properties (e.g., endpoint accuracy, movement time, kinematic profiles and EMG patterns) of these relatively simple movements, even after hundreds of trials of practice (e.g., Gottlieb, Corcos, Jaric, & Agarwal, 1989; Moore & Marteniuk, 1986). It is generally accepted that vision plays an important role in both the control and acquisition of goal directed movement. However, despite a considerable body of research which dates back to the work of Woodworth (1899), it is still not fully understood how vision is used during these movements and in what way its role changes as a function of practice.

1.1. Methods of studying visual control

Several methods have been used to investigate the role of vision in movement control. Typically, these methods have involved examining how performance is affected by systematically altering the visual field. For example, manipulations of visual feedback have included distortion of

the visual field through prismatic lens (Elliott, Calvert, Jaeger & Jones, 1990) and delaying of visual feedback (Pratt & Abrams, 1996; Smith & Bowen, 1980). Perhaps the most commonly employed manipulation involves occlusion of visual feedback, either from the movement itself and/or specific aspects of the environment (Prablanc, Echallier, Jeannerod & Komilis, 1979; Prablanc, Echallier, Komilis & Jeannerod, 1979). Usually, these manipulations have entailed varying the time and duration for which visual feedback is available (Carlton, 1981; Chua & Elliott, 1993; Elliott, Chua & Pollock, 1994; Elliott, Chua, Pollock & Lyons, 1995). Occlusion methods have ranged from turning the lights off (Keele & Posner, 1968) to the use of opaque shields (Carlton, 1981) or liquid crystal goggles (Elliott et al., 1994; Milgram, 1987; Spijkers & Lochner, 1994). However, these techniques have the limitation that vision of both the moving limb as well as other aspects of the surrounding environment are eliminated. Thus, the specific roles of these sources of information could not be evaluated. Computer or video aiming tasks have also been employed in which limb movement is translated to motion of a cursor on a video monitor. Although these tasks differ from conventional aiming tasks in that the visual display is removed from limb movement, they have the advantage that visual feedback regarding limb movement can be selectively manipulated by controlling the visibility of the cursor on the screen.

The rationale behind occlusion studies is that if performance is affected by the removal of a particular source of information, then this information was relevant for movement control. Proteau and colleagues (Proteau & Cournoyer, 1990; Proteau & Marteniuk, 1993; Proteau, Marteniuk, Girouard & Dugas, 1987) have used this rationale in the most strict sense by assuming that the magnitude of the performance decrement is proportional to the importance of the information in question. For example, in the study of Proteau et al. (1987), participants practiced an aiming task either with visual information about limb movement (FV group) or without visual feedback (NV group). All participants received knowledge of results (KR) regarding movement

time and accuracy after each trial. The role of visual feedback at different levels of practice was assessed by comparing the effect of removing visual feedback and KR from the FV group with the effect of removing KR from the NV group. The size of the decrement for the FV group relative to the NV group was said to be indicative of the importance of visual feedback. Also, Proteau and colleagues reasoned that inferences could be made about how the role of visual feedback changes as a function of practice from comparing the magnitude of the decrements at different levels of practice.

Although the effects of removing vision have been investigated since the days of Woodworth (1899), researchers have questioned whether the role of a particular source of sensory information can be properly inferred from comparing conditions with and without sensory feedback. The removal of one source of feedback likely affects the reliance on other sources of information thereby affecting sensory processing beyond that of the manipulated information. Similarly, if participants adopt different control strategies depending on what information is available, performance in one condition will not necessarily reflect performance in another condition plus or minus sensory feedback. Also, in cases where performance decrements have not been realized (e.g., Lashley, 1917), it is possible that participants did use sensory feedback when it was available but it was not essential to accomplish the task goal (Schmidt & Lee, 1999, p. 134).

Despite these concerns, there are arguments in favor of using occlusion paradigms such as that adopted by Proteau and colleagues. First, a difference in performance between vision and no vision conditions during acquisition would imply that visual feedback has an influence over and above that provided by other sources of information. Therefore, even if the processing of other sources of information differed between visual conditions, the advantage of having vision would have been clearly demonstrated. Second, an adverse effect of removing vision in transfer tests would indicate that visual feedback was processed. Otherwise, a decrement in performance

would not be expected. Along these lines, the use of a transfer paradigm is critical because similar performance between vision and no vision conditions during acquisition could lead to the erroneous conclusion that vision was not used when it was available. Third, using the magnitude of the decrement as an indicator of the importance of vision is consistent with the idea that an increasing reliance on visual feedback adversely affects the ability to use other sources of information. Therefore, in the event that different control strategies are adopted when vision is removed, the success of these strategies would likely reflect the reliance on visual feedback.

Additional insight to visual control processes has been gained through the analysis of kinematic profiles (Abrams, Meyer & Kornblum, 1990; Abrams & Pratt, 1993; Chua & Elliott, 1993; Meyer et al., 1988). Kinematic data provide detailed information about movement trajectory from which specific landmarks can be identified. These events have been linked to particular mental operations and therefore can be used to make inferences about the processes involved in visuomotor control. Based on the assumption that the control of movement is accomplished through both central planning and the processing of sensory information, researchers have proposed that aiming movements consist of two phases, an initial impulse and an error correction phase (Abrams et al., 1990; Meyer et al., 1988; Woodworth, 1899). The initial impulse is assumed to be programmed to end at the location of the target and is characterized by a fairly rapid, continuous change in the position of the limb. If the endpoint of the initial impulse misses the target, the limb movement may enter an error correction phase. Error corrections are indexed by discontinuities in kinematic profiles which are said to reflect the presence of on-line adjustments to movement. Here, based on sensory information, an attempt is made to reduce any discrepancy between the endpoint of the initial impulse and the position of the target.

The initial impulse, by definition, does not contain movement modifications and is therefore comprised of one submovement. Error correction phases may consist of only a single

submovement (Meyer et al., 1988) or they may contain multiple submovements (Crossman & Goodeve, 1983; Meyer, Smith, Kornblum, Abrams, & Wright, 1990). Parsing of movements into their initial impulse and error correction phases has been accomplished by locating the first moment at which one of the following movement modifications occurs: a positive to negative zero line crossing in velocity, a negative to positive zero line crossing in acceleration or a significant deviation in acceleration (see Figure 1.1). Positive to negative transitions in velocity correspond to reversals in the direction of the movement, going from a forward to backward direction. Zero line crossings in the acceleration trace represent an increase in the velocity of the movement after the limb was slowing down. Significant deviations are relative minimums in the absolute value of acceleration while the acceleration is negative. In contrast to zero line crossings, significant deviations represent abrupt changes in the acceleration trace which reflect a decrease in the net braking force of the limb without an increase in velocity.

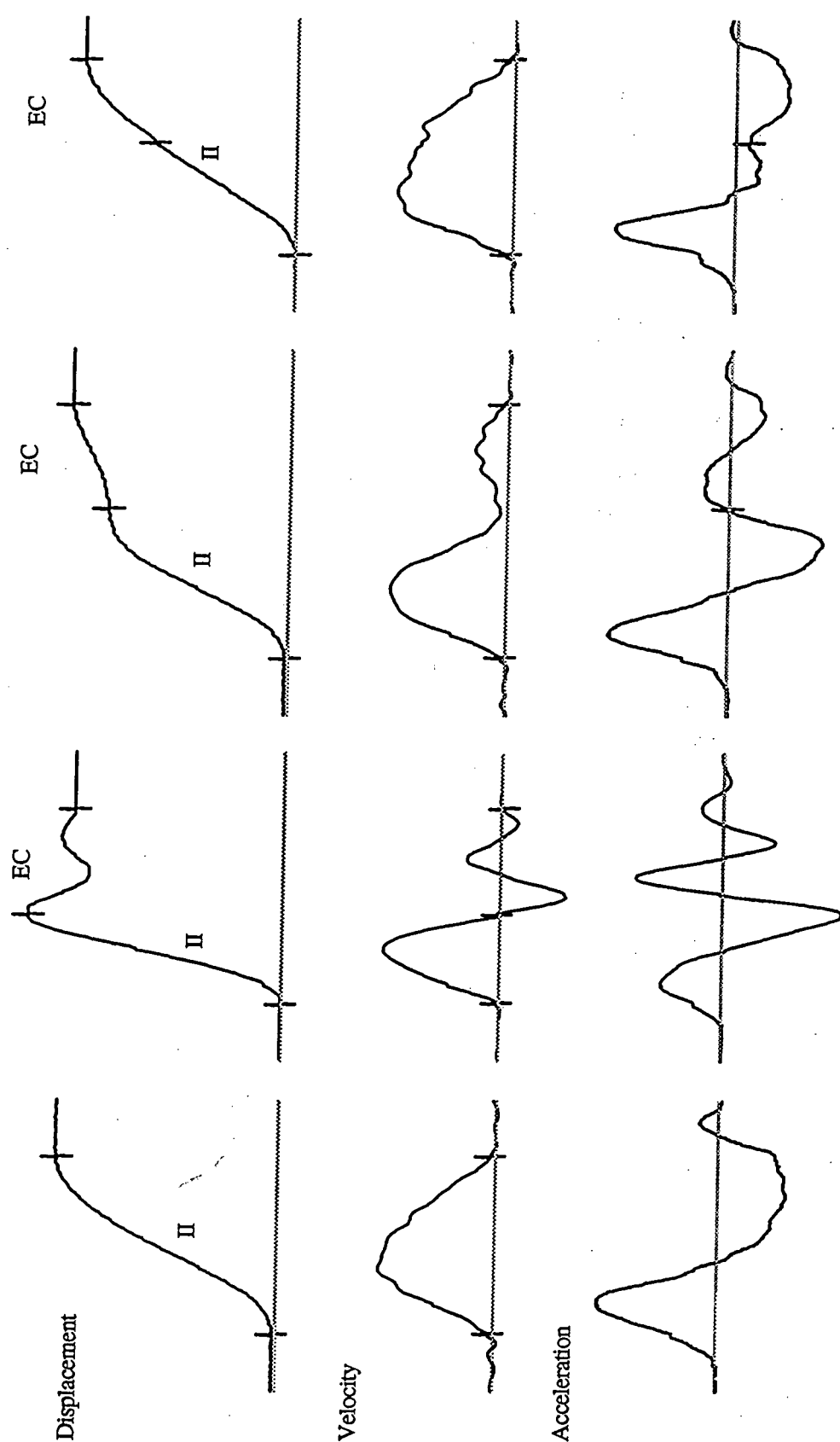
The advantage of using kinematic analysis is that it provides detailed information about performance under various experimental conditions thus enabling a more precise investigation of the role of vision in motor control and the nature of visuomotor processing. Also, by parsing movements into their initial impulse and error correction phases, the influence of feedback manipulation on sensory processing as well as movement planning/programming can be evaluated.

1.2. The effects of occluding visual feedback on performance and movement kinematics:

Implications for the role of vision in movement control

Research has typically shown that when movement durations are relatively long, movements performed with visual feedback are more accurate than those performed in the absence of vision. However, as movement time is reduced, the benefit of visual feedback decreases until, at some critical movement time, there is no longer a difference in accuracy

Figure 1.1. Sample position, velocity and acceleration profiles showing parsing of movements into their initial impulse and error correction phases. Movements may contain no error corrections, or they may contain error corrections initiated either by a change in direction, a zero line crossing in acceleration, or a significant deviation in the acceleration profile. Markers indicate the beginning of movement, the end of initial impulse phases and movement endpoints. (II-initial impulse phase, EC-error correction phase).



between vision and no vision conditions (Keele & Posner, 1968; Woodworth, 1899; Zelaznik, Hawkins & Kisselburgh, 1983). This minimum movement time for which visual feedback benefits accuracy has been used as a basis to estimate visual feedback processing time. The reasoning is that if movement times are shorter than the time required to process visual feedback, then vision cannot be used to enhance performance. The question of how long it takes to process visual feedback (or sensory information in general) has important theoretical implications with regard to the relative contribution of central and sensory processes in movement control. It is reasonable that sensory information plays a role only when movement times are sufficiently long to encompass sensorimotor delays. Otherwise, movement control would be based fully on open-loop processes uninfluenced by sensory feedback.

From comparing performance under vision and no-vision conditions over a range of movement times, early estimates of visual feedback processing time were about 400-450 msec (Vince, 1948; Woodworth, 1899). However, Keele and Posner (1968) argued that these relatively long estimates were likely due to the use of reciprocal aiming tasks where a significant proportion of the movement time is taken up in reversing the movement. Using a discrete aiming task in which the availability of visual feedback was manipulated randomly, they estimated visual processing times to be between 190-260 msec. Further work by Zelaznik et al. (1983) has shown that when participants know a priori whether or not vision would be available, vision can benefit performance when movement times are below 190 msec.

In those studies which have used total movement time as an indicator of visual feedback processing time, it was implicitly assumed that vision was used from the initiation of the movement. However, it is quite possible that useful visual information was not available until early portions of the movement had been completed. Also, the interval from the initiation of a corrective modification to the end of the movement was not taken into account. Therefore, the

time required to process visual feedback was likely shorter than the minimum movement time for which vision enhanced accuracy. In order to address this concern, Carlton (1981) varied the time at which visual feedback became available during movement execution. By measuring the time from when vision was provided to the initiation of the first movement modification, Carlton estimated that visuomotor delays were in the order of 135 msec. Other studies have estimated visual feedback processing times as short as 100 msec using paradigms involving feedback delay (Smith & Bowen, 1980) and target perturbation (Paulignan, Mackenzie, Marteniuk & Jeannerod, 1990).

Kinematic analysis has revealed that participants typically spend more absolute time and a greater proportion of the total movement time after peak velocity when visual feedback is available compared to when movements are made without vision (Chua & Elliott, 1993; Elliott, Carson, Goodman & Chua, 1991). The additional time spent after peak velocity is said to reflect the time needed to perform visually based online adjustments. Although the lengthening of the time spent after peak velocity has been associated with a higher presence of discrete adjustments (Chua & Elliott, 1993), there are cases in which the number of movement modifications did not differ between visual conditions (Elliott et al., 1991; Meyer et al., 1988). Whether the slowing of movement is characterized by a smooth change in velocity or by discrete adjustments has been said to have important implications regarding the nature of visuomotor control (Elliott, 1992; Jeannerod, 1988). Discrete modifications are thought to be representative of intermittent control where each visual sample goes through the information processing stages of stimulus identification, response selection and programming of a corrective submovement (Craig, 1947). It has been suggested that when the momentum of the limb is relatively high, discrete modifications are filtered out and are therefore not detected as discontinuities in movement kinematics (Jeannerod, 1988). Alternatively, smooth velocity profiles during deceleration may

represent a more continuous mode of control (Elliott, 1992).¹ According to this viewpoint, visual samples are not interspersed between information processing sequences which prepare and generate ballistic submovements. Instead, vision regulates motor output on a continual basis, progressively driving the limb to the desired end location.

1.3. Speed-accuracy tradeoffs

One of the most robust findings in motor behavior research is that movement time increases as the ratio of movement amplitude to target width increases (Fitts, 1954). However, there has been much controversy over the form of the relationship between speed and accuracy and the control mechanisms responsible for speed-accuracy tradeoffs. For example, Schmidt et al. (1979) and Meyer et al. (1982) have described speed-accuracy tradeoffs solely in terms of impulse variability principles. These theories have derived linear relationships between movement speed and accuracy based on the assumption that movement is controlled by programming pulses of force having specified height and duration parameters which vary randomly about their assigned values. Other researchers have accounted for speed-accuracy tradeoffs in terms of the number of submovements needed to attain the target (Crossman & Goodeve, 1983; Keele, 1968; Woodworth, 1899). According to the iterative-corrections model (Crossman & Goodeve, 1983), each submovement is said to be made on the basis of sensory feedback and is assumed to have a constant duration and travel a constant proportion of the remaining distance to the center of the target. Thus, the number of submovements needed to attain a target increases as movement amplitude increases and target width decreases.

The stochastic optimized-submovement model developed by Meyer et al. (1988) incorporates ideas from both impulse variability and multiple submovement theories. Total

¹ The term deceleration is used throughout to refer to negative acceleration.

movement times are thought to be minimized while maintaining a high degree of accuracy through the realization of an optimum tradeoff between the durations of the initial impulse and error correction phases. For example, given a direct relationship between movement speed and spatial variability (Schmidt et al., 1979; Meyer et al., 1982), initial impulses with high velocities will have short durations but will frequently miss the target region. The subsequent need for error correction would yield a net-increase in total movement time even though the associated initial impulses have short durations. On the other hand, initial impulses with low velocities will be highly accurate but the result would again be long total movement times because of the long initial impulse durations. Therefore, achieving maximum performance would entail assuming an initial impulse velocity such that the combined duration of the initial impulse and error correction phases is minimized.

Meyer et al. (1988) offered the suggestion that programming of the initial impulse may be influenced by the availability of visual feedback. That is, when visual feedback is available, initial impulses may be programmed with higher velocities compared to when visual feedback is not available. The higher variability in the initial impulse endpoints for the full vision condition may then be overcome by effective visual feedback processing. Conversely, producing slower initial impulses when visual feedback is not available would decrease the need for sensory based error corrections. However, Meyer et al. found no support for these different strategies as participants produced initial impulses in the same manner regardless of feedback condition. Therefore, the availability of visual feedback was not considered a relevant factor in the underlying assumptions of the stochastic optimized submovement model and in the derivations of speed-accuracy tradeoff functions. It should be noted, however, that in their study visual conditions were alternated between trials. Therefore, it may not be surprising that participants adopted similar strategies under the two feedback conditions.

Recently, Plamondon and Alimi (1997) have put forth what is perhaps the most radical open-loop account of speed-accuracy tradeoffs. They claim that sensory feedback is not used during movement execution but that with practice 'advance information from sensory events is used as a feedforward control to adjust the properties of the neuromuscular system with respect to the task objective' (p. 287). According to their kinematic theory, movement is produced from a pair of synchronous pulses generated by the agonist and antagonist muscles. The pulse from each system is modeled as a log-normal function and the complete velocity profile is given by the weighted difference of the two log-normals. Multiple peaks in the velocity profiles emerge from the differences in timing properties of the impulses. Thus, discontinuities in kinematic profiles are said to arise from a single "ballistic" control process and not online sensory based corrections. Although this model offers a viable account of how multiple peaks in velocity and acceleration emerge from neuromuscular dynamics, it has been criticized because it does not account for the influence of visual feedback on performance and movement kinematics (Chua & Elliott, 1997). As mentioned earlier, visual feedback has been shown to have an influence on the symmetry of velocity profiles (Chua & Elliott, 1993; Elliott et al., 1991). Also, the higher occurrence of zero line crossings in velocity and acceleration under full vision compared to no vision conditions (Chua & Elliott, 1993) suggests that discontinuities arise from control processes over and above a single ballistic process.

1.4. The effect of practice

In the past, there have been different viewpoints regarding how the role of sensory information changes throughout the learning of a motor skill. Some researchers have suggested that there is a progression from closed- to open-loop control whereby the importance of sensory feedback is reduced with practice (Franks & Romanow, 1993; Schmidt & McCabe, 1976).

Through practice with knowledge of results (KR), open-loop motor programs are developed and refined which then free the participant of the need to use time consuming feedback-based control (Schmidt, 1975). Others have suggested that with learning, there is not a decrease in the importance of sensory information, but a shift in the importance of one source of sensory information to another, for example, from visual to proprioceptive feedback (Adams et al., 1977; Fleishman & Rich, 1963). Although both of these viewpoints differ in their account of how the use of sensory information changes as a function of practice, common to both positions is the proposition that there is a decreasing reliance on visual feedback with practice.

In a study which required participants to perform aiming movements as fast and as accurately as possible, Abrams and Pratt (1993) have shown that with practice, the duration of the initial impulse phases increased while the time spent in the error correction phases decreased. The net effect was a decrease in total movement time as a function of practice. Likewise, there was an increase in the distance traveled in the initial impulse phases while the distance traveled during error correction decreased. From these findings it was not clear whether participants became less dependent on visual feedback due to improved programming of the initial impulse and/or more efficient at using visual feedback. However, in a subsequent study, Pratt and Abrams (1996) indicated that the availability of visual information regarding the moving limb appeared to have little impact on the above mentioned practice effects. Pratt and Abrams therefore concluded that the 'practice related changes observed in the component submovements of rapid aimed limb movements arise from improved planning of the primary submovement and not improved efficiency of feedback processing' (p. 155). Moreover, the availability of visual feedback, whether manipulated within (Abrams et al., 1990; Meyer et al., 1988) or between participants (Pratt & Abrams, 1996), appeared to have little impact on the control strategies adopted by participants.

In contrast, Proteau et al. (1987) have demonstrated, using a temporally constrained aiming task (movement time = 550 msec), that even after extensive practice, performance was better for participants who had visual feedback compared to participants who did not. Furthermore, when participants who practiced with visual feedback were transferred to a no vision condition, there was a larger decrement in performance later in practice compared to when vision was removed earlier in practice. Therefore, instead of movement control becoming less dependent on visual feedback with practice, the dependency appeared to increase.

Research has shown that vision of the moving limb, target location and surrounding environment are important for aiming accuracy (Carlton, 1981; Prablanc et al., 1979a; Prablanc, Pélisson, & Goodale, 1986). However, it appears that the increasing reliance on vision was primarily due to the increasing ability of participants to effectively use on-line visual information from the moving limb (Proteau & Cournoyer, 1990; Proteau & Marteniuk, 1993). According to the specificity of learning hypothesis (Proteau, 1992), separate sensory stores are said to exist for vision and proprioception during the early stages of practice. Hence, when one source of sensory information is removed, participants can still rely on other sources of sensory information. However as learning progresses, the available sources of sensory feedback are integrated to form an intermodal representation of the expected sensory consequences thereby mediating a shift from intramodal to intermodal sensory processing. At this point, the removal of one source of information would cause performance to deteriorate because the incoming sensory information can no longer be compared to the single integrated sensory store. Similarly, the addition of a significant source of information interferes with the processing of the specific sources of sensory information that were available during practice (Proteau, Marteniuk, & Lévesque, 1992).

Support for the specificity of learning hypothesis has been obtained from studies using other laboratory tasks such as waveform production (Ivens & Marteniuk, 1997). However, there

has been some debate as to whether specificity of learning holds for more “real world” tasks such as gymnastic beam walking (Robertson, Collins, Elliott & Starkes, 1994), power lifting (Bennett & Davids, 1995) and catching (Whiting, Savelsbergh & Pijpers, 1995). Proteau, Tremblay and DeJaeger (1998) have pointed out that there are two main reasons why these studies lack support for the specificity of learning hypothesis. First, novice-expert paradigms were typically employed where the effect of removing vision was compared between the two populations. Decrements in performance were found to be similar between the novices and experts or in some cases, greater for the novices. Hence, it appeared that the higher levels of practice usually associated with experts resulted in a decreasing reliance on visual feedback. However, Proteau et al. reasoned that experts likely had a considerable amount of practice without visual feedback outside of the experimental setting and this would have benefited their performance in the no vision transfer test. The second reason offered by Proteau et al. was that in tasks such as catching and beam walking, participants were able to evaluate their performance in the transfer tests by using intrinsic sources of feedback. For example, in catching, participants know whether or not they have caught the ball and in cases where the ball is not caught cleanly, information about ball contact with the hand can be readily picked up. In beam walking, participants can sense the placement of their feet on the beam and any loss of balance through the vestibular system. Using a precision walking task in which participants could not detect the boundary lines marked on the ground, Proteau et al. showed that the decrement in performance when vision was removed increased with practice thereby gaining support for specificity of learning. However, the role and importance of visual feedback from the arm and hand in catching is still questionable (Proteau, 1998).

In terms of aiming movements, the different interpretations offered by Proteau and colleagues (1987, 1990, 1993) and Pratt and Abrams (1996) may be a result of the different types of aiming tasks employed by these two groups of researchers. In the experiments of Proteau and

colleagues, movements were temporally constrained (i.e., movement times had to be within a bandwidth of a criterion movement time) whereas in the work of Pratt and Abrams, movements were to be made as fast as possible. Evidence from both kinematic (Carlton, 1994) and EMG (Gottlieb, Corcos & Agarwal, 1989) analysis has indicated that movements which are produced as fast as possible have different control characteristics compared to movements which are constrained temporally. In addition, while a logarithmic speed-accuracy tradeoff function provides the best fit to data obtained from time minimization movements, a linear function more adequately describes movements with a temporal constraint (Wright & Meyer, 1983; Zelaznik, Mone, McCabe, & Thaman, 1988). Therefore, it is likely that the changes that occur with practice in the control of these two types of aiming tasks are quite different. Another possibility for the opposing viewpoints of Proteau and colleagues and Pratt and Abrams stems from the number of practice trials administered. Proteau and colleagues gave participants up to 2000 trials of practice with the first transfer task typically occurring after 200 trials. In comparison, Pratt and Abrams administered a maximum of 150 practice trials. It is possible that more extensive practice at an aiming movement performed as fast as possible is needed for participants to develop the ability to effectively use visual feedback to detect and correct errors during movement.

Elliott et al. (1995) have shown that with practice, participants learn to adapt their movement trajectories to make optimal use of available visual feedback. One group of participants practiced with visual feedback for the first 600 msec of movement while a second group practiced with vision for the first 400 msec. Consistent with other studies (Corcos, Jaric, Agarwal & Gottlieb, 1993; Moore & Marteniuk, 1985), both groups increased the velocity of their movements with practice while also being able to lower the variability of movement endpoints. Following acquisition, participants in each group were transferred to the visual condition in which the other group had practiced. When participants who practiced with 600

msec of visual feedback were transferred to the 400 msec condition, they further increased the velocity of their movements allowing them to get to the vicinity of the target even earlier. This allowed them to maintain their accuracy level despite having less vision time since they were able to get closer to the target before vision was eliminated. Participants who practiced with 400 msec of vision became more accurate when transferred to the 600 msec condition. This was accomplished primarily by increasing movement times to take advantage of the additional time for which visual feedback was available. These results illustrate that participants modulate their control strategies by adapting movement trajectories to accommodate for the available (or not available) sensory information under the given task constraints.

The importance of developing such feedback processing procedures was further demonstrated in a study by Elliott, Lyons and Dyson (1998). In this study, participants performed movements with a mouse which translated to motion of a cursor on a computer monitor. One group practiced the task with a mouse:cursor gain of 1 to 1, while two other groups practiced with .5 to 1 and 2 to 1 gains. Following acquisition each group performed the task under the 1 to 1 condition. Participants who practiced under the 2 to 1 gain had great difficulty when transferred to the 1 to 1 condition while participants who practiced under the .5 to 1 condition showed reasonably good transfer to the 1 to 1 condition. Elliott et al. proposed that the .5 to 1 group developed feedback processing procedures which involved making high precision movements. This ability to make precise corrective movements transferred well to the 1 to 1 condition. However, practice under the 2 to 1 condition involved making relative large movements and the difficulty experienced by the 2 to 1 group was due to the increase in precision needed to perform corrective movements under the 1 to 1 condition.

This more general procedural or strategy based account of motor learning has been offered as an alternative to the less flexible specificity of learning hypothesis (Bennett & Davids,

1996; Elliott et al., 1995). However, it should be kept in mind that in the studies of Proteau and colleagues, movement times were constrained whereas in the studies of Elliott and colleagues, participants were given the freedom to modulate movements times to optimize performance. Hence, the ability to develop and exhibit flexible control strategies may depend on, among other factors, the constraints imposed during practice and transfer.

1.5. The present experiments

One hundred years ago Woodworth (1899) wrote 'Whether the great virtuosos do away entirely with the later adjustments and achieve their wonderful accuracy by means of the first impulse, would be an interesting thing to find out' (p. 59). It is important to clarify that in making this statement, Woodworth was not implying a progression from closed- to open-loop control whereby the accuracy of initial impulses is increased to the extent that error corrections are eliminated. According to Woodworth, 'The path to skill lies in increasing the accuracy of the initial adjustment, so that the later groping need be only within narrow limits; and through increasing the speed of the groping process, so that finally there seems to be no groping at all' (p. 59). The implication here is that sensory based error corrections may still be present but are no longer visible because they are made with such "perfect smoothness" that they are indistinguishable from the rest of the movement.

Interestingly, these points made by Woodworth are central to issues raised recently in the motor control literature regarding whether learning is due primarily to improved programming (Pratt & Abrams, 1996) and/or increased efficiency of feedback processing (Elliott et al., 1995). However, although the work of Woodworth has been the precursor to much research on issues such as the speed of visual feedback processing and speed-accuracy tradeoff theories, the literature on how the control of aiming movements changes through extensive practice is

relatively limited. Proteau and colleagues have examined performance over extensive levels of practice (2000 trials), but kinematic measures were not recorded. Conversely, in the work of Elliott and colleagues and Pratt and Abrams, movement trajectories were analyzed in detail but participants received rather moderate levels of practice (120 trials and 150 trials, respectively).

The focus of this research is on the particular class of aiming movements in which participants are encouraged to move as fast as possible while maintaining a high degree of accuracy. This is in contrast to the temporally constrained movements used by Proteau and colleagues in which participants were required to produce movements having a specified duration while attempting to maximize accuracy. We investigated the changes in visuomotor control in rapid aiming movements throughout extensive practice by examining (1) the influence of visual feedback on the initial impulse and error correction phases during acquisition; and (2) the effect of removing visual feedback at different levels of practice. Video aiming tasks were employed in which manual movements were translated to movement of a cursor on an oscilloscope screen. Using such a task, visual feedback associated with motion of the limb can be easily manipulated without altering vision of other aspects of the environment such as the home position and target location. The movements used were self terminating (i.e., without a mechanical stop) thus increasing the contribution of antagonist muscles and the precision needed in the deceleration of the movement. Also, movements involved only one spatial degree of freedom thereby simplifying the analysis of movement kinematics.

There were two primary goals of the present research. The first was to test whether the specificity of learning hypothesis holds for movements in which participants are required to minimize movement time while achieving high accuracy levels. If visual feedback is useful for movement control then performance should be better for participants who have this information available during acquisition compared to those who practice without visual feedback. Also, based

on the rationale of Proteau and colleagues (1987, 1990, 1993), the removal of relevant sources of information should result in a decrement in performance with the size of the decrement being directly related to amount of practice that participants receive.

A second goal was to investigate how participants adapt their control strategies to optimize performance with practice. The advantage of examining the influence of vision on both the initial impulse and error correction phases is that inferences can be made about how the effect of practice on visual feedback processing is related to the planning and programming of movements. According to Meyer et al. (1988), the availability of visual feedback does not influence the control strategies adopted by participants and hence the assumptions underlying the stochastic optimized submovement model regarding the spatial and temporal characteristics of submovements do not take into account the role played by visual feedback. The present experiments examine whether movements will be planned differently depending on the availability of visual feedback after extensive levels of practice. Further, if it is assumed that with practice, feedforward control emerges through the use of advance sensory information (Plamondon & Alimi, 1997), one would not expect the manipulation of online sensory information to have a significant impact, especially after extensive practice. On the other hand, if vision is used during movement execution, its withdrawal would have an effect on movement trajectories and performance would deteriorate.

2. The effect of practice on the control of rapid aiming movements: Evidence for an interdependency between programming and feedback processing

In the present experiment, participants were required to perform wrist rotation (supination-pronation) movements in order to move a cursor on an oscilloscope screen from a home position to a target. Wrist movements were a logical choice to begin our investigation since they have been used extensively in past investigations of speed-accuracy tradeoffs (Crossman & Goodeve, 1983; Meyer et al., 1988; Wright & Meyer, 1983). Also, because of their relatively low moment of inertia they are less influenced by passive mechanical factors which could mask active control processes (Meyer et al., 1988).

One group of participants practiced the task with vision of the cursor throughout the movement (FV group) while another group practiced without vision of the cursor (NV group). Knowledge of results (KR) regarding both movement time and accuracy was given after each trial. Three transfer tests were administered under the no vision condition and without verbal KR after 100, 1300 and 2100 trials of practice. If participants do progress from closed-loop to open-loop control, the accuracy of the initial impulse should increase as a function of practice. Concomitant with these changes should be decreases in the percentage of movements that contain error correction phases, as well as, the time spent and the distance traveled during error correction. In addition, any influence of visual feedback on the initial impulse and error correction phases should decrease as a function of practice. On the other hand, if vision becomes increasingly important with practice, differences should exist between visual conditions in the initial impulse and error correction phases even after extensive levels of practice. Also, consistent with Proteau and colleagues (1987, 1990, 1993), the acquisition to transfer decrements for the FV group relative to the NV group ought to increase as participants receive more practice at the aiming task.

2.1. Method

2.1.1. Participants

Sixteen self declared, right hand dominant, university students served as participants in the study. All were naive to the hypothesis being tested and inexperienced at the experimental task. The experiment was carried out according to the ethical guidelines laid down by the University of British Columbia Behavioral Sciences Ethics Board for studies involving human participants.

2.1.2. Apparatus

The participants sat in a chair and positioned their left forearm on a padded horizontal base located in the sagittal plane. From this position the participants grasped a handle which rotated along the axis of their forearm with minimal friction. The position of the base was adjusted to accommodate for varying forearm lengths. Also, the height of the chair was adjusted such that the angle between the forearm and the upper arm was approximately 90 degrees. The forearm and hand were hidden from the participants' view by an opaque shield.

Visual displays of the home position, target region, and a cursor representing limb position appeared on an oscilloscope screen that was positioned in front of the participants at a distance of 50 cm. The home position was located to the left of the screen and consisted of a box 4.5 mm wide. The target was located 9 cm to the right of the home position (center to center) and also consisted of a box 4.5 mm wide. The cursor was a round dot 1 mm in diameter. Clockwise and counterclockwise rotation of the handle caused the cursor to move to the right and left, respectively. Each degree of forearm rotation corresponded to 2 mm of cursor movement. Therefore, the angular distance between the home position and the target was 45 degrees of wrist rotation (-22.5 to +22.5 vertical) while the width of the target was 2.25 degrees of wrist rotation. This distance-width combination yielded an Index of Difficulty of 4.3 bits (Fitts, 1954).

Knowledge of results (KR) regarding accuracy (degrees of rotation) and movement time (msec) was presented on a monitor located to the left of the oscilloscope screen.

Angular displacement was obtained through a precision potentiometer which was attached to the handle. The analog signal was sampled at 1000 Hz. The angular displacement data were filtered using a two pass digital Butterworth filter with a cutoff frequency of 20 Hz and then differentiated in order to obtain angular velocity. Angular acceleration data were obtained through the use of a Kistler accelerometer (type 8638B50, ± 50 G) which was positioned at the upper end of the handle, 7.5 cm from the axis of rotation. Its analog signal was first filtered using a Krone-Hite, # 3750 analog filter with a lowpass frequency of 50 Hz and then digitally sampled at 1000 Hz. To correct for the influence of gravity, the displacement data were differentiated twice and then filtered at 5 Hz to obtain an envelope of an acceleration profile that was not biased due to gravity. The biased acceleration profile from the accelerometer was also filtered at 5 Hz. The difference between these two envelopes, which represents the offset due to gravity, was then added to the original acceleration profile from the accelerometer.

2.1.3. Procedure

At the beginning of each trial, the home position, target area and the cursor representing rotation of the forearm appeared on the oscilloscope screen. Participants were required to move the cursor to the middle of the home position. Once the cursor was steadily placed at the home position a tone was presented. Participants were free to initiate their movements anytime within 1500 msec following the onset of the tone and were informed that it was not necessary to minimize reaction time. Participants were instructed to move the cursor from its starting location to the target region as quickly and as accurately as possible. However, it was explained that the goal was to minimize total movement time (i.e., the interval from when the limb started to move

to when it came to a complete stop). This was encouraged by means of a point system similar to that used by Abrams and Pratt (1993) and Meyer et al. (1988). That is, participants had to hit the target in order to earn points and the number of points gained was inversely related to their movement time.

The participants were divided into two groups of eight. One group practiced the aiming task with vision of the cursor throughout each trial (full vision condition (FV)). The second group of participants practiced under a condition in which the cursor disappeared from view as soon as the velocity of the handle became greater than 10 deg/sec (no vision condition (NV)). Therefore, in this condition, participants were able to see the cursor only at the home position prior to movement initiation. The cursor did not reappear until it was time to prepare for the subsequent trial. For both visual conditions, the home position and target remained visible for 5 seconds from the initiation of each trial.

Participants in each group were required to perform 2100 acquisition trials in eight sessions over a two week period (see Table 2.1). During the acquisition phases, participants were given KR regarding accuracy and movement time after each trial. The participants of both groups were submitted to three transfer tests which consisted of 20 trials performed under the no vision condition, but with no KR. The first transfer test took place after 100 trials, the second after 1300 trials and the third after 2100 trials of practice. Participants were given five minutes rest before each transfer test.

2.1.4. Movement analysis

The method used to separate the initial impulse and error correction phases of movement in the present study was based on the movement parsing algorithm developed by Meyer et al. (1988) (see Figure 1.1). The algorithm involved implementing various criteria so that

Table 2.1

Breakdown of trials for participants in the full vision (FV) and no vision (NV) groups

<u>Participants</u>	<u>Day1</u>	<u>Day2</u>	<u>Day3</u>	<u>Day4</u>	<u>Day5</u>	<u>Day6</u>	<u>Day7</u>	<u>Day8</u>
1-8(FV group)	100FV 20NV*	300FV	300FV	300FV	300FV 20NV*	300FV	300FV	200NV 20NV*
9-16(NV group)	100NV 20NV*	300NV	300NV	300NV	300NV 20NV*	300NV	300NV	200NV 20NV*

* No KR

submovements due to active control processes were detected rather than movement due to physiological tremor and passive springlike oscillations. A search was first performed for peak angular velocity. The angular velocity profile was then traversed backwards in time until the velocity fell below 10 deg/sec. This point was defined as the beginning of the movement. The end of the movement was defined as the point in time following peak velocity in which the absolute angular velocity of the handle fell below 10 deg/sec for 150 msec. A search was then performed from peak velocity to the end of the movement for a possible initiation of an error correction phase, i.e., the occurrence of one of the following movement modifications, (a) a positive to negative zero line crossing in velocity, (b) a negative to positive zero line crossing in the acceleration trace, or (c) a significant deviation in the acceleration trace, i.e., a relative minimum in the absolute value of the acceleration while the acceleration is negative. In order to qualify as a significant deviation, neither a preceding nor postceding absolute maximum could lie within 30 msec of the relative minimum (see also Chua & Elliott, 1993; and van Donkelaar & Franks, 1991). Also, the difference in the absolute values of acceleration between the minimum and maximums had to be at least 100 deg/sec². If the duration between the first movement modification and the end of the movement was greater than 60 msec and the distance traveled during this time was more than .5 degrees, the movement was said to contain an error correction phase. When neither of these criteria were met, the movement was deemed to contain only an initial impulse phase and the end of the movement was repositioned at the first movement modification. Within the error correction phases, all movement modifications in the acceleration profile that were separated by at least 60 msec were recorded.

2.2. Results

2.2.1. Acquisition

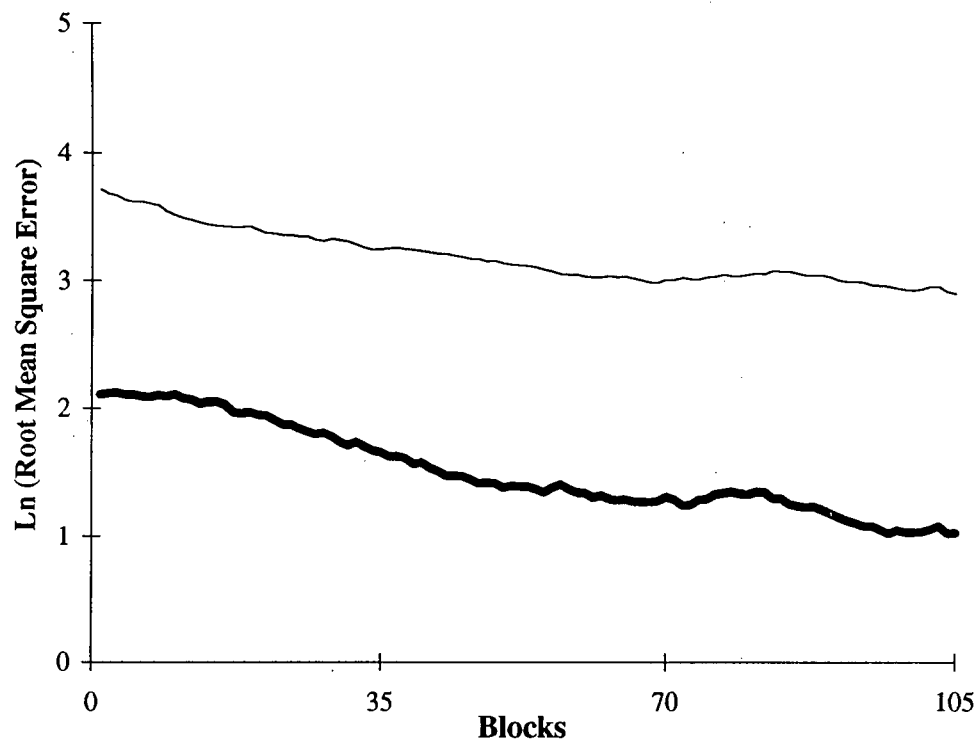
In order to compare performance at different levels of practice, the 2100 practice trials for each participant were divided into three stages of practice each consisting of 700 trials. The trials for each level of practice were then divided into 35 blocks of 20 trials. All dependent measures were separately analyzed by performing a 2 Visual Condition x 3 Practice x 35 Blocks ANOVA with repeated measures on the last two factors (please see Note 1, page 137). Since relatively permanent changes in performance were of interest (cf. Magill, 1992, p. 44), reported here are the results of linear and quadratic trend analyses and not multiple comparisons among blocks.

Performance Measures: In keeping with Proteau and colleagues (1987, 1990, 1993), spatial accuracy was assessed by using root mean square error (RMSE) as the dependent variable. RMSE represents the total variability of responses about a target and is considered to be the best overall measure of performance accuracy (Henry, 1975). Because RMSE has a positively skewed distribution, a logarithmic transformation was performed before submitting the data to analysis (Proteau et al., 1992).

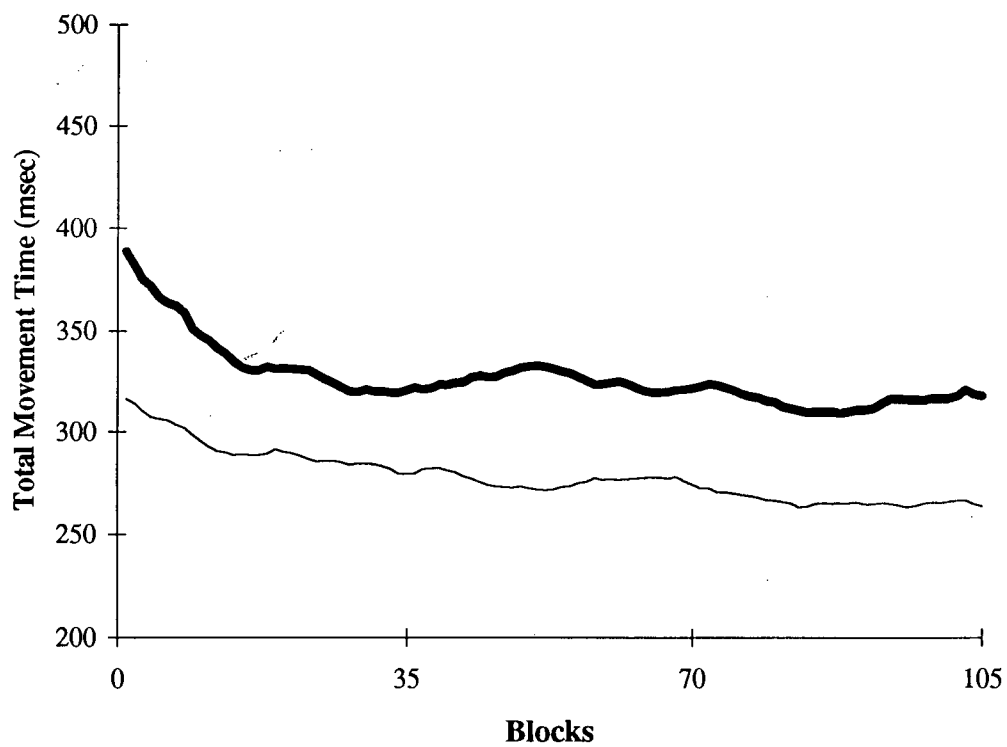
In the present study, participants were instructed to move as fast and as accurately as possible. Participants improved their performance on both accounts as they lowered movement times and became more accurate with practice, $F(1,14) = 11.4, p < .01$ (linear) and $F(1,14) = 42.7, p < .001$ (linear), respectively (see Figure 2.1). Also, consistent with past research (Chua & Elliott, 1993; Pratt & Abrams, 1996), movements performed with visual feedback were more accurate, $F(1, 14) = 65.1, p < .001$, but had longer movement times, $F(1,14) = 8.7, p < .01$, compared to movements performed without visual feedback. No interactions between visual condition and practice were significant ($p > .05$).

Figure 2.1. Mean root mean square error (after logarithmic transformation) (a) and total movement times (b), as a function of practice for the full vision (thicker lines) and no vision conditions (thinner lines). Group means have been smoothed using a 15 point moving average filter.

(a)



(b)



Initial Impulse Phase: The results of the ANOVAs performed on the dependent measures of the initial impulse and error correction phases are presented in Table 2.2. As shown in Figure 2.2, participants increased the distance traveled in the initial impulse phase with practice. While there was no significant difference between visual conditions in initial impulse distance, there was a tendency for participants in the NV group to travel further in the initial impulse phase compared to participants in the FV group ($p = .10$).²

When the distance traveled in the initial impulse was taken as a proportion of the total distance, there was a significant difference between visual conditions with participants in the NV group travelling a significantly larger proportion of their movements in the initial impulse phase compared to participants in the FV group. Also, a triple interaction between practice, blocks and visual condition revealed that the difference between the two visual conditions tended to decrease early in practice while it appeared to increase later in practice.

Main effects of practice and blocks on the standard deviations of the initial impulse endpoints revealed that the variability of the distance traveled in the initial impulse decreased with practice. Also, initial impulse variability was higher for participants in the NV compared to FV group. This effect decreased with practice as indicated by a practice x visual condition interaction.

Only a main effect of blocks on the time spent in the initial impulse was significant. However, similar to the initial impulse distance/total distance results, participants in the NV group spent proportionally more time in the initial impulse phase compared to participants in the FV

² Separate ANOVAs performed over the first 800 and last 1300 trials indicated that a significant difference did emerge later in practice ($p < .05$).

Table 2.2. Summary of ANOVA results performed on the dependent measures of the initial impulse and error correction phases

<u>Initial Impulse Phase</u>	F value	
	linear	quadratic
<i>Initial Impulse distance</i>		
Practice	0.1	1.2
Blocks	1.1	7.6**
Visual Condition	2.9	
Practice x Blocks	2.5	0.2
Practice x Visual Condition	0.7	0.7
Blocks x Visual Condition	0.6	2.2
Practice x Blocks x Visual Condition	0.5	0.0

Initial Impulse Distance/Total Distance

Practice	10.9**	1.3
Blocks	22.0***	6.6*
Visual Condition	7.1**	
Practice x Blocks	7.7**	2.6
Practice x Visual Condition	0.8	4.8*
Blocks x Visual Condition	1.8	0.1
Practice x Blocks x Visual Condition	8.2**	0.7

Initial Impulse Variability

Practice	68.3***	5.2*
Blocks	39.3***	13.9**
Visual Condition	8.6**	
Practice x Blocks	22.0***	2.9
Practice x Visual Condition	7.5**	0.4
Blocks x Visual Condition	0.2	2.8
Practice x Blocks x Visual Condition	0.0	0.0

Initial Impulse MT

Practice	1.6	0.1
Blocks	6.3*	0.0
Visual Condition	0.0	
Practice x Blocks	1.1	1.3
Practice x Visual Condition	0.1	3.2
Blocks x Visual Condition	1.5	1.3
Practice x Blocks x Visual Condition	.5	0.0

Initial Impulse MT/Total MT

Practice	5.6*	0.0
Blocks	4.7*	2.7
Visual Condition	5.9*	
Practice x Blocks	1.9	1.7
Practice x Visual Condition	0.9	8.7**
Blocks x Visual Condition	0.0	1.1
Practice x Blocks x Visual Condition	3.5	0.1

* significant at .05

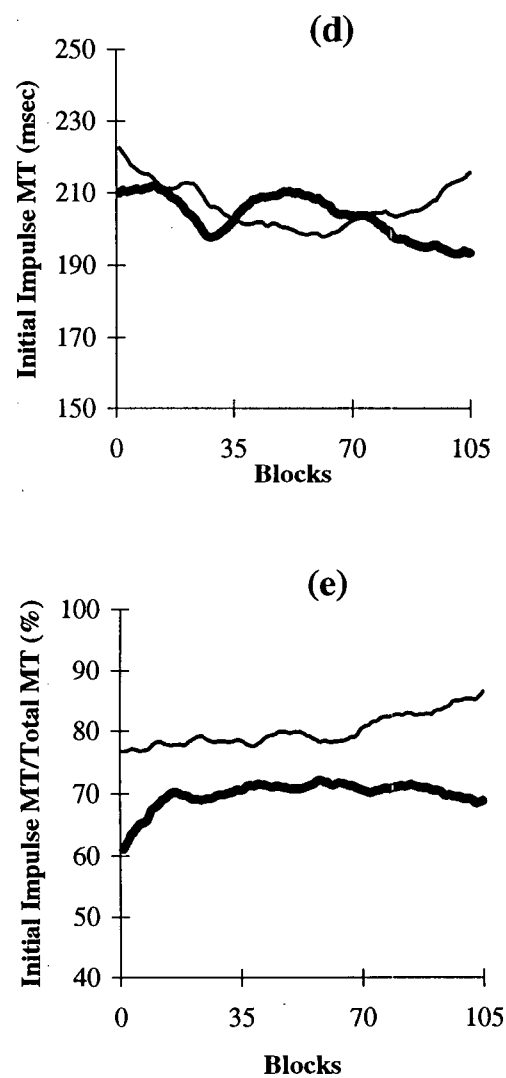
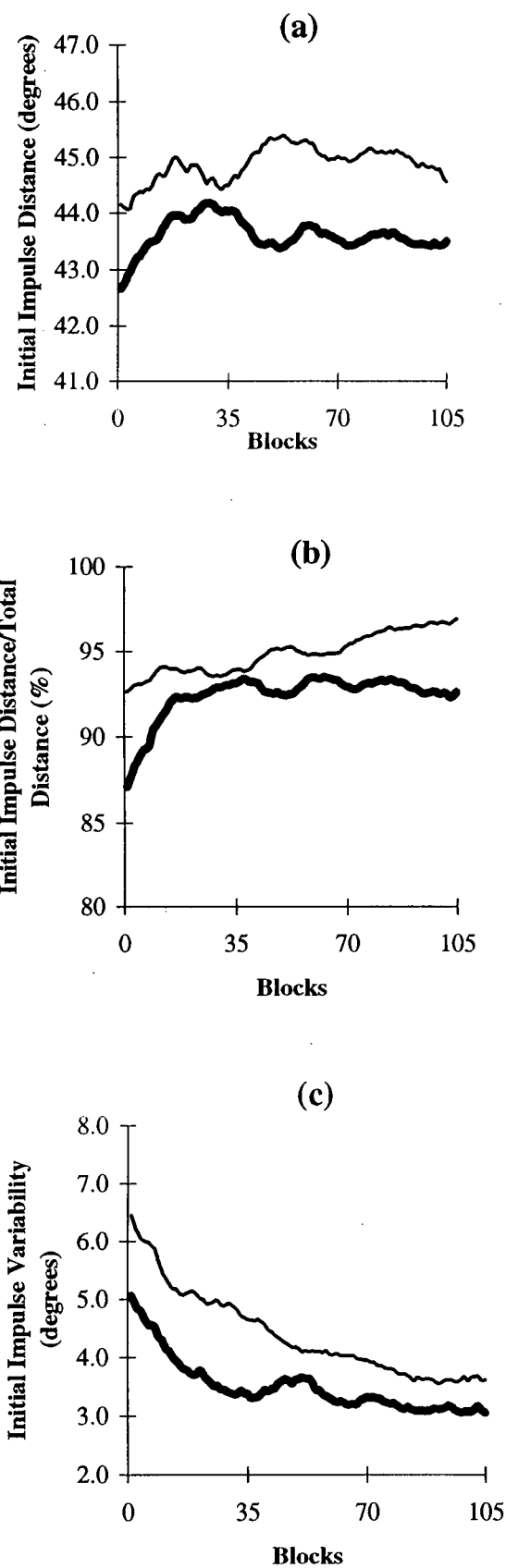
** significant at .01

*** significant at .001

Table 2.2 continued

<u>Error Correction Phase</u>	<u>F value</u>	
<i>% of Movements with Error Correction</i>	linear	quadratic
Practice	11.2**	0.0
Blocks	6.7*	0.6
Visual Condition	6.7*	
Practice x Blocks	1.0	0.9
Practice x Visual Condition	1.6	5.3*
Blocks x Visual Condition	0.0	0.8
Practice x Blocks x Visual Condition	1.2	0.0
<i>Error Correction Distance</i>		
Practice	6.1*	0.3
Blocks	7.7**	13.4**
Visual Condition	0.15	
Practice x Blocks	1.9	2.0
Practice x Visual Condition	0.6	0.5
Blocks x Visual Condition	1.9	0.6
Practice x Blocks x Visual Condition	1.3	2.1
<i>Error Correction MT</i>		
Practice	1.3	0.3
Blocks	2.4	8.8**
Visual Condition	17.2***	
Practice x Blocks	2.6	2.8
Practice x Visual Condition	0.0	0.4
Blocks x Visual Condition	0.1	0.1
Practice x Blocks x Visual Condition	1.8	0.0
<i>Number of Modifications per Trial</i>		
Practice	3.3	0.8
Blocks	4.1	3.2
Visual Condition	22.1***	
Practice x Blocks	3.5	3.7
Practice x Visual Condition	0.0	0.8
Blocks x Visual Condition	0.6	0.1
Practice x Blocks x Visual Condition	2.9	0.2
<i>IECE</i>		
Practice	1.0	0.1
Blocks	0.0	7.4**
Visual Condition	79.5***	
Practice x Blocks	1.0	0.0
Practice x Visual Condition	.9	0.0
Blocks x Visual Condition	1.2	1.0
Practice x Blocks x Visual Condition	1.0	0.0

Figure 2.2. Mean initial impulse distance (a), initial impulse distance/total distance (b), initial impulse variability (c), initial impulse movement time (d), and initial impulse movement time/total movement time (e), as a function of practice for the full vision (thicker lines) and no vision conditions (thinner lines). Group means have been smoothed using a 15 point moving average filter.



group. In addition, there was a tendency for the difference between the two groups to decrease during the early stages of practice but increase later in practice ($p = .08$).

Error Correction Phase: The results of the error correction phases are illustrated in Figure 2.3. Both groups significantly reduced the percentage of movements that contained an error correction phase with practice. A significant visual condition main effect indicated that a greater percentage of movements contained error corrections in the FV compared to the NV condition.

For those movements that did contain error correction phases, the absolute distance traveled and the time spent during error correction decreased with practice. Also, there was a tendency for the number of movement modifications made in the error correction phases to decrease with practice ($p = .06$). Although no differences existed between visual conditions in the distance traveled in the error correction phase, error correction movement time and the number of movement modifications were greater in the FV condition compared to the NV condition. Therefore, error corrections performed with vision were characterized by more numerous but smaller adjustments to the movement compared to corrections performed without vision. These differences between the two visual conditions in error correction movement time and the number of modifications persisted throughout practice.

In order to specifically examine how effective the error correction phases were in reducing error, we computed the following index of error correction effectiveness (see Figure 2.4),

$$\text{IECE} = \frac{\text{AE(ii)} - \text{AE(ec)}}{\text{AE(ii)} + \text{AE(ec)}}$$

where AE(ii) is the absolute error at the end of the initial impulse phase and AE(ec) is the absolute error after the error correction phase. The numerator gives an indication of how much closer the participants got to the target from the end of the initial impulse to the termination of the

Figure 2.3. Mean percentage of movements that contain error correction phases (a), error correction distance (b), error correction movement time (c), number of movement modifications per trial (d), and index of error correction effectiveness (e), as a function of practice for the full vision (thicker lines) and no vision condition (thinner lines). Group means have been smoothed using a 15 point moving average filter.

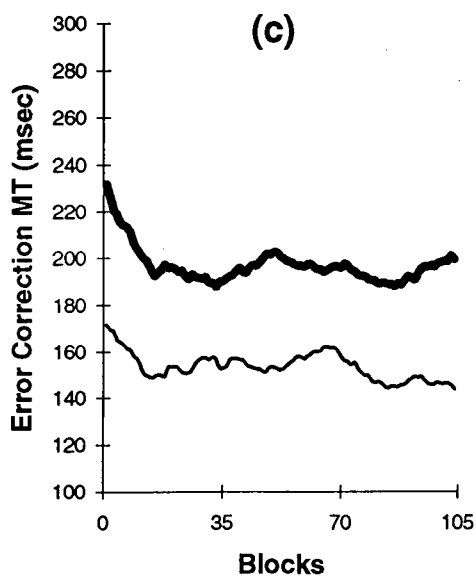
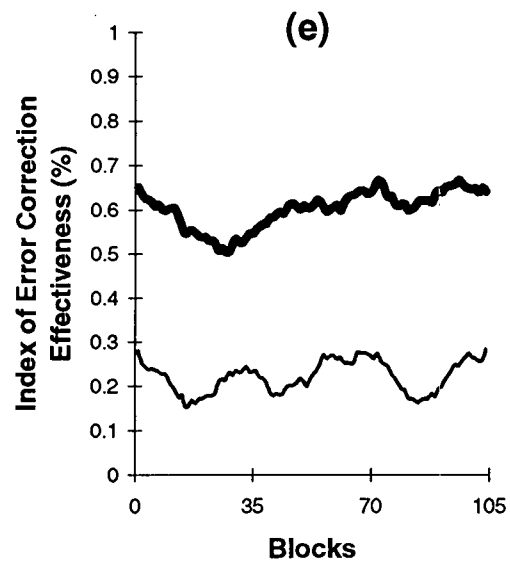
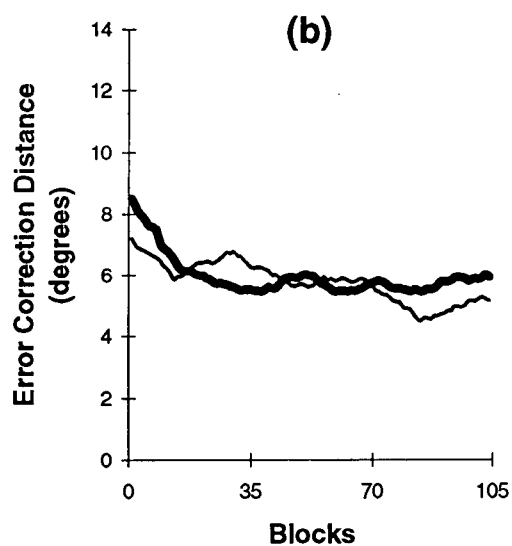
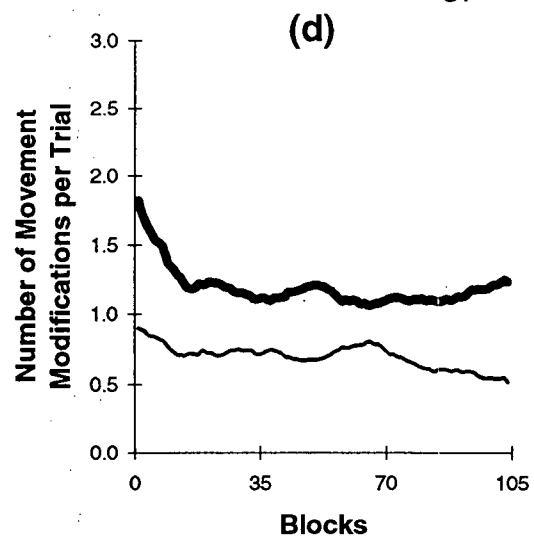
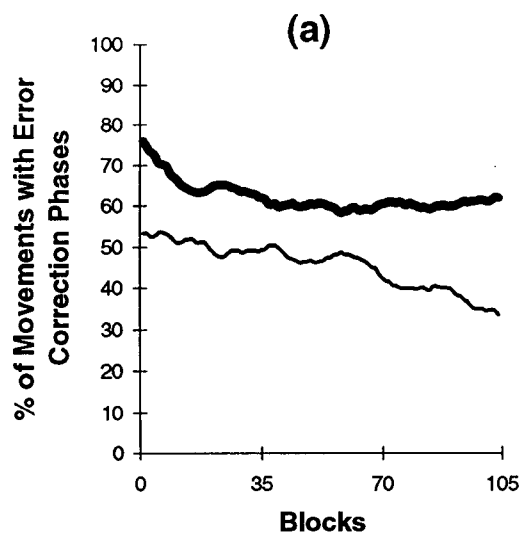
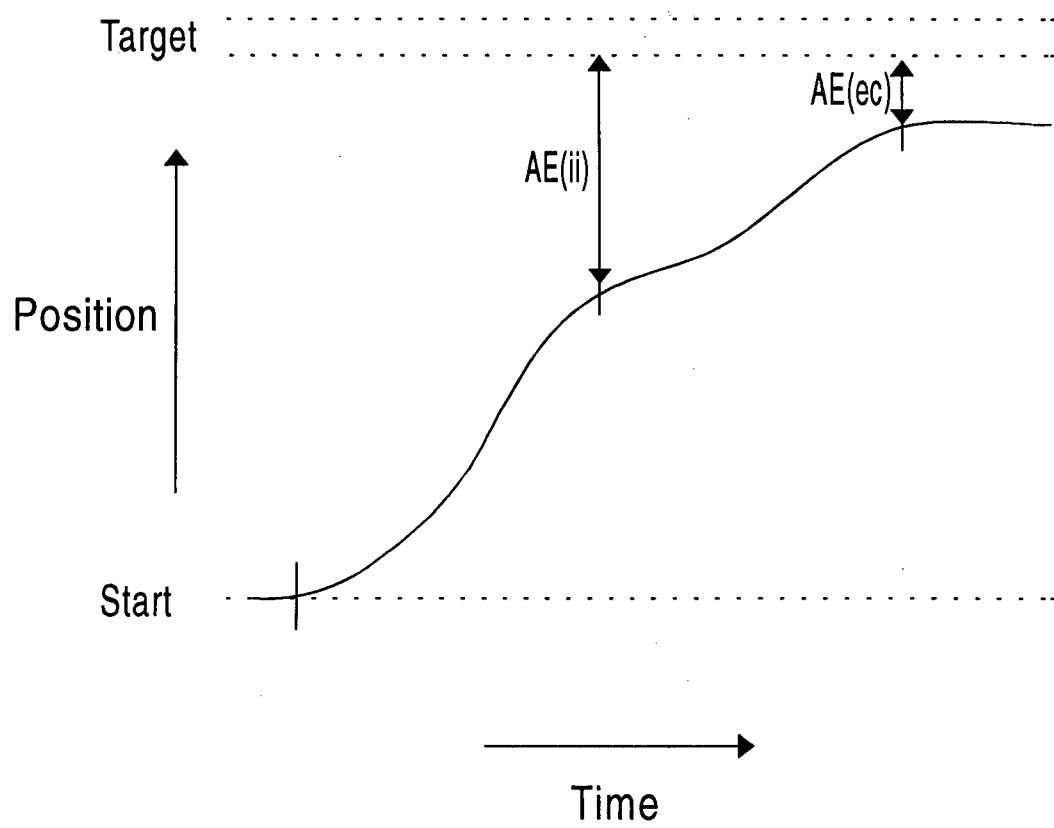


Figure 2.4. Sample position vs time profile illustrating calculation of the index of error correction effectiveness (AE(ii)-absolute error following initial impulse phase, AE(ec)-absolute error following error correction phase).



movement, while the denominator normalizes for the size of the errors following the initial impulse and error correction phases.³ An ANOVA performed on IECE revealed a significant effect of blocks. Also, error corrections performed with vision of the cursor were significantly more effective than error corrections performed without vision.

2.2.2. Practice vs transfer performance

In the present study, the FV group practiced with visual information about the position of the limb and were given KR after each trial, while the NV group practiced with no visual feedback but were given KR. Based on the work of Proteau and colleagues (1987, 1990, 1993), the importance of visual feedback was assessed by comparing the effect of removing both visual feedback and KR from the FV group with the effect of removing KR from the NV group. Towards this end, the difference in the results between the 20 transfer trials and the preceding 20 practice trials was calculated. A 2 visual conditions x 3 levels of practice ANOVA was then performed on the difference between the acquisition and transfer phases.

Performance measures: The ANOVA performed on $\ln(\text{RMSE})$ revealed main effects for visual condition, $F(1,14) = 160.8$, $p < .001$, and practice, $F(2, 28) = 6.1$, $p < .01$. In addition, there was a significant interaction between visual condition and practice, $F(2, 28) = 5.6$, $p < .05$ (see Figure 2.5). A breakdown of this interaction using Scheffé post hoc tests ($p < .05$) indicated that the difference in the practice to transfer decrements between the FV and NV conditions was larger after 1300 and 2100 compared to after 100 trials of practice. Also, the difference between the

³ $0 < \text{IECE} \leq 1$ implies that the limb moved closer to the target following the initial impulse phase with a value of 1 being a perfect error correction. $\text{IECE} = 0$ indicates that the limb did not move closer to the target while $-1 \leq \text{IECE} < 0$ indicates that the limb moved further from the target following the initial impulse.

Figure 2.5. Mean difference in $\text{Ln}(\text{root mean square error})$ between twenty transfer trials and preceding twenty practice trials after 100, 1300 and 2100 practice trials for the full vision and no vision conditions.

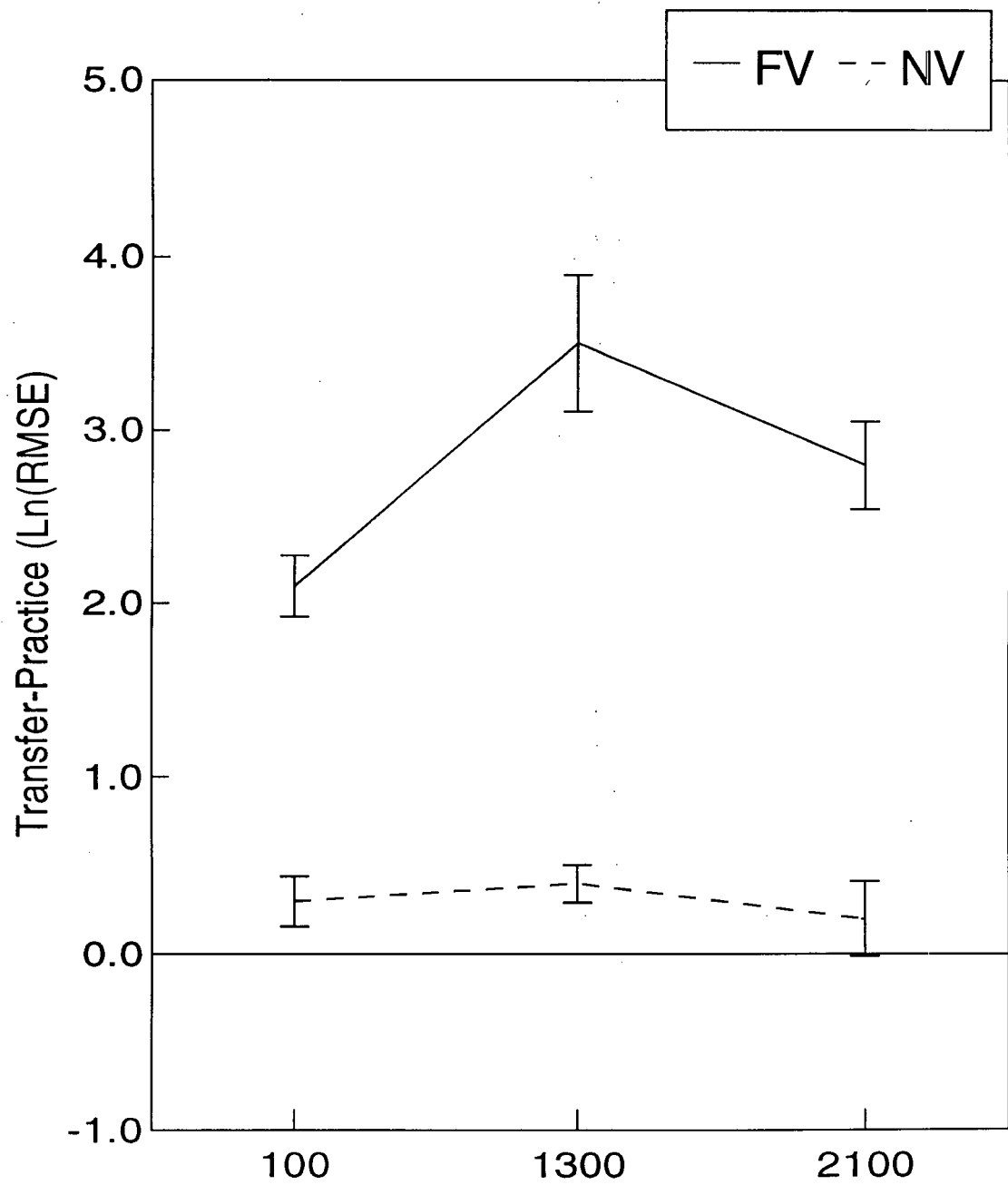


Table 2.3. Mean and standard deviations of dependent variables for performance, initial impulse and error correction phases for transfer (T) tests and previous twenty acquisition (A) trials.

		A1	T1	A2	T2
Ln(RMSE)	FV	2.1(0.5)	4.1(0.5)	0.7(0.7)	4.2(0.7)
	NV	3.6(0.4)	4.0(0.3)	3.1(0.3)	3.5(0.4)
Total MT (msec)	FV	365(58)	338(87)	303(45)	310(68)
	NV	310(63)	314(20)	290(32)	297(50)
Initial Impulse Distance (degrees)	FV	42.5(3.4)	44.4(8.0)	43.8(1.5)	50.0(6.8)
	NV	44.8(2.7)	45.1(3.4)	45.7(3.6)	46.5(4.7)
Initial Impulse Variability (degrees)	FV	4.9(1.6)	6.6(2.5)	2.8(0.8)	6.1(2.6)
	NV	6.0(1.6)	7.3(1.1)	4.2(1.2)	4.9(1.2)
Initial Impulse MT (msec)	FV	216(42)	218(38)	194(45)	201(46)
	NV	238(53)	233(46)	202(52)	203(45)
% of Movements with error corrections	FV	71(23)	63(25)	52(21)	66(14)
	NV	44(24)	48(23)	49(31)	55(33)
Error Correction Distance (degrees)	FV	7.9(1.9)	7.6(3.9)	5.4(1.7)	6.6(3.6)
	NV	7.8(4.5)	9.5(5.8)	5.9(4.7)	6.4(4.2)
Error Correction MT (msec)	FV	205(26)	175(57)	211(59)	163(45)
	NV	156(61)	169(29)	164(53)	166(44)
# of Movement Modifications per Trial	FV	1.6(0.5)	1.1(0.7)	1.0(0.6)	1.0(0.6)
	NV	0.7(0.4)	0.8(0.3)	0.9(0.7)	0.9(0.6)
IECE (%)	FV	75(13)	13(20)	78(22)	11(23)
	NV	28(32)	23(26)	32(26)	29(26)
Initial Impulse Distance/Total Distance (%)	FV	88(4)	90(7)	94(3)	92(5)
	NV	94(5)	93(4)	94(6)	93(6)
Initial Impulse MT/Total MT (%)	FV	66(14)	72(15)	73(14)	72(8)
	NV	82(10)	79(10)	76(18)	75(18)

Table 2.3. Continued

		A3	T3
Ln(RMSE)	FV	1.0(0.6)	3.8(0.5)
	NV	2.8(0.6)	3.0(0.4)
Total MT (msec)	FV	299(38)	298(50)
	NV	267(36)	277(45)
Initial Impulse Distance (degrees)	FV	43.3(1.1)	47.3(6.4)
	NV	45.0(1.2)	44.4(2.8)
Initial Impulse Variability (degrees)	FV	2.9(0.9)	4.7(1.1)
	NV	3.8(.7)	3.7(0.9)
Initial Impulse MT (msec)	FV	188(44)	195(43)
	NV	220(50)	221(43)
% of Movements with error corrections	FV	59(26)	56(27)
	NV	33(18)	37(22)
Error Correction Distance (degrees)	FV	5.0(1.8)	5.2(1.7)
	NV	5.4(2.6)	3.9(2.3)
Error Correction MT (msec)	FV	181(52)	174(50)
	NV	137(29)	128(58)
# of Movement Modifications per Trial	FV	1.1(0.5)	1.0(0.7)
	NV	0.4(0.3)	0.6(0.4)
IECE (%)	FV	74(20)	20(18)
	NV	41(28)	24(24)
Initial Impulse Distance/Total Distance (%)	FV	94(4)	94(4)
	NV	97(1)	97(3)
Initial Impulse MT/Total MT (%)	FV	71(16)	73(18)
	NV	86(7)	85(10)

visual conditions was less after 2100 compared to after 1300 trials of practice. There were no main effects of visual condition or practice on total movement time ($F < 1$). The interaction between visual condition and practice was also non-significant ($F < 1$).

Initial impulse phase: As illustrated in Figure 2.6a, an ANOVA performed on the difference between the practice and transfer trials revealed that there was an increase in the distance traveled in the initial impulse phase for the FV group which was not apparent for the NV group, $F(1, 14) = 4.2$, $p < .05$. Also, there was an increase in the variability of the initial impulse endpoints which was greater for the FV compared to the NV group, $F(1, 14) = 7.2$, $p < .01$. No other effects of the transfers on the properties of the initial impulse were significant ($p > .05$).

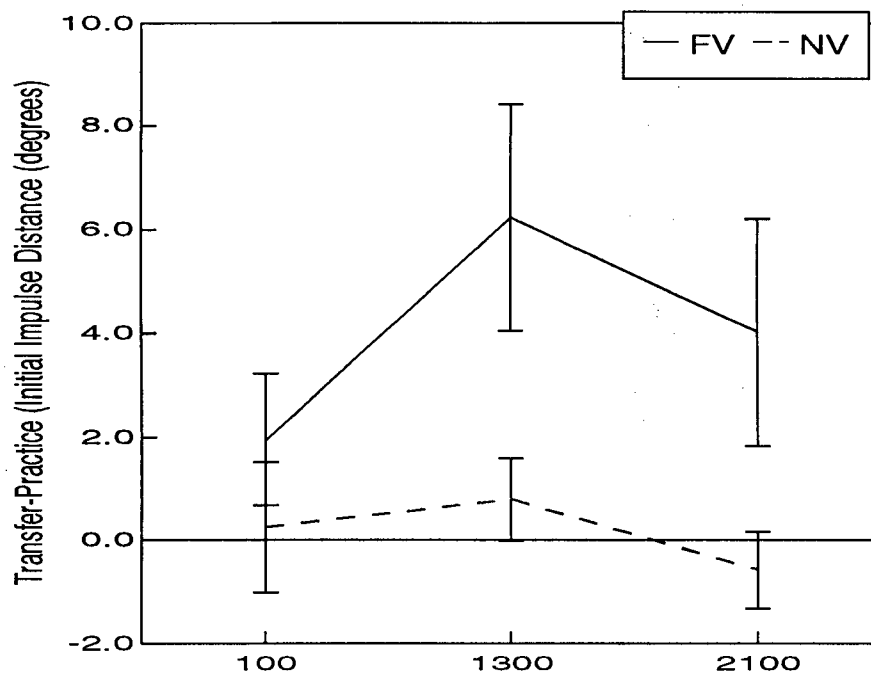
Error correction phase: The only significant effects of the transfers were on the effectiveness of the error correction phases (IECE) (see Figure 2.6b). A visual condition main effect indicated that there was a significantly larger drop in the effectiveness of the error correction phases for the FV group compared to the NV group, $F(1, 14) = 9.6$, $p < .01$. This effect did not interact with practice ($F < 1.0$).

2.3. Discussion

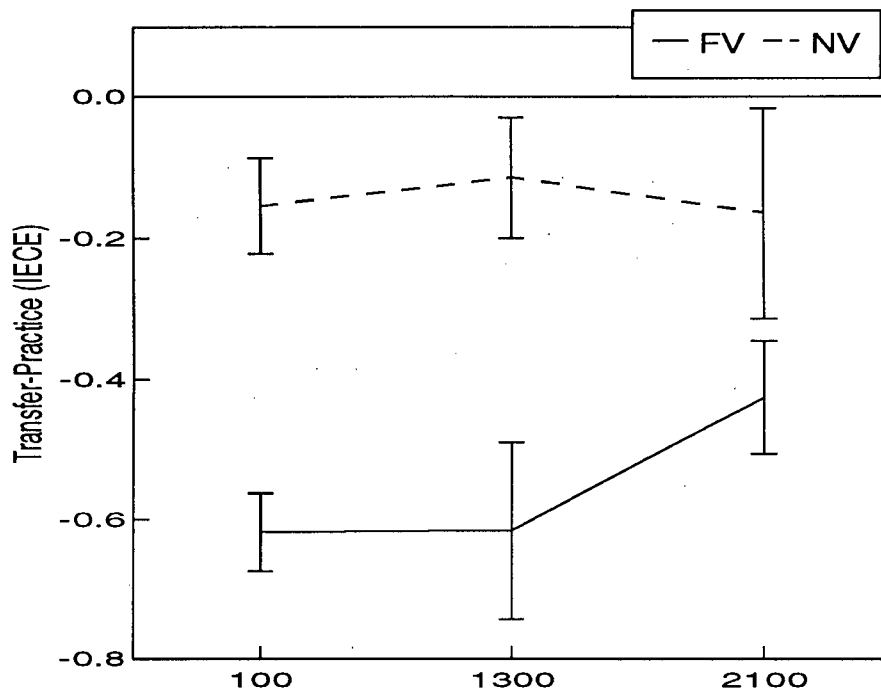
The control of movement is assumed to occur through central programming and the processing of feedback information. In aiming movements, the study of these two control processes has been undertaken through analysis of the initial impulse and error correction phases. The initial impulse is assumed to be pre-programmed while the error correction phase is said to be controlled by feedback processing. Past work has shown that for movements performed as fast and as accurately as possible, participants adopted similar control strategies under different visual conditions (Meyer et al., 1988) and that vision had a relatively minor impact on practice related

Figure 2.6. Mean difference in initial impulse distance (a) and error correction effectiveness (b) between twenty transfer trials and preceding twenty practice trials after 100, 1300, 2100 practice trials for the full vision and no vision conditions.

(a)



(b)



changes to the initial impulse and error correction phases (Pratt & Abrams, 1996). In contrast, studies using temporally constrained movements have shown that visual feedback plays an important role in movement control and that the reliance on vision increases as a function of practice (Proteau et al., 1987, 1990, 1993). The goal of the present experiment was to examine whether more extensive practice at a task in which participants are encouraged to move as fast and as accurately as possible enables participants to develop the ability to effectively use visual feedback. If such were the case, of interest was whether participants became increasingly reliant on vision as a function of practice.

The results indicated that after extensive practice, differences did exist between visual conditions in the organization of the initial impulse and error correction phases. During the later stages of practice, participants in the FV group showed a tendency to undershoot the target in the initial impulse phase. In contrast, there was no evidence for undershooting of the initial impulse for participants in the NV group. Likewise, the differences between visual conditions in both the proportion of total MT spent in the initial impulse phase and the proportion of the total distance traveled during the initial impulse phase increased during the later stages of practice. It is believed that these differences emerged between conditions because of different control strategies adopted by participants. Participants in the FV group may have undershot the target in the initial impulse phase in order to enable visually based on-line error corrections to proceed in the same direction in which the movement was originally programmed (Ricker, Elliott, Lyons, Gauldie & Byblow, in press; Meyer et al., 1988). This mode of control was evident even after extensive levels of practice. In contrast, participants without visual feedback exhibited a progression towards a more open loop mode of control whereby they attempted to produce movements which were predominantly preprogrammed in order to avoid the use of less effective proprioceptive feedback. Indeed, error corrections were more abundant and proved to be more effective in reducing error

when visual feedback was available compared to when it was not. Furthermore, the more extensive error corrections in the full vision condition cannot be attributed to impulse variability differences (Meyer et al., 1988) since initial impulses were more variable for the no vision condition.

These differences between conditions suggest that vision may be playing a larger role in the learning of rapid aiming movements than previously posited (Meyer et al., 1988; Pratt & Abrams, 1996). Additional evidence which suggests that participants were largely dependent on vision after considerable levels of practice was revealed in the results of the transfer tests. When participants went from the acquisition to the transfer trials, there was a larger increase in RMSE for the FV compared to the NV condition. In addition, as participants received more practice at the task, the practice to transfer decrement increased for the FV group relative to the NV group. The larger decrement for the FV group at later stages of practice reflects a greater cost of removing visual feedback and hence an increasing importance of vision as a function of practice (Proteau et al., 1987, 1990, 1993). Hence, similar to temporally constrained movements, there appears to be an increasing reliance on visual feedback as a function of practice for movements which are performed as fast and as accurately as possible.

The difference in practice to transfer decrements between visual conditions was greater after 1300 and 2100 trials compared to after 100 trials. As stated, this suggests that vision was more important at later stages of practice compared to earlier in practice. However, the difference between visual conditions did decrease from 1300 to 2100 trials of practice. This would suggest a decreasing reliance on visual feedback, either a progression from closed to open loop control, or an increasing reliance on proprioceptive feedback. A progression from closed to open loop control seems unlikely given the results of the practice trials where the differences between groups persisted throughout practice. A more plausible explanation is that vision was

used to accurately calibrate proprioceptive feedback (see Proteau & Marteniuk, 1993) and that later in practice a greater dependence was placed on the processing of proprioceptive feedback. Such a proposal would point to the importance of intersensory correlations in the development of distinct unimodal sensory stores. This is in contrast to Proteau and Cournoyer (1990) who proposed that with practice, sensory information is integrated to form an intermodal representation of expected sensory consequences. In any event, this issue warrants further investigation. A comparison of the results after 100 trials with those after 1300 or 2100 trials is consistent with the findings of Proteau and colleagues who typically employed a maximum of two transfer tests. Therefore, no intermediate comparison was possible. While the present study has the advantage that comparisons can be made at more than two levels of practice, it was possible that the experience participants received in the first two transfer tests may have aided their performance on the third.

The removal of visual feedback from the FV group in all three transfer phases resulted in RMSEs roughly similar to that of the NV group at the beginning of acquisition. This might suggest that regardless of how much participants practiced with visual feedback, its removal resulted in performance reverting to that of participants untrained in the no vision condition. However, a more detailed analysis reveals that initial impulses undershot the centre of the target early in practice for the NV group while they overshot the target when vision was removed from the FV group. This was particularly evident during the later stages of practice. Hence, performance in the transfer tests was fundamentally different from that of the NV group early in acquisition and therefore, whatever changes occurred in the visual control of the movements were reflected in transfer performance.

As mentioned, the removal of visual feedback had a major impact on the accuracy of initial impulse endpoints. This result was surprising at first, since one would have expected the initial

impulse, which is supposedly preprogrammed, to not be influenced by feedback manipulation. Also, it seriously questions whether kinematic profiles emerge solely from ballistic control processes described by the weighted difference between pulses from the agonist and antagonist muscles (Plamondon & Alimi, 1997). If visual feedback is not used during the execution of movement, one would not expect the timing of these pulses to be affected by the removal of vision, especially after extensive practice.

One possible reason for the effect of the transfer on movement kinematics may be due to a change in strategy. As discussed earlier, when visual feedback was available, participants undershot the target in the initial impulse phase and then relied on vision to 'home-in' on the target. The removal of visual feedback would have disrupted this interplay between programming and feedback processes. Consistent with this interpretation is that the effectiveness of the error correction phases was adversely affected by the removal of vision. Participants may have attempted to compensate for the loss of effective feedback processing by altering the programming of the initial impulse thereby increasing the distance and variability of initial impulse endpoints. Similar findings have been reported by other researchers who have shown that participants learn to flexibly adapt the early trajectory of their movements to accommodate for the available (or not available) sensory information (Bennett & Davids, 1996; Elliott et al., 1995).

Another plausible explanation for the effect of the transfer on the initial impulse phase is that continual visual guidance may be operating during deceleration of the movement (Bootsma & Van Wieringen, 1990; Elliott et al., 1995). If visual control operates during deceleration, possibly to specify time to contact with the target, it is likely that initial impulse endpoints may be dependent on visual guidance. In this sense, the initial impulse can be viewed as a high velocity phase of movement for which vision plays a vital role in bringing it to an end. Subsequent discrete error corrections may then be performed in order to attain the target. Of course, such a

position is inconsistent with the assumption that initial impulses are preprogrammed, and indeed initial impulse durations are long enough (> 190 msec) for visual control to take effect. Further support for this proposition is that, although the reliance on visual feedback was greater after extensive practice compared to after moderate practice, as indicated by decrements in RMSE, the number of movements with error corrections decreased with practice. If vision became more important with practice, it is not reflected in the extent to which discrete error corrections are produced. Elliott et al. (1995) have suggested that with practice participants may adopt a continuous mode of control which involves the "graded adjustment of muscle activity during deceleration" (p. 80). Such regulation would not be reflected in discrete adjustments to the acceleration profile. It is possible that participants develop the ability to use vision to bring the initial impulse to an end and that this information becomes more critical as the velocity of the initial impulse and hence the precision needed in the breaking process increases with practice.

In summary, the results of the present experiment demonstrated that visual feedback plays an important role in the learning and control of movements made as fast and as accurately as possible. Also, consistent with studies using temporally constrained movements, the importance of vision increased as a function of practice (Proteau & Cournoyer, 1990; Proteau & Marteniuk, 1993; Proteau et al., 1987). Finally, stemming from the ideas of Woodworth (1899), it is believed that learning involves a dual process of improved programming of the initial impulse and increased efficiency of feedback processing. Within this framework, practice not only acts on programming and feedback processes directly, but also indirectly through a reciprocal interplay between processes. On one side, reductions in the variability of the initial impulse with practice decreases the frequency and extent of error correction phases and facilitates the efficiency of the correction process. On the other side, the proficiency to utilize the available feedback sources influences the programming of the initial impulse. The extent to which the initial impulse can be accurately

programmed given the variability in the neuromotor system and the ability to efficiently use available feedback sources define the interdependency to which the system progresses with practice.

3. The effect of practice on component submovements is dependent on visual feedback.

The results of Experiment I showed that after extensive practice, different control strategies emerged between visual feedback conditions. During the later stages of practice, participants in the FV group tended to undershoot the target in the initial impulse phase and then use online error corrections to “home in” on the target. Conversely, participants without visual feedback did not bias their initial impulse endpoints to either side of the target. Instead, throughout practice, they showed a steady decline in the extent to which error corrections were produced.

While the results of Experiment I showed that the location of initial impulse endpoints was influenced by the availability of visual feedback, the effects of practice on the duration of initial impulses was minor and did not differ between visual conditions. Hence, participants did not adjust the velocity of their movements depending on whether or not visual feedback was available. Past research has shown that the contribution of visual feedback increases under relatively high index of difficulties (> 4.58) (Wallace & Newell, 1983). Further, it has been suggested that target size is the primary determinant of the extent to which visual feedback is used (Sheridan, 1979; Wallace & Newell, 1983). We therefore propose that the tradeoff between the durations of the initial impulse and error correction phases (Meyer et al., 1988) would be affected by visual feedback only when movements are produced to relatively small targets. Hence, in the present study we kept movement amplitude the same as that in Experiment I (i.e., 45 degrees) but decreased the size of the target from 2.25 degrees (ID = 4.3 bits) to 1.5 degrees (ID = 5.9 bits). An optimal control strategy for participants in the FV group would be to produce high velocity initial impulses and then rely on effective visual feedback processing to attain the target. For participants without visual feedback, a preferred strategy would be to produce slower but less variable initial impulses thereby reducing the need for feedback based corrections.

Another point of interest was whether the difference between visual conditions in initial impulse distance that was demonstrated in Experiment I using wrist rotations would be observed using elbow flexion movements. Abrams and Pratt (1993) have shown that for both wrist rotation and arm pointing movements, participants undershot the target in the initial impulse phase. This was the case regardless of whether or not visual feedback was available (Pratt and Abrams, 1996). Similarly, eye movements are typically characterized by a primary saccade which undershoots the target followed by a second error correcting saccade (Becker & Fuchs, 1969; Prablanc & Jeannerod, 1975). This has been argued to be a deliberate mechanism of the saccadic control system to keep the target to one side of the fovea so that corrections can be made in the same direction as the primary saccade (Henson, 1977). However, it is important to note that in these studies that have shown a tendency for initial impulses to undershoot the target, the tasks have involved movements in which the momentum of the effector was relatively low. Wrist rotation and eye movements involve small moments of inertia and it is likely that the velocities of the arm-pointing movements used by Abrams and Pratt were low since movement amplitude was only 6.7 cm. Incidentally, movements such as wrist rotations have commonly been studied because they are less affected by mechanical factors which could mask active control processes. However, if undershooting the target and then relying on visual feedback to home in on the target is considered to be an optimal control strategy, it is important to test whether this is the case for movements having different mechanical characteristics. Therefore, it was of interest to determine whether the pattern of results obtained in Experiment I regarding the amplitude of initial impulses would generalize to a different type of movement.

Similar to Experiment I, we tested the importance of visual feedback at different levels of practice by examining the cost of removing vision.

3.1. Method

3.1.1. Participants

Sixteen self declared, right hand dominant, university students served as participants in the study. All were naive to the hypothesis being tested and inexperienced at the experimental task. The experiment was carried out according to the ethical guidelines laid down by the University of British Columbia Behavioral Sciences Ethics Board for studies involving human participants.

3.1.2. Apparatus

The participants were seated with their left forearm positioned on a manipulandum which consisted of a padded horizontal lever attached to a bearing-mounted vertical shaft. The left hand was placed face down on an adjustable platform such that the elbow was coaxial with the axis of rotation. This allowed the elbow to rotate freely in the horizontal plane. The arm and hand were secured to the manipulandum with Velcro straps and were hidden from the participants' view by an opaque shield.

Visual displays of the home position, target region, and a cursor representing limb position appeared on an oscilloscope screen positioned in front of the participants at a distance of 75 cm. The home position was located to the left of the screen and consisted of a dot 1 mm wide. The target was located 9 cm to the right of the home position (center to center) and consisted of two dots 3.0 mm apart. The cursor was a round dot 1 mm in diameter. Elbow flexion and extension movements caused the cursor to move to the right and left, respectively. Each degree of forearm rotation corresponded to 2 mm of cursor movement. Therefore, the angular distance between the home position and the target was 45 degrees (120-75 degrees, where 180 degrees was full extension) while the width of the target was 1.5 degrees of elbow rotation. This distance-width combination yielded an Index of Difficulty of 5.9 bits (Fitts, 1954). Knowledge of results (KR)

regarding accuracy (degrees of rotation) and movement time (msec) were presented on a monitor located to the left of the oscilloscope screen.

Angular displacement data were obtained from an optical encoder (Dynapar E20-2500-130), attached to the shaft of the manipulandum. Its analog signal was sampled at 1000 Hz. The displacement data were filtered using a two pass digital Butterworth filter with a cutoff frequency of 20 Hz and then differentiated in order to obtain angular velocity. Angular acceleration data were obtained through the use of a Kistler accelerometer (type 8638B50, ± 50 G) positioned at the upper end of the handle, 42 cm from the axis of rotation. Its analog signal was first filtered using a Krone-Hite, # 3750 analog filter with a lowpass frequency of 50 Hz and then digitally sampled at 1000 Hz.

3.1.3. Procedure

At the beginning of each trial, the home position, target area and the cursor representing rotation of the elbow appeared on the oscilloscope screen. Participants were required to move the cursor to the home position. Once the cursor was steadily aligned a tone was presented. Participants were free to initiate their movements anytime within 1500 msec following the onset of the tone and were informed that it was not necessary to minimize reaction time. They were instructed to move the cursor from its starting location to the target region as quickly and as accurately as possible. Again, it was explained that the goal was to minimize total movement time (i.e., the interval from when the limb started to move to when it came to a complete stop). This was encouraged by means of a point system similar to that used in Experiment I and by other researchers (Meyer et al., 1988; Pratt & Abrams, 1996). That is, participants had to hit the target in order to earn points and the number of points gained was inversely related to their movement time. No further instructions were given regarding how this was to be accomplished.

The participants were randomly divided into two groups of eight. One group practiced the aiming task with vision of the cursor throughout each trial [full vision condition (FV)]. The other group practiced under a condition in which the cursor disappeared from view as soon as the velocity of the handle became greater than 8 deg/sec [no vision condition (NV)]. Thus, in this condition, participants saw the cursor only at the home position prior to movement initiation. The cursor did not reappear until it was time to prepare for the subsequent trial. For both visual conditions, the home position and target remained visible for 5 seconds from the initiation of each trial.

Participants in each group were required to perform 1500 acquisition trials in 5 sessions over a one week period (see Table 3.1). During the acquisition phases, participants were given KR regarding accuracy and movement time after each trial. All participants were submitted to two transfer tests which consisted of 25 trials under the NV condition, but with no KR. The first transfer test was administered after 100 trials and the second after 1500 trials of practice. Participants were given two minutes rest before each transfer test.

3.1.4. Movement analysis

The method used to separate the initial impulse and error correction phases was similar to that in Experiment I. First, peak velocity was located. The velocity profile was then traversed backwards in time until the velocity fell below 8 deg/sec. This point was defined as the beginning of the movement. The end of the movement was defined as the point in time following peak velocity in which the absolute angular velocity of the handle fell below 8 deg/sec for 180 msec. A search was then performed from peak velocity to the end of the movement for a possible initiation of an error correction phase, i.e., the occurrence of one of the following movement modifications, (a) a positive to negative zero line crossing in velocity, (b) a negative to positive zero line crossing

Table 3.1

Breakdown of trials for participants in the full vision (FV) and no vision (NV) groups.

<u>Participants</u>	<u>Day1</u>	<u>Day2</u>	<u>Day3</u>	<u>Day4</u>	<u>Day5</u>
1-8 (FV group)	100FV 25NV*200FV	300FV	300FV	300FV	300FV 25NV*
9-16 (NV group)	100NV 25NV*200NV	300NV	300NV	300NV	300NV 25NV*
* No KR					

in the acceleration trace, or (c) a significant deviation in the acceleration trace, i.e., a relative minimum in the absolute value of the acceleration while the acceleration is negative. In order to qualify as a significant deviation, neither a preceding nor postceding absolute maximum could lie within 30 msec of the relative minimum (see also Chua & Elliott, 1993; and van Donkelaar & Franks, 1991). Also, the difference in the absolute values of acceleration between the minimum and maximums had to be at least 100 deg/s^2 . If the duration between the first movement modification and the end of the movement was greater than 60 msec and the distance traveled during this time was more than .5 degrees, the movement was said to contain an error correction phase. When neither of these criteria were met, the movement was recorded as containing only an initial impulse phase and the end of the movement was repositioned at the first movement modification. Within the error correction phases, all movement modifications in the acceleration profile that were separated by at least 60 msec were recorded.

The effectiveness of the error correction phases in reducing error following the initial impulse phase was assessed by computing the index of error correction effectiveness (IECE) that was developed in Experiment I. That is,

$$\text{IECE} = \frac{\text{AE(ii)} - \text{AE(ec)}}{\text{AE(ii)} + \text{AE(ec)}}$$

$$\text{AE(ii)} + \text{AE(ec)}$$

where AE(ii) is the absolute error at the end of the initial impulse phase and AE(ec) is the absolute error after the error correction phase.

3.2. Results

3.2.1. Acquisition

In order to compare performance at different levels of practice, the 1500 practice trials for each participant were divided into two stages of practice each consisting of 750 trials. The trials

for each level of practice were then divided into 30 blocks of 25 trials. All dependent measures were separately analyzed by performing a 2 Visual Condition x 2 Practice x 30 Blocks ANOVA with repeated measures on the last two factors. The results of linear trend analyses are reported and not multiple comparisons among blocks. In order to avoid redundancy in the presentation of the results, the effects of blocks are reported only when they interact with visual condition and/or practice.

Performance Measures: Main effects of practice on Ln(RMSE) and total MT indicated that participants became more accurate with practice, $F(1, 14) = 27.9, p < .001$ while also being able to lower movement times, $F(1, 14) = 118.2, p < .001$ (see Figure 3.1). Movements performed with visual feedback were more accurate than those performed without visual feedback, $F(1, 14) = 209.3, p < .001$. This was the case throughout practice. Although there was no significant main effect of visual condition on total MT, $F(1, 14) = 2.4, p > .05$, there was a significant interaction between visual condition and practice, $F(1, 14) = 11.1, p < .01$. As shown in Figure 3.1b, differences in total MTs between visual conditions decreased as a function of practice.

Initial Impulse Phase: The results of the initial impulse phase are illustrated in Figure 3.2. There were no significant main effects of practice or visual condition on the distance traveled in the initial impulse phase ($F < 1.0$). However, there was a significant interaction between practice and visual condition, $F(1, 14) = 7.0, p < .05$, as well as a triple interaction between practice, blocks and visual condition, $F(1, 14) = 7.6, p < .05$. As shown in Figure 3.2a, the difference between groups decreased during the early stages of practice while there was relatively little effect of practice and visual condition late in practice. Also, note that participants of both groups tended to overshoot the center of the target in the initial impulse phase late in practice.

Figure 3.1. Mean root mean square error (after logarithmic transformation) (a) and total movement times (b), as a function of practice for the full vision and no vision conditions.

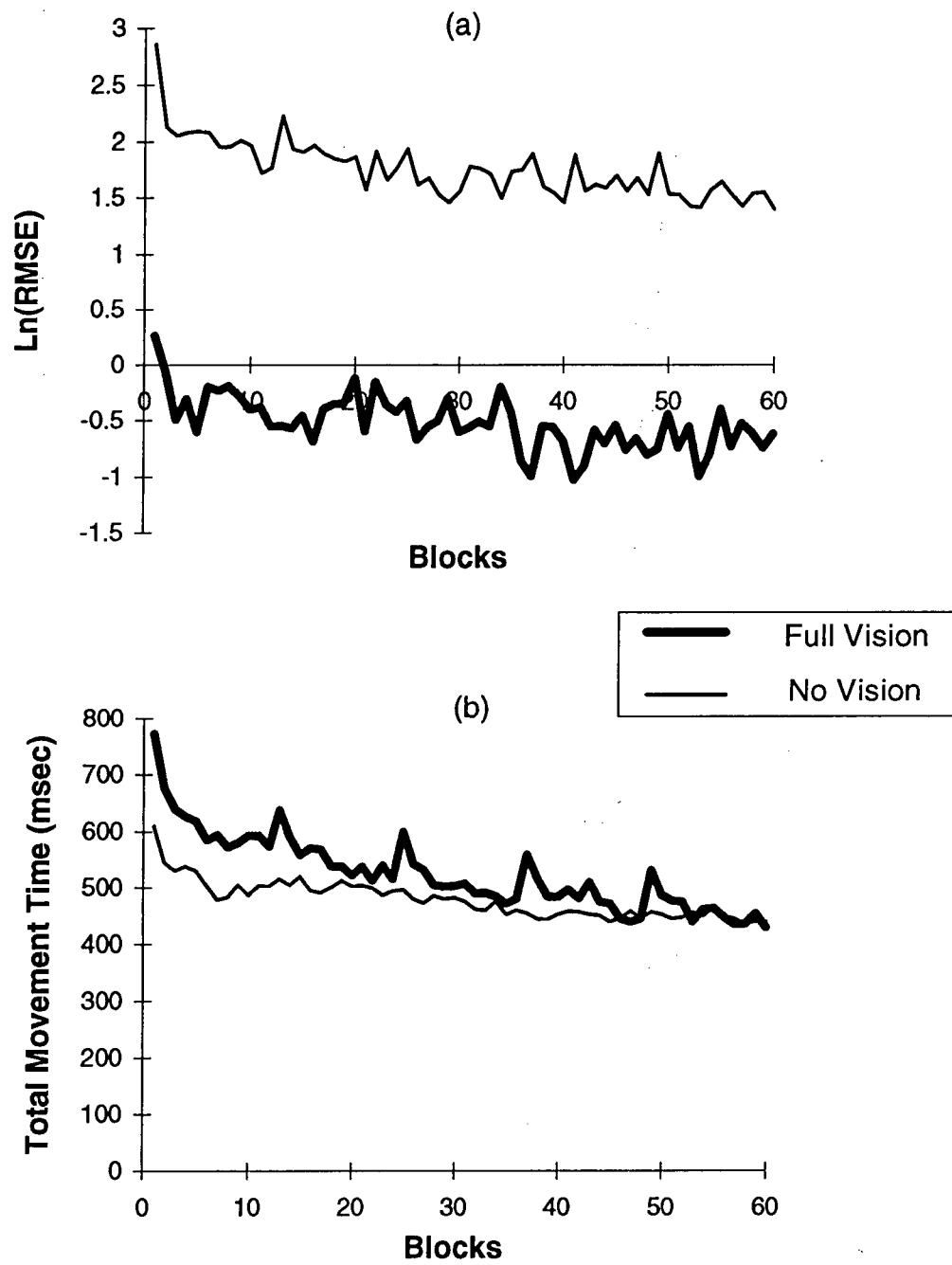
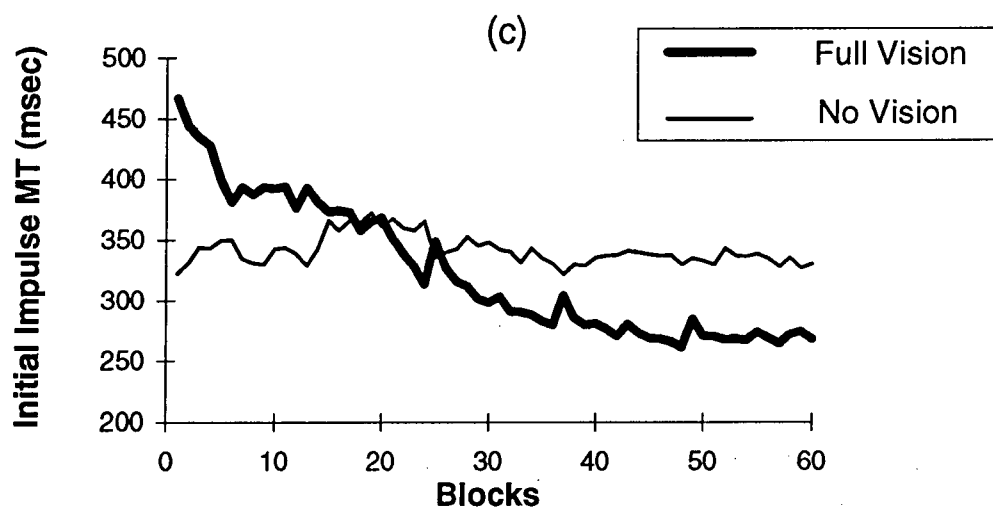
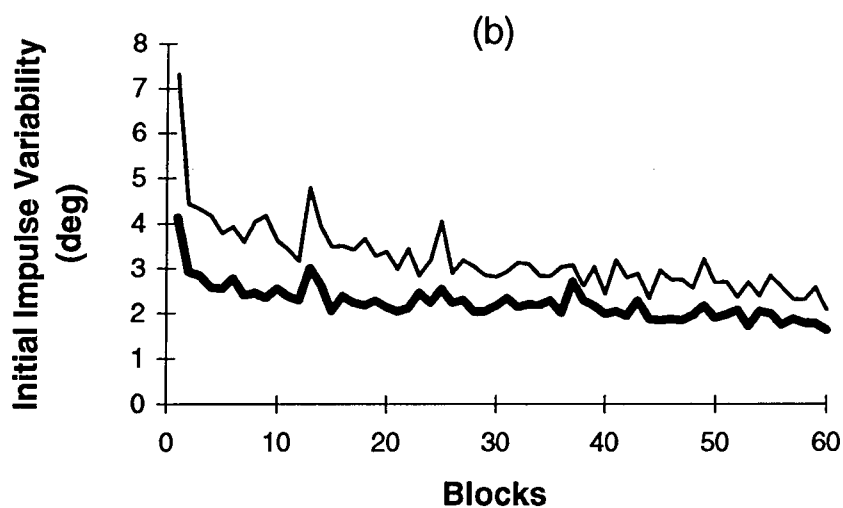
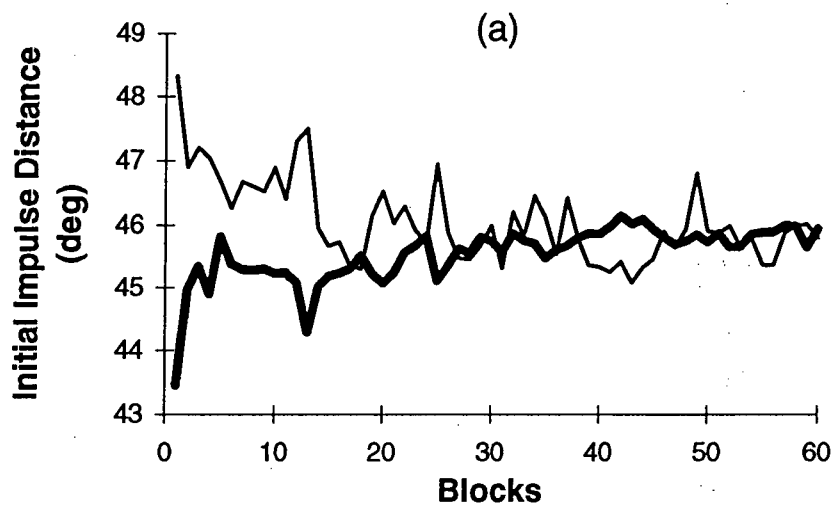


Figure 3.2. Mean initial impulse distance (a), initial impulse variability (b), initial impulse movement time (c), as a function of practice for the full vision and no vision conditions.



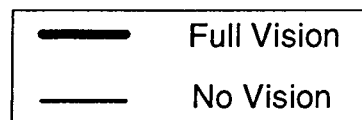
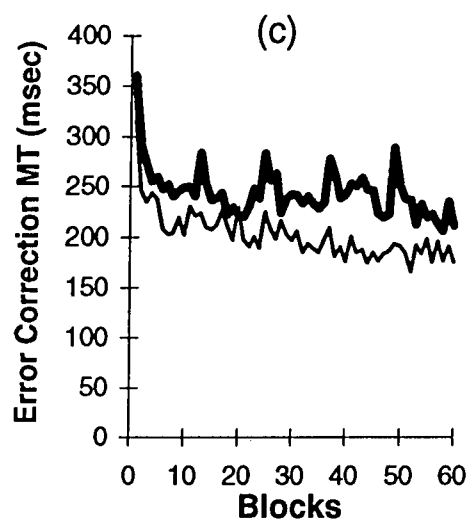
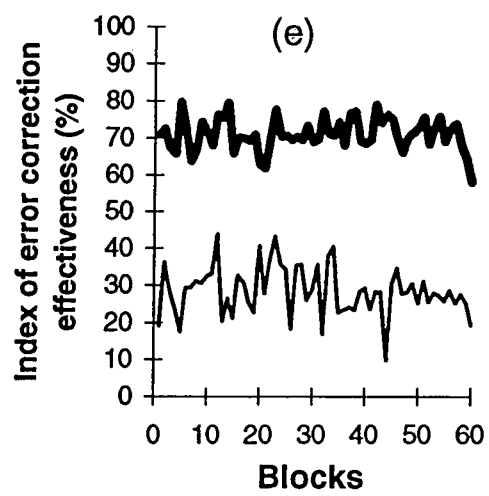
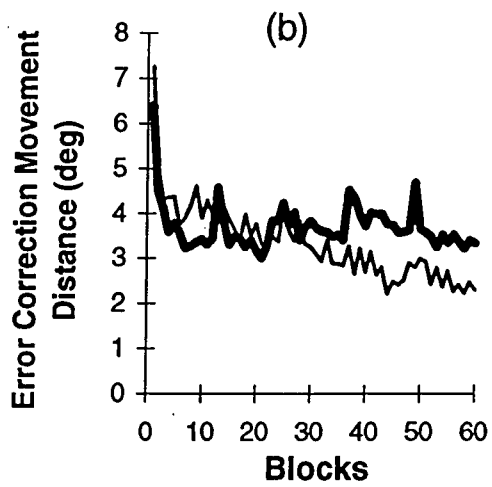
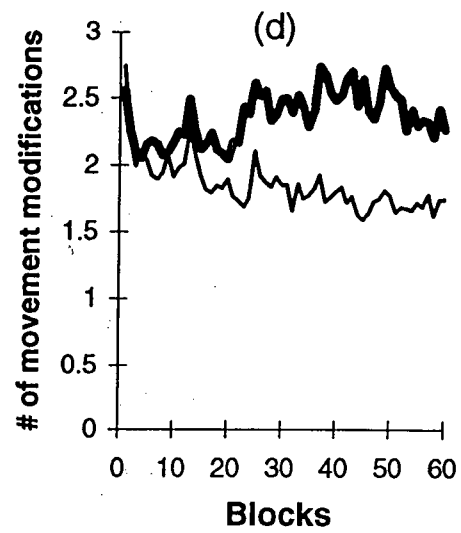
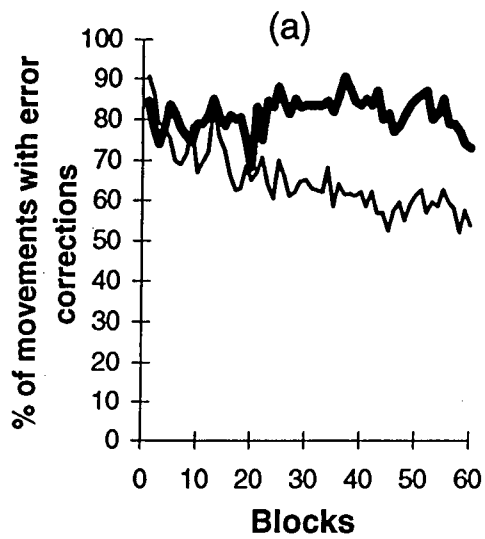
A main effect of practice on the standard deviations of the initial impulse endpoints revealed that initial impulse variability decreased with practice $F(1, 14) = 58.2, p < .01$. Also, initial impulse variability was higher for participants in the NV compared to FV group, $F(1, 14) = 11.6, p < .01$. This effect decreased with practice as indicated by a practice x visual condition interaction, $F(1, 14) = 8.7, p < .01$.

There was a significant main effect of practice on the time spent in the initial impulse phase, $F(1, 14) = 14.5, p < .01$. Although the main effect of visual condition was not significant ($F < 1$), there was a significant interaction between practice and visual conditions, $F(1, 14) = 8.4, p < .01$, as well as a triple interaction between practice, blocks and visual condition $F(1, 14) = 5.6, p < .05$. Figure 3.2c illustrates that very different trends were evident for the two groups. Participants in the FV group decreased the time spent in the initial impulse phase with practice while there was relatively no effect of practice on the NV group.

Error Correction Phase: The results of the error correction phases are illustrated in Figure 3.3. The main effect of practice and visual condition on the percentage of movements that contained an error correction phase approached conventional levels of significance, $F(1, 14) = 4.1, p = .06$, and $F(1, 14) = 3.6, p = .08$, respectively. There was a significant interaction between practice and visual condition, $F(1, 14) = 9.2, p < .01$, as well as a triple interaction between practice, block and visual condition interaction, $F(1, 14) = 5.6, p < .05$. As shown in Figure 3.3a, the difference between groups increased as a function of practice with the FV group having a greater percentage of movements with error corrections compared to the NV group.

For those movements that contained error correction phases, there were significant effects of practice on the absolute distance traveled, $F(1, 14) = 5.6, p < .05$, and the time spent, $F(1, 14) = 9.8, p < .01$, during error correction. Main effects of visual condition indicated that the time

Figure 3.3. Mean percentage of movements that contain error correction phases (a), error correction distance (b), error correction movement time (c), number of movement modifications per trial (d), and index of error correction effectiveness (e), as a function of practice for the full vision and no vision conditions.



spent, $F(1, 14) = 5.7$, $p < .05$, and the number of movement modifications made, $F(1, 14) = 4.2$, $p = .05$, during error correction was greater for the FV compared to NV group. Also, there were significant interactions between practice and visual condition in the distance traveled, $F(1, 14) = 5.2$, $p < .05$, and the number of movement modification made, $F(1, 14) = 6.6$, $p < .05$, during error correction. In both cases, the difference between groups increased as a function of practice.

An ANOVA performed on IECE did not reveal a significant effect of practice ($F < 1.0$). However, error corrections performed with vision of the cursor were significantly more effective than error corrections performed without vision, $F(1, 14) = 126.5$, $p < .001$. The effect of vision did not interact with practice ($F < 1.0$).

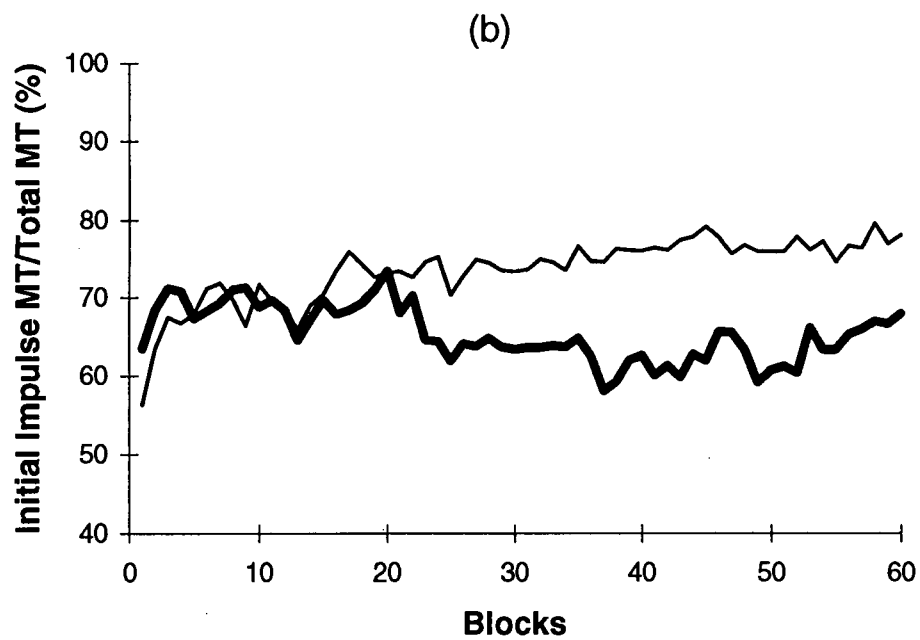
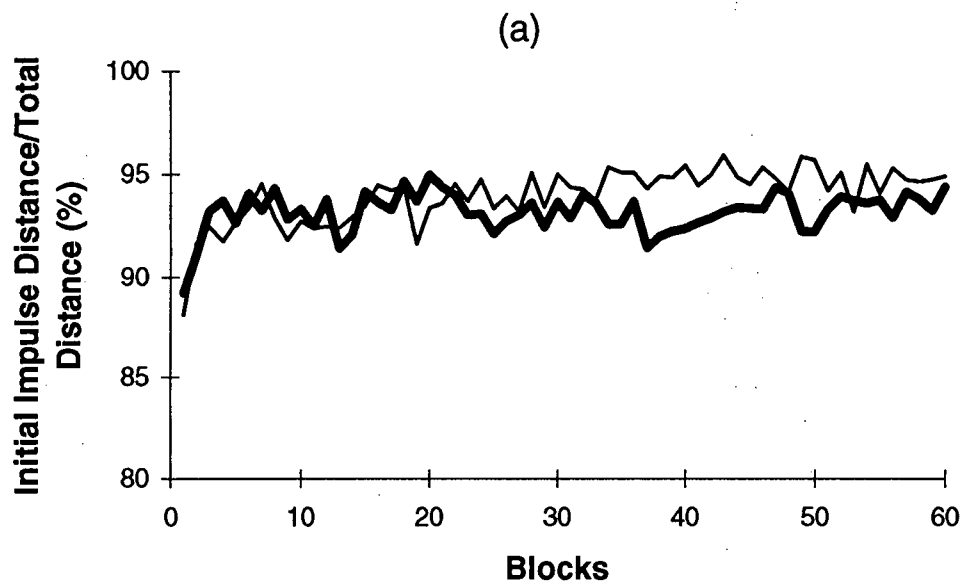
Initial impulse distance/total distance and initial impulse MT/total MT: The proportion of the total distance traveled in the initial impulse increased with practice, $F(1, 14) = 4.4$, $p < .05$ (see Figure 3.4). There was no main effect of visual condition on the proportion of the total distance traveled in the initial impulse ($F < 1.0$). However, there was a tendency for the difference between groups to increase with practice, $F(1, 14) = 3.6$, $p = .08$.

The only significant effect on the proportion of the total MT spent in the initial impulse was an interaction between practice and visual condition, $F(1, 14) = 7.7$, $p < .05$. Figure 3.4b shows that the difference between groups increased as function of practice with participants in the FV group spending proportionally less time in the initial impulse compared to participants in the NV group.

3.2.2. Practice vs transfer performance

The effect of the transfer tests were examined by first calculating the difference in the results between the 25 transfer trials and the preceding 25 practice trials. A 2 Visual Condition x

Figure 3.4. Mean initial impulse distance/total distance (a) and initial impulse movement time/total movement time (b) as a function of practice for the full vision and no vision conditions.



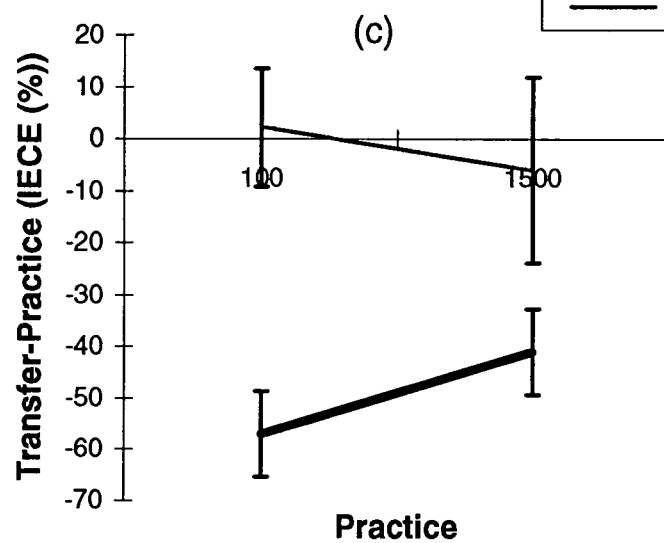
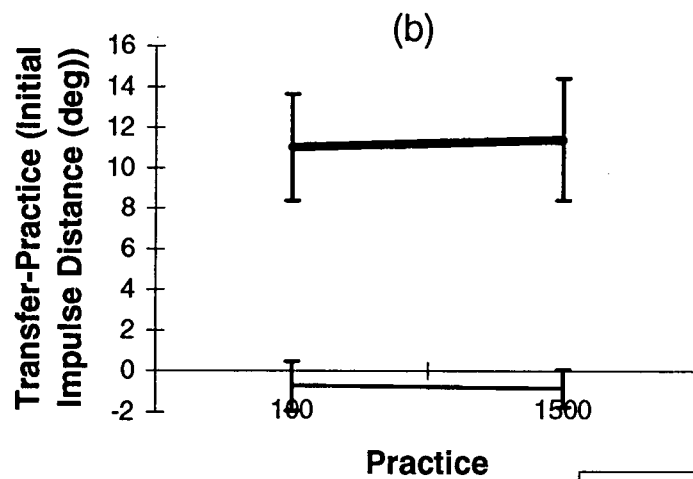
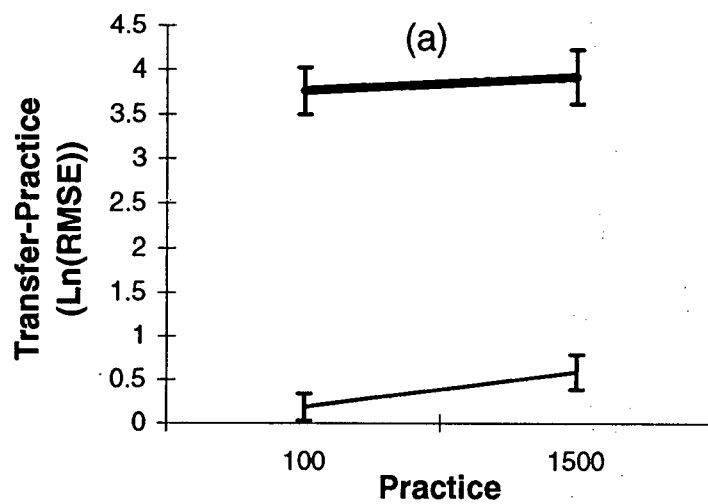
2 Practice ANOVA was then performed on the differences between acquisition and transfer phases.

Performance measures: The ANOVA performed on Ln(RMSE) revealed a significant main effect for visual condition, $F(1, 14) = 160.81, p < .001$. As indicated in Figure 3.5a, there was a larger acquisition-transfer decrement for participants in the FV compared to NV group. Both the main effect of practice and the interaction between visual condition and practice were non-significant ($F < 1.0$). A main effect of visual condition on total movement time, $F(1, 14) = 14.8, p < .1$, revealed that participants in the FV group showed larger increases in MT compared to the NV group. However, there was no effect of practice, $F(1, 14) = 1.2, p > .05$, or interaction between visual condition and practice ($F < 1.0$).

Initial impulse phase: A main effect of visual condition revealed that there was an increase in the distance traveled in the initial impulse phase for the FV group which was not apparent for the NV group, $F(1, 14) = 4.25, p < .05$. As shown in Figure 3.5b, participants increased the distance traveled in the initial impulse by about 11 degrees on average. This increase in initial impulse distance was also accompanied by an increase in the variability of the initial impulse endpoints, $F(1, 14) = 7.2, p < .01$, and the time spent in the initial impulse phase, $F(1, 14) = 5.9, p < .05$. No other effects of the transfers on the properties of the initial impulse were significant ($p > .05$).

Error correction phase: A significant effect of visual condition on the distance traveled in the error correction phase, $F(1, 14) = 17.2, p < .001$, indicated that the removal of vision caused an increase in error correction distance. However, these error corrections proved to be less effective as a significant visual condition main effect on IECE indicated that the removal of vision caused a

Figure 3.5. Mean difference in $\text{Ln}(\text{root mean square error})$ (a), initial impulse distance (b) and error correction effectiveness (c) between twenty five transfer trials and preceding twenty five practice trials after 100 and 1500 practice trials for the full vision and no vision conditions.



— Full Vision
— No Vision

Table 3.2. Mean and standard deviations of dependent variables for performance, initial impulse and error correction phases for transfer (T) tests and previous twenty five acquisition trials.

		A1	T1	A2	T2
Ln(RMSE)	FV	-0.3(0.6)	3.5(0.6)	0.6(0.4)	3.3(0.7)
	NV	2.1(0.4)	2.3(0.5)	1.4(0.3)	1.8(0.6)
Total MT (msec)	FV	626(51)	668(51)	427(51)	513(72)
	NV	537(76)	541(62)	437(55)	449(54)
Initial Impulse Distance (degrees)	FV	44.9(1.4)	55.9(7.8)	45.9(1.2)	57.3(8.4)
	NV	47.0(1.7)	46.1(4.0)	45.7(1.2)	45.0(3.0)
Initial Impulse Variability (degrees)	FV	2.5(0.9)	6.8(1.9)	1.6(0.4)	5.5(2.1)
	NV	4.1(1.0)	4.2(1.2)	2.0(0.5)	2.5(0.6)
Initial Impulse MT (msec)	FV	428(85)	462(80)	267(57)	286(69)
	NV	343(95)	354(106)	330(94)	321(89)
% of Movements with error corrections	FV	77(9)	76(13)	73(10)	87(12)
	NV	78(18)	78(23)	53(31)	59(31)
Error Correction Distance (degrees)	FV	3.5(1.2)	4.0(1.5)	3.3(2.2)	5.3(2.2)
	NV	4.3(2.0)	4.1(1.6)	2.3(1.5)	2.6(1.6)
Error Correction MT (msec)	FV	255(44)	263(53)	211(54)	258(45)
	NV	243(60)	239(53)	175(65)	199(59)
# of Movement Modifications per Trial	FV	2.0(0.4)	1.8(0.5)	2.2(0.7)	2.5(0.4)
	NV	2.1(0.7)	1.9(0.7)	1.7(0.8)	1.7(0.8)
IECE (%)	FV	65(22)	8(9)	58(27)	17(19)
	NV	23(13)	19(23)	19(51)	15(20)
Initial Impulse Distance/Total Distance (%)	FV	93(2)	92(3)	94(4)	92(3)
	NV	91(3)	91(3)	94(3)	94(3)
Initial Impulse MT/Total MT (%)	FV	70(8)	71(10)	67(13)	59(10)
	NV	66(13)	67(15)	78(19)	75(18)

large drop in error correction effectiveness, $F(1, 14) = 9.6$, $p < .01$ (see Figure 3.5c). No other effects were significant.

3.3. Discussion

Similar to the results of Experiment I, participants improved movement accuracy while also being able to decrease their movement times. Also, in contrast to previous research which has shown that vision had a relatively minor impact on practice related effects (Pratt & Abrams, 1996), the results of the present experiment indicated that the effects of practice differed substantially between the two feedback conditions. Participants who practiced with visual feedback were more accurate than those who practiced without visual feedback. This was the case even after extensive levels of practice. Past research has shown that accuracy advantages of FV conditions were usually at the cost of longer movement times. The difference in movement times was said to reflect the time needed to make visually based error corrections (Chua & Elliott, 1993; Elliott et al., 1991). However, the results of the present study indicated that the difference in movement times between the two groups decreased as a function of practice. Therefore, of interest is how did participants in the FV group sustain higher accuracy levels while reducing their movements times to the extent that they were actually quite similar to that of the NV group.

The submovement analysis revealed that both the initial impulse and error correction phases contributed to the higher accuracy levels of the FV compared to NV group. In terms of the initial impulse phase, participants who practiced with visual feedback had less variability in the location of initial impulse endpoints. Here, it is evident that vision has an influence on the phase of movement that was previously assumed to be programmed. Since participants received detailed information about movement trajectory when visual feedback was available, it is possible that information from previous trials was used offline to improve programming of initial impulses

on subsequent trials. However, another possibility is that visual feedback was used online during the production of the initial impulses. This control may have taken the form of continuous graded adjustments during deceleration (Elliott et al., 1995) and as such, was not reflected in discrete adjustments to the kinematic profiles. In terms of the error correction phases, the number of movements that contained error corrections, the time spent and the number of modifications made during error correction was greater when visual feedback was available compared to when it was not. Also, regardless of the magnitude of the error following the initial impulse and error correction phases, the corrections performed with vision proved to be more effective in reducing error following the initial impulse. Therefore, it appears that vision is playing a role in both the production of initial impulses and in reducing error following the initial impulse phase.

In contrast to Experiment I, the effects of practice on initial impulse movement times were quite different between visual conditions. Participants in the FV group decreased the time spent in the initial impulse phase as a function of practice while initial impulse movement times were relatively constant for participants in the NV group. One possible reason for these different practice effects is that participants in the FV group were highly accurate and therefore improved their performance by increasing the speed of their movements. The less accurate NV group may not have reduced errors sufficiently to warrant increases in movement speed. A second interpretation is that both groups progressed towards different control strategies based on their ability to make discrete error corrections. That is, the FV group increased the speed of their movements such that they could get to the vicinity of the target quickly and then used visual feedback to "home in" on the target (also see Elliott et al., 1995; Moore & Marteniuk, 1986). On the other hand, participants in the NV group progressed towards a single submovement strategy in order to reduce reliance on online corrections. Consequently, the extent to which error

corrections were produced remained relatively high for participants in the FV group while there was a more gradual decrease throughout practice for participants in the NV group.

The results from Experiment I indicated that after extensive practice, participants undershot the target in the initial impulse phase when visual feedback was available whereas initial impulse endpoints were not biased to either side of the target when visual feedback was not available. We had proposed that participants undershot the target in the initial impulse phase to allow visually based corrections to occur in the same direction in which the movement was originally programmed. This has the advantage that uncertainty about the required direction of a corrective submovement is reduced and it prevents any need to change the order of agonist-antagonist muscle activation patterns in programming corrective submovements (see Larish & Frekany, 1985). The results of the present study indicated that initial impulse movement distance did not differ between visual conditions in the later stages of practice. Both groups actually showed a tendency to over-shoot the target in the initial impulse phase. This may be due to the differences in the mechanical properties between the wrist movements used in our previous work and elbow movements used in the present study. Although both studies used movement amplitudes of 45 degrees, elbow movements are more susceptible to endpoint oscillations because of their larger moment of inertia. A more optimal strategy for movements at the elbow may be to produce fast movements which overshoot the target and then "spring back" towards the target instead of reducing movement speed to the extent that oscillations are eliminated. Since these oscillations are due to passive mechanical factors, they do not involve costs associated with active control processes such as programming changes in the sequencing of agonist-antagonist activation patterns. Further, maintaining high velocities, but travelling a longer distance by overshooting the target, may outweigh the benefits of reducing oscillations by slowing down the velocity of the initial impulse.

In the present experiment, the number of movement modifications per trial was approximately 2.5 when visual feedback was available. Although this number is consistent with multiple correction models (Crossman & Goodeve, 1983; Keele, 1968), it is possible that changes in direction detected by the movement parsing algorithm were not due entirely to sensory information processing but were due in part to passive mechanical factors as mentioned above. Hence, the number of feedback based error corrections was likely overestimated.

Notwithstanding, there is evidence that the error correction phases on the whole were dependent on the availability of visual feedback. Although both groups overshot the target in the initial impulse phase during the later stages of practice, the FV group did produce more movement modifications despite having less variability in initial impulse endpoints. Also, these modifications were more effective in reducing error compared to those performed without vision. Therefore, movement modifications in the presence of visual feedback resulted from processes beyond passive mechanical oscillations.

The results from the transfer tests indicated that the removal of visual feedback had an adverse effect on accuracy after both moderate and extensive levels of practice. This finding supports past work which has demonstrated that there is not a progression towards open loop control but that the importance of visual information remains even after extensive levels of practice (Elliott et al., 1995; Proteau, 1995; Proteau & Cournoyer, 1990; Proteau & Marteniuk, 1993; Proteau et al., 1987). Furthermore, similar to Experiment I, the removal of visual feedback affected both the initial impulse and error correction phases. This result adds further evidence against the idea that discontinuities in kinematic profiles emerge solely from ballistic control processes described by the weighted difference between pulses from the agonist and antagonist muscles (Plamondon & Alimi, 1997). Also, the effect of removing vision on the distance travelled in the initial impulse phase does not appear to be the result of the implementation of a different

control strategy as suggested in Experiment I. In Experiment I, participants with vision tended to undershoot the target in acquisition and it was reasoned that the removal of visual feedback caused an increase in initial impulse distance because participants could no longer rely on vision to home in on the target. In this experiment, initial impulses already overshoot the target in the later stages of acquisition and hence, it is unlikely that participants would have purposefully increased initial impulse distance when vision was removed. Therefore, it appears that vision is playing a dual role in the execution of rapid aiming movements. As mentioned earlier, continual visual guidance may be operating during deceleration of the initial impulse. Here, it may be that vision is used to specify time to contact with the target and hence plays an important role in bringing the initial impulse to an end. Based on information obtained during the production of the initial impulse, corrective submovements can then be prepared and executed in order to attain the target.

While the results from the transfer tests showed that the importance of visual feedback remained after extensive practice, Experiment I indicated that the reliance on vision actually increased with practice. Such an inconsistency in findings is also apparent in the work of Proteau and colleagues. Some of their studies have reported non-significant effects of practice on the acquisition to transfer decrement (Proteau & Cournoyer, 1990; Proteau & Marteniuk, 1993) while others have demonstrated that the decrement in performance increases significantly with practice (Proteau et al., 1987; Proteau et al., 1992). According to their specificity of practice hypothesis (Proteau, 1992; Proteau et al., 1992), different sources of sensory information are integrated to form an intermodal sensory-motor representation. Removal or addition of one source of afferent information will cause performance to suffer because incoming sensory information is no longer compatible with the sensory store. Since it takes a considerable amount of practice for specificity to develop, decrements in performance are greater after extensive compared to moderate levels of practice. An alternative explanation recently suggested by

Proteau, Tremblay and DeJaeger (1998) holds that with practice, the source of afferent information which is most suited to meet the demands of the task progressively dominates other sources of sensory information. The withdrawal of this information will lead to a deterioration in performance only when its dominance has been firmly established. At this point the increase in error reaches plateau and therefore would not be affected by further increases in practice.

It may be that visual dominance was established earlier in practice in the present experiment compared to Experiment I and hence decrements in performance were subject to a ceiling effect. The reason for the early dominance of visual feedback may be two-fold. First, because of the musculoskeletal geometry of the arm, the wrist pronation-supination movements used in the previous study were likely more constrained physically than the elbow flexion movements used here. Therefore, it is possible that more practice was needed before vision dominated proprioception in wrist rotation compared to elbow movements. Second, the smaller target size used in the present study may have prompted participants to focus attention on visual sources of information from the outset. Examination of initial impulse movement times between the two studies revealed the following. In Experiment I, initial impulse MT decreased from 210 early in practice to 190 msec late in practice. In the present study, initial impulse MT was approximately 450 msec early in practice and 250 msec late in practice. Therefore, it is likely that the slower initial impulse MTs in the present study, particularly at the early stages of practice, enabled participants to effectively utilize visual information from the initial impulse phase. This may not have been the case during the early stages of practice in Experiment I where initial impulse movement times were considerably faster. However, with practice, participants developed the ability to use visual feedback from faster movements.

In summary, the results of the present study demonstrated that under very small target sizes, visual feedback had a major impact on how the control of rapid aiming movements are

altered with practice. With practice, participants progressed towards control strategies which differed in terms of the time spent in the initial impulse phase. It is believed that the progression towards these strategies was dependent on the participants' ability to use online sensory information to make corrective submovements. When visual feedback was available, participants planned their movements to use it. They increased the speed of their initial impulses to get to the target area quickly and then relied on vision to make discrete error corrections. Through the development of such "feedback processing procedures" (Elliott et al., 1995), participants remained heavily reliant on vision even after extensive levels of practice. When visual feedback was not available, practice effects were associated primarily with a reduction in the extent to which discrete error corrections were produced. Thus, it appeared that participants reduced the reliance on less effective sensory sources.

4. The effect of practice on the control of rapid aiming movements under partial visual conditions

Numerous studies have investigated how performance in tasks such as aiming (Elliott et al., 1994), catching (Whiting & Sharp, 1974), and locomotion (Assaisante, Marchand, & Amblard, 1989) is affected when vision is provided for only brief intervals during the movement trajectory. Two issues that have received much attention concern (1) where in the movement trajectory is visual information most critical and (2) how much vision is needed for optimal performance.

According to the two component model of movement control, the initial impulse is programmed and therefore would not be expected to be affected by the manipulation by visual feedback (Meyer et al., 1988; Woodworth, 1989). On the other hand, error corrections are based on sensory information obtained "on the fly" during the production of the initial impulse (Meyer et al., 1988, p. 347). Here, an attempt is made to reduce any discrepancy between the endpoint of the initial impulse and the position of the target.

However, the results of Experiments I and II suggested that the role of visual information was not limited to the production of error corrections. During acquisition, initial impulses were less variable when visual feedback was available and the removal of visual feedback significantly affected the production of the initial impulse in the transfer tests. Further evidence that vision is being used in the production of the initial impulse stems from a study by Proteau and Masson (1997). In their study, participants were required to apply pressure on a handle to move a cursor on an oscilloscope screen from a home position to a target marker. Participants were told to hit the target in one continuous motion ($MT = 450-550$ msec) and were not allowed to make corrections to their movements. In essence, this meant that movements were comprised of only the initial impulse phase. On some trials, the visual background was unexpectedly moved opposite to the direction of the cursor. The results showed that movement endpoints undershot

the target when the background information was perturbed. It was reasoned that participants prematurely decelerated their movements because moving the background opposite to the movement of the cursor had the effect of making the cursor appear that it was moving faster than it really was. Therefore, it appeared that velocity information was playing a critical role in bringing the high velocity initial impulse phase to an end.

Considering the possibility that vision is involved in both the production of the high velocity initial impulse and low velocity error correction phases, the present experiment was designed to investigate where in the movement trajectory visual feedback is most critical for the production of the respective movement phases. Research has typically indicated that vision early in an aiming movement is relatively unimportant in comparison to visual feedback later in the movement. For example, studies have shown that performance is significantly worse when participants are given visual feedback only over the first half of movement compared to when the second half of movement can be seen (Beaubaton & Hay, 1986; Chua & Elliott, 1993; Temprado, Vieilledent & Proteau, 1996). Carlton (1981) has also reported that removing vision over the first half of the movement had no effect on movement time or accuracy. However, when the occlusion period was extended to the second half of the movement, significant increases in movement time and error rates were observed. Further, Temprado et al. have shown that when participants practiced with vision over the first half of the movement, the removal of this information in transfer did not affect movement accuracy. In contrast, for those participants who practiced with vision of the second half of the movement, there was a significant decrement in performance when this information was withdrawn.

One reason that researchers have not shown evidence for the importance of early visual information stems from the experimental designs that have been employed. In Carlton's (1981) study, visual condition was a within participants factor and only 45 trials were administered in

each condition (15 trials on each of three days). Chua and Elliott (1993) also used a within participants design with participants receiving 60 trials in each partial vision condition, 40 of which were presented in a random fashion with the remaining 20 given in blocks. Therefore, it is possible that participants did not receive enough practice under the partial vision conditions to effectively use the available information to optimize aiming accuracy. With more extensive practice under a particular visual condition, participants may learn to use early sources of visual information. In the study of Temprado et al. (1996), visual condition was manipulated between participants during acquisition with participants receiving 240 trials of practice. However, this level of practice was probably still not sufficient to allow participants to calibrate and extrapolate early sources of visual information to achieve desired levels of endpoint accuracy.

Proteau, Linossier and Abahnini (1998) have recently suggested that an important determinant of whether or not early sources of visual feedback are important for movement control is the visual angle between the home position and the target. They estimated that in the studies of Beaubaton and Hay (1986), Carlton (1981) and Temprado et al. (1996), the midpoint of the movement trajectories were all at eccentricities greater than 20 degrees. Previous research has indicated that seeing ones hand in the periphery benefits the control of movement direction but not movement amplitude (Bard, Paillard, Fleury, Hay & Larue, 1990). In contrast, Proteau et al. showed that vision up to 10 degrees eccentricity (or the first 75% of the movement in their case) was important for the control of movement amplitude. Although submovement data were not analyzed, Proteau et al. reasoned that early visual information was used to prepare corrective submovements which would minimize error following the initial impulse phase. Such an explanation is in agreement with proposals made by Meyer et al. (1988) concerning the use of dynamic visual information from the initial impulse phase.

Further evidence for the use of early visual information has been provided in the studies of Spijkers and Lochner (1994) and Spijkers and Spellerberg (1995). Removal of visual feedback over the initial portion of the trajectory adversely affected movement accuracy when compared to a full vision condition. Similarly, increasing the length of the vision period over the early portions of the movement trajectory was shown to improve aiming accuracy. However, these findings should be taken with some degree of caution. In their studies, visual feedback was manipulated through the use of liquid crystal visual occlusion spectacles (Milgram, 1987) which in their closed state prevents vision of the entire visual field and not just the movement of the limb. It is therefore possible that the decrement in performance when vision was removed early in the trajectory was caused by a decay of a visual representation of the environment (Elliott, 1992) and not a lack of visual information of the moving limb *per se*. Also, when the length of the interval for which vision was available at the beginning of the movement was manipulated, the design did not include a no vision condition for comparison. Therefore, it was quite possible that performance in the early vision conditions would not have differed from a condition in which no feedback was available.

In this experiment, we focused our attention on the ability of participants to utilize early sources of visual information over extensive levels of practice. Spijkers and Lochner (1994) have distinguished between the use of early and late sources of visual information. Early visual information must be extrapolated in order to estimate the spatiotemporal trajectory of the limb over the remainder of the movement. In this case, visual information has a predictive role. On the other hand, visual information at the end of the movement is used in a predominantly corrective role where errors in the early part of the trajectory can be assessed and minimized. From their work in ball catching studies, Sharp and Whiting (1974) have pointed out that given delays in visuomotor processing, the time from the viewing period to the end of the movement

must be sufficiently long to enable time for the information to be processed. On the other hand, if this interval is too long, participants would not be able to accurately extrapolate the spatio-temporal trajectory to reliably predict where the movement will end.

In the present study, participants practiced a rapid aiming task (1500 trials) with no visual feedback, vision of the first half of the movement, vision of the first 75% of the movement, or full visual feedback. Movements were partitioned into their initial impulse and error correction phases so that the role of early sources of visual information could be specifically investigated. If visual information is used in the production of the initial impulse, one would expect initial impulses to differ in the partial vision conditions compared to the no vision condition. Similarly, by comparing the effectiveness of the error correction phases in the different visual conditions we could determine where in the movement trajectory visual feedback is most crucial for preparing corrective submovements. Of interest was whether with practice, participants can learn to utilize early sources of visual information in order to produce effective error corrections. If this is the case, it would be interesting to determine if participants modulate their control strategies depending on their ability to use sensory information to adjust movement trajectories.

4.1. Method

4.1.1. Participants

Forty self declared, right hand dominant, university students served as participants in the study. The experiment was carried out according to the ethical guidelines laid down by the University of British Columbia Behavioral Sciences Ethics Board for studies involving human participants.

4.1.2. Apparatus

The apparatus was the same as that used in Experiment II with the following exceptions. The home position was located to the left of the screen and consisted of one dot 1 mm in width while the target consisted of two dots 5.4 mm apart. The target was located 9 cm to the right of the home position (center to center) subtending a visual angle of 6.8 degrees. Each degree of elbow rotation corresponded to 3.6 mm of cursor movement. Therefore, the angular distance between the home position and the target was 25 degrees while the width of the target was 1.5 degrees of elbow rotation. This distance-width combination yielded an Index of Difficulty of 4.06 bits (Fitts, 1954).

4.1.3. Procedure

The procedure was the same as that used in Experiment II with the exception that the spatial mapping of the visual display on the oscilloscope screen to the movement of the arm was randomly varied from trial to trial. This was done by fixing the location of the home position and the target on the oscilloscope screen but varying the starting location of the movement through a range of 10 degrees in 2.5 degree increments. Therefore, the home and target positions ranged between 120-110 and 95-85 degrees of elbow angle, respectively, where 180 degrees was full extension. Participants were informed that the starting position of their arm would vary from trial to trial, but that the required movement amplitude was always constant. The reason for varying the position of the arm was to discourage participants from relying on a spatially coded endpoint during the transfer tests. Similar to Experiment I and II, participants were informed that they were to minimize total movement time while being as accurate as possible. However, they were given additional instructions which stressed that they should move as fast as possible while also trying to lower their total MTs.

Participants were randomly divided into four groups of ten. The first group practiced the task with vision of the cursor throughout the entire movement (FV). Two other groups practiced the task with the cursor visible for only a specified portion of initial trajectory of the movement. For one group, the cursor disappeared midway through the movement (50%V) while for the other group, it was visible for only the first 75% of the movement (75%V). The final group of participants practiced with no vision of the cursor during the movement (NV).

Participants in each group performed 1500 acquisition trials in 5 sessions over a one week period (see Table 4.1). KR regarding accuracy and movement time was given after each trial. All participants were submitted to two transfer tests which consisted of 25 trials under the no vision condition, but with no KR. The first transfer test was administered after 100 trials and the second after 1500 trials of practice. Participants were given two minutes rest before each transfer test.

4.1.4. Movement analysis

The method used to separate the initial impulse and error correction phases of movement was the same as that used in Experiment II.

4.2. Results

4.2.1. Acquisition

All dependent measures were separately analyzed by performing a 4 Visual Condition x 5 Days ANOVA with repeated measures on the last factor. All post hoc comparisons were made using Tukey HSD tests.

Performance Measures: There were significant main effects of days, $F(4, 144) = 33.7$, $p < .001$, and visual condition, $F(3, 36) = 348.9$, $p < .001$, for $\ln(\text{RMSE})$. Post hoc comparisons revealed

Table 4.1

Breakdown of trials for participants in the four vision conditions (FV; 75%V, 50%V, NV)

<u>Participants</u>	<u>Day1</u>	<u>Day2</u>	<u>Day3</u>	<u>Day4</u>	<u>Day5</u>
1-10(FVgroup)	100 25NV* 200	300	300	300	300 25NV*
11-20(75%V group)	100 25NV* 200	300	300	300	300 25NV*
21-30(50%V group)	100 25NV* 200	300	300	300	300 25NV*
31-40(NV group)	100 25NV* 200	300	300	300	300 25NV*

* No KR

that the FV group was more accurate than the other three groups while the 75%V group was more accurate than the 50%V and NV groups (see Figure 4.1). The ANOVA performed on total MT also revealed significant main effects of days, $F(4, 144) = 55.8, p < .001$, and visual condition, $F(3, 36) = 13.4, p < .001$. Post hoc comparisons indicated that the FV group had slower MTs than the other three groups. No interactions for Ln(RMSE) and Total MT were significant.

Initial Impulse Phase: The only significant effect for the distance traveled in the initial impulse phase was a main effect of days, $F(4, 144) = 18.0, p < .001$. As indicated in Figure 4.2, participants decreased the extent to which they overshoot the target in the initial impulse with practice. An ANOVA performed on the standard deviation of initial impulse endpoints indicated that initial impulse variability decreased with practice, $F(4, 144) = 68.8, p < .001$. There was also a significant difference between visual conditions in the variability of initial impulse endpoints, $F(3, 36) = 28.9, p < .001$, as well as an interaction between days and visual condition, $F(12, 144) = 2.1, p < .05$. A breakdown of the interaction indicated that on Day 1, initial impulses were less variable for the FV compared to the 50%V and NV conditions while the 75%V was less variable than the NV condition. On Days 2 to 4, the FV group was less variable than the other three groups and the 75%V group was less variable than the NV group. On Day 5 the pattern of results were similar but now the 75% group was also significantly different from the 50%V group. It is also worth noting that although the 50%V and NV conditions did not differ statistically, there was a consistent ordering of conditions which is similar to the results obtained from Ln(RMSE). No significant effects were observed for initial impulse MT ($p > .05$).

Figure 4.1. Mean root mean square error (after logarithmic transformation) (a) and total movement times (b), as a function of practice for the FV, 75%V, 50%V and NV conditions.

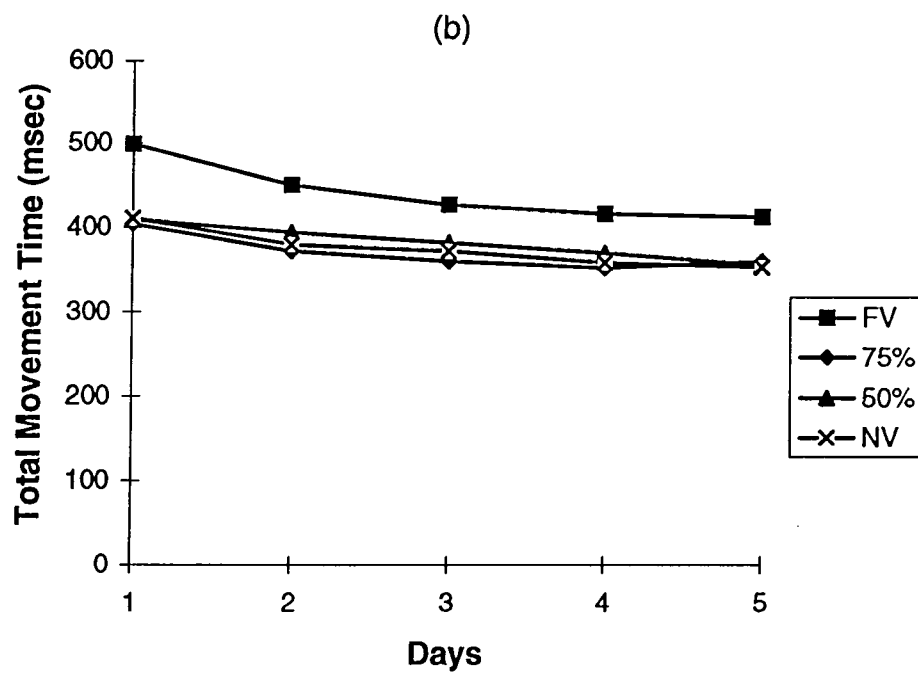
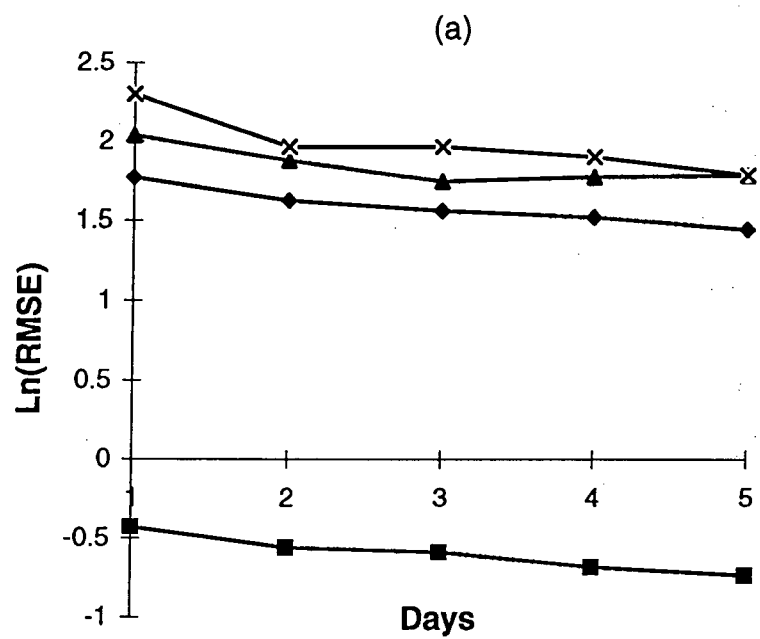
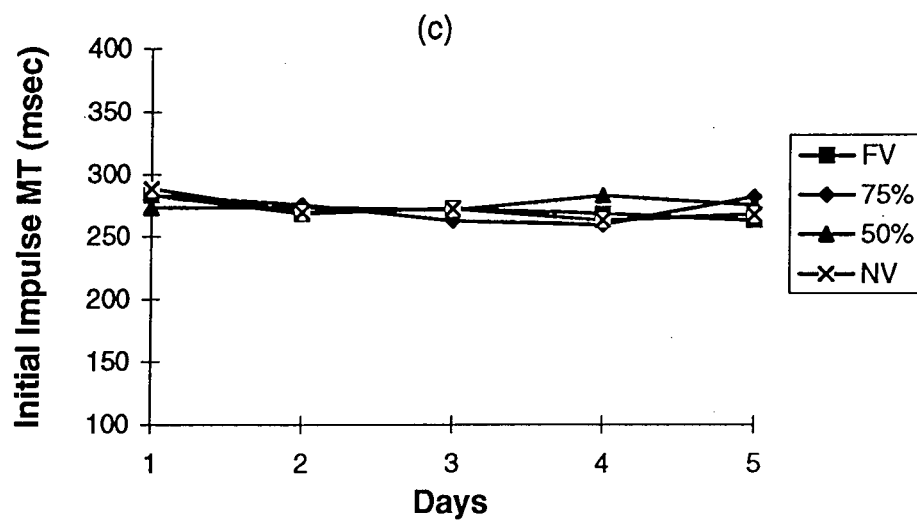
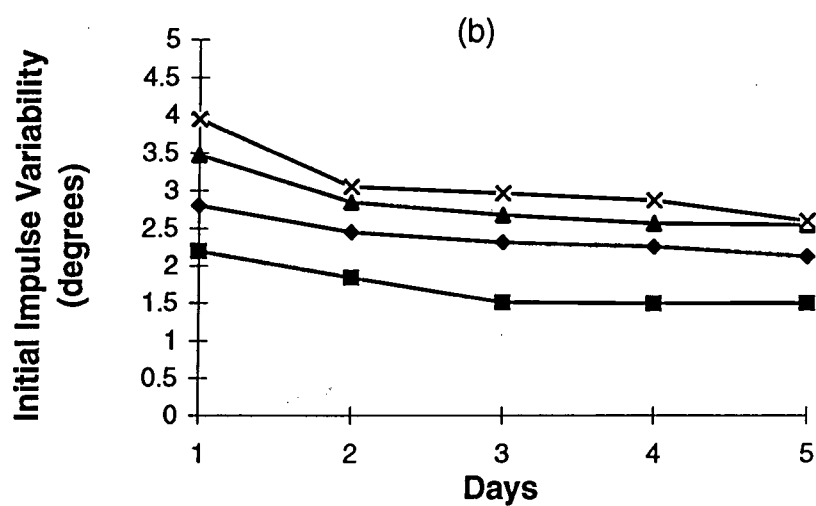
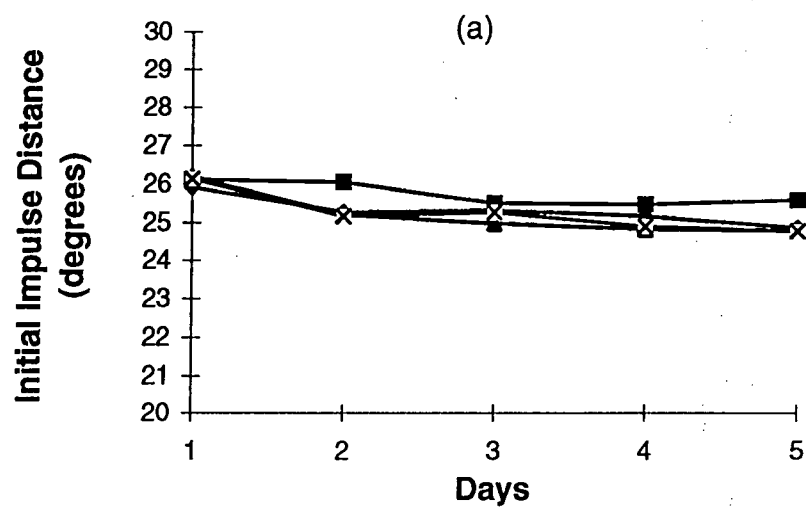


Figure 4.2. Mean initial impulse distance (a), initial impulse variability (b), initial impulse movement time (c), as a function of practice for the FV, 75%V, 50%V and NV conditions.

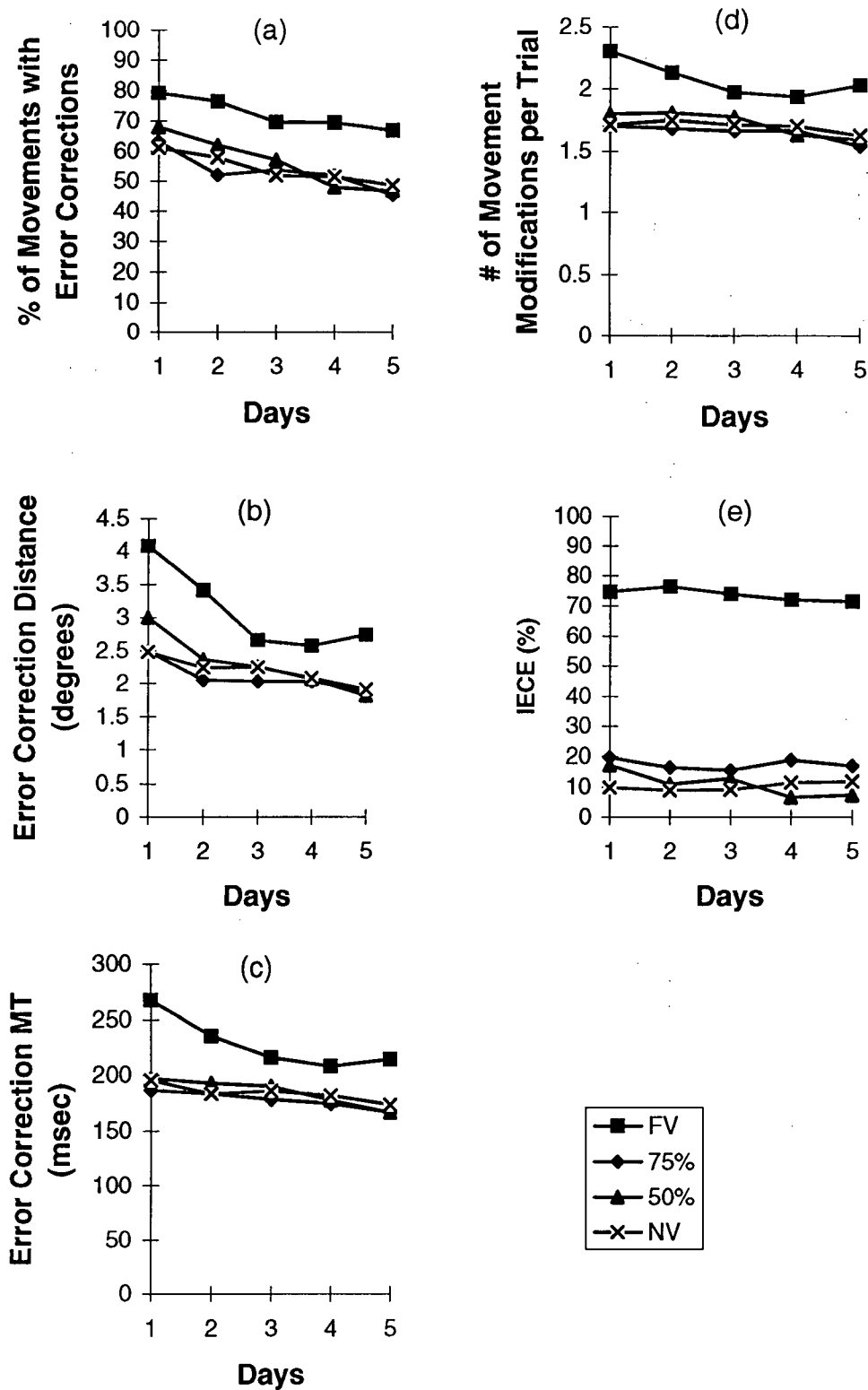


Error Correction Phases: An ANOVA performed on the percentage of movements that contained error correction phases revealed a significant main effect of days, $F(4, 144) = 20.1, p < .001$, and visual condition, $F(3, 36) = 5.2, p < .01$ (see Figure 4.3). Post hoc tests indicated that the FV group had more movements with error corrections than the other three groups.

For those movements that did contain error corrections, there were significant reductions in the distance traveled, $F(4, 144) = 16.3, p < .001$, the time spent $F(4, 144) = 17.2, p < .001$, and the number of movement modifications made, $F(4, 144) = 5.1, p < .01$, in the error correction phases with practice. There were also significant main effects of visual condition on the distance traveled, $F(3, 36) = 6.6, p < .001$, the time spent, $F(3, 36) = 8.6, p = .001$, and the number of movement modifications made, $F(3, 36) = 4.0, p < .05$, during error correction. In all cases, post hoc comparisons revealed significant differences between the FV group and the 75%V, 50%V and NV groups which did not differ from each other. The only significant interaction was on error correction movement time $F(12, 144) = 2.6, p < .05$. Post hoc comparisons revealed that on Days 1 and 2, the FV group spent more time in error correction than the other three groups. On Days 3 and 4, the FV group was significantly different from only the 75%V group, while on Day 5 the difference between the FV and all the other three groups was again significant. On none of the days was there a difference between the 75%V, 50%V and NV groups.

Although there was no effect of days on the effectiveness of the error correction phases (IECE), $F(4, 144) = 1.2, p > .1$, there was a significant main effect of visual condition, $F(3, 36) = 459.9, p < .001$. Post hoc tests indicated that error corrections were more effective for participants in the FV group compared to the other three groups. There was also a small but significant advantage for the 75%V condition over the 50%V and NV conditions.

Figure 4.3. Mean percentage of movements that contain error correction phases (a), error correction distance (b), error correction movement time (c), number of movement modifications per trial (d), and index of error correction effectiveness (e), as a function of practice for the FV, 75%V, 50%V and NV conditions.



Initial Impulse Distance/Total distance and Initial Impulse MT/Total MT: The proportion of the total distance traveled in the initial impulse phases increased with practice, $F(4, 144) = 18.9$, $p < .001$ (see Figure 4.4). There was also a significant main effect of visual condition, $F(3, 20) = 6.4$, $p < .01$. Post hoc tests indicated that the proportion of the total distance traveled in the error correction phase was smaller for the FV condition compared to the 75%V, 50%V and NV conditions. No differences existed between the 75%V, 50%V and NV conditions.

There were also significant main effects of days, $F(4, 144) = 14.7$, $p < .001$, and visual condition, $F(3, 36) = 5.6$, $p < .01$, on the proportion of total MT spent in the initial impulse phase. Post hoc tests indicated that proportionally less time was spent in the initial impulse phase for the FV group compared to the other three groups.

4.2.2. Practice vs transfer performance

The effect of removing visual feedback was examined by first calculating the difference in the results between the 25 transfer trials and the preceding 25 practice trials. A 4 Visual Condition x 2 Practice ANOVA was then performed on the differences between acquisition and transfer phases.

Performance Measures: The ANOVA performed on $\ln(\text{RMSE})$ revealed only a significant main effect of visual condition, $F(3, 36) = 136.4$, $p < .001$. Post hoc analyses indicated that the acquisition to transfer decrement in accuracy was larger for the FV group compared to the other three groups while the 75%V and 50%V conditions were significantly different from the NV condition (see Figure 4.5). No effects of the transfer on Total MT were significant.

Figure 4.4. Mean initial impulse distance/total distance (a) and initial impulse movement time/total movement time (b) as a function of practice for the FV, 75%V, 50%V and NV conditions.

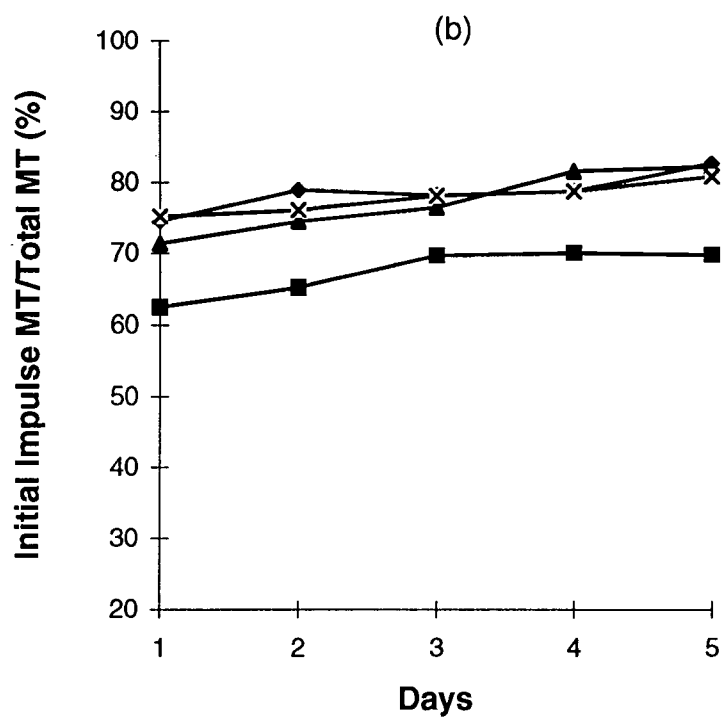
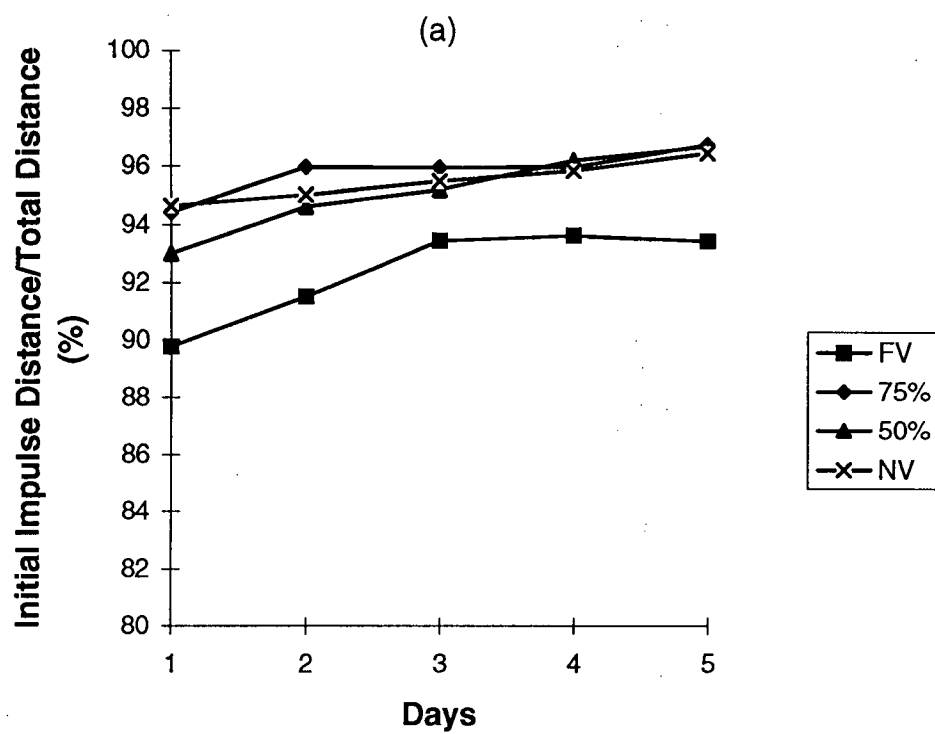


Figure 4.5. Mean difference in endpoint $\text{Ln}(\text{root mean square error})$ (a), initial impulse $\text{Ln}(\text{root mean square error})$ (b) and error correction effectiveness (c), between twenty five transfer trials and preceding twenty five practice trials after 100 and 1500 practice trials for the FV, 75%V, 50%V and NV conditions.

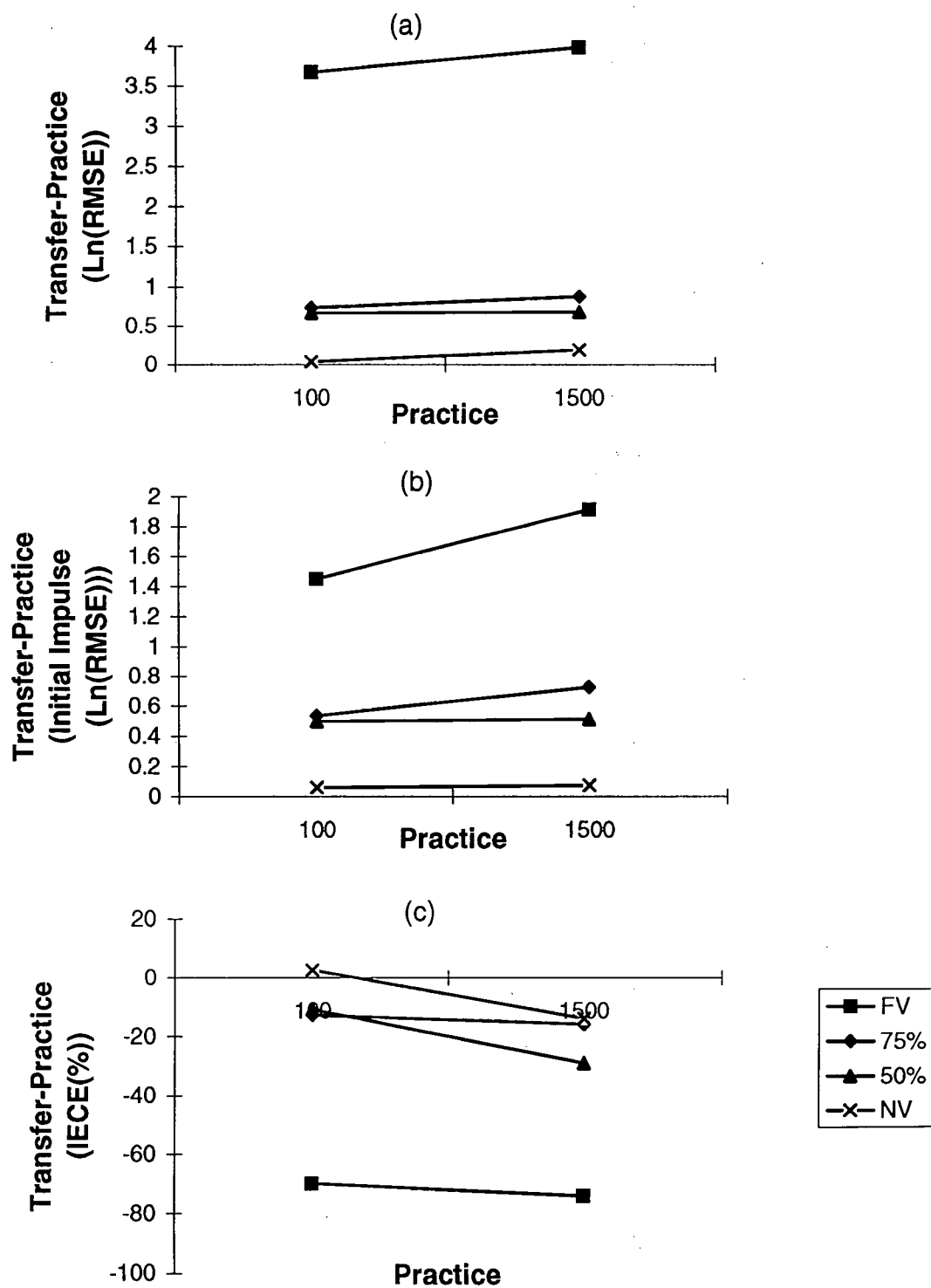


Table 4.2. Mean and standard deviations of dependent variables for performance, initial impulse and error correction phases for transfer (T) tests and previous twenty five acquisition trials.

		A1	T1	A2	T2
Ln(RMSE)	FV	-0.5(0.6)	3.2(0.5)	-0.9(0.6)	2.9(0.9)
	75%V	1.7(0.4)	2.4(0.5)	1.3(0.3)	2.2(0.6)
	50%V	1.9(0.3)	2.6(0.7)	1.7(0.2)	2.4(0.3)
	NV	2.3(0.4)	2.3(0.5)	1.7(0.3)	1.9(0.3)
Total MT (msec)	FV	512(71)	545(111)	400(47)	464(66)
	75%V	422(51)	436(43)	366(34)	380(53)
	50%V	406(49)	432(56)	342(37)	363(45)
	NV	423(27)	407(46)	357(47)	358(41)

		A1	T1	A2	T2
Initial Impulse Distance (degrees)	FV	26.4(1.4)	31.7(9.3)	25.4(7.9)	33.1(7.2)
	75%V	25.8(1.8)	27.7(3.8)	24.9(7.9)	26.4(3.5)
	50%V	26.4(1.2)	29.4(4.4)	24.5(10.1)	27.4(2.2)
	NV	27.1(2.2)	26.6(3.5)	25.1(11.1)	25.3(1.4)
Initial Impulse Variability (degrees)	FV	2.3(0.8)	6.4(3.3)	1.5(0.7)	4.2(2.2)
	75%V	2.6(0.7)	3.5(0.7)	1.9(0.6)	2.4(0.7)
	50%V	3.0(0.5)	4.0(1.4)	2.5(0.2)	2.9(0.3)
	NV	3.6(1.3)	3.3(0.7)	2.4(0.4)	2.4(0.5)
Initial Impulse MT (msec)	FV	291(47)	307(46)	263(57)	296(63)
	75%V	282(34)	308(43)	281(47)	291(50)
	50%V	267(43)	283(44)	260(20)	278(29)
	NV	298((45)	300(47)	276(36)	276(39)

Table 4.2. Continued

		A1	T1	A2	T2
% of Movements with Error Corrections	FV	80(11)	80(12)	60(21)	68(18)
	75%V	69(18)	61(20)	49(25)	42(22)
	50%V	70(20)	67(25)	46(19)	44(23)
	NV	63(19)	55(17)	47(19)	52(13)
Error Correction Distance (degrees)	FV	4.6(3.3)	6.3(5.0)	2.7(1.7)	3.5(1.4)
	75%V	2.5(0.8)	2.4(1.0)	1.9(0.9)	2.1(0.6)
	50%V	2.8(1.5)	3.2(1.4)	1.7(0.4)	2.0(0.5)
	NV	2.4(0.6)	2.4(0.5)	1.7(0.3)	1.7(0.3)
Error Correction MT (msec)	FV	269(66)	286(91)	214(63)	240(48)
	75%V	194(43)	202(40)	160(36)	203(55)
	50%V	192(35)	213(41)	173(36)	180(35)
	NV	191(32)	191(24)	167(30)	159(27)
# of Movement Modifications per Trial	FV	2.3(0.6)	2.3(0.6)	1.9(0.8)	2.0(0.6)
	75%V	1.8(0.5)	1.7(0.4)	1.6(0.5)	1.6(0.4)
	50%V	1.9(0.4)	1.9(0.5)	1.7(0.3)	1.6(0.4)
	NV	1.8(0.4)	1.6(0.4)	1.5(0.3)	1.5(0.2)
IECE (%)	FV	75(15)	5(27)	77(15)	3(21)
	75%V	9(25)	-3(18)	17(29)	1(22)
	50%V	17(10)	6(14)	23(18)	-5(21)
	NV	16(25)	18(15)	8(27)	-6(27)

		A1	T1	A2	T2
Initial Impulse Distance/Total Distance (%)	FV	89(6)	87(7)	93(5)	93(3)
	75%V	93(3)	95(3)	96(3)	96(2)
	50%V	93(5)	93(5)	97(2)	97(2)
	NV	94(3)	95(2)	97(2)	97(1)
Initial Impulse MT/Total MT (%)	FV	62(10)	61(12)	72(15)	69(12)
	75%V	71(11)	75(11)	80(13)	81(11)
	50%V	70(12)	70(14)	81(8)	82(11)
	NV	74(11)	78(7)	81(9)	81(6)

Initial impulse Phase: There was a significant main effect of visual condition on the distance traveled in the initial impulse, $F(3, 36) = 5.8, p < .01$. Post hoc analyses indicated that participants in the FV group increased the distance traveled in the initial impulse phase more than participants in the 75%V and NV conditions when going from acquisition to transfer. There was also a main effect of visual condition on the variability of initial impulse endpoints, $F(3, 36) = 11.7, p < .001$, with the FV group having a larger increase in variability compared to the other three conditions. In order to assess the effect of the transfer on the overall accuracy of the initial impulse, we calculated the variability of initial impulse endpoints with respect to the target (see Figure 4.5b). This provided a more complete account since there was high between participant variability in the distance traveled in the initial impulse phase in the transfer tests. Some participants overshot the target while others had a tendency to undershoot. The ANOVA revealed a significant main effect of visual condition, $F(3,36) = 22.7, p < .001$. Post hoc analyses indicated that the effect of the transfer on the accuracy of the initial impulses was greatest for the FV group while the 75%V group was affected more than the NV group.

The ANOVA performed on initial impulse MT revealed a significant main effect of visual condition, $F(3, 36) = 3.5, p < .05$. Post hoc tests indicated that there was a larger increase in the time spent in the initial impulse phase for the FV compared to the NV group.

Error Correction Phase: The only significant effects of the transfer on the error correction phases were main effects of visual condition on the distance traveled during error correction, $F(3, 36) = 4.9, p < .01$, and the effectiveness of the error correction phases, $F(3, 36) = 21.5, p < .001$. Post hoc analyses indicated that the removal of feedback resulted in a larger increase in the distance traveled during error correction for the FV compared to 75% and NV groups. Also, the decrement in IECE was greater for the FV compared to the other three groups (see Figure 4.5c).

4.3. Discussion

The present experiment was designed to investigate how visual information that was provided early in the movement trajectory was used to control rapid aiming movements and to examine what effect practice had on the ability to use this information. Of particular interest were the roles of vision during the production of both the initial impulse and error correction phases. In the past, researchers have claimed that the role of vision during movement execution is limited to the error correcting "homing in" phase (Meyer et al., 1988; Woodworth, 1899). However, the results of Experiments I and II have shown that visual feedback affected both the initial impulse and error correction phases. Given this evidence, it was our intent to offer an account of where in the movement trajectory is vision most critical and what is the role of this information in the production of the two phases of movement.

4.3.1. Critical sources of visual feedback

During acquisition, the 50% vision group did not differ reliably from the NV group. This finding is consistent with past research which has shown that visual feedback from the initial portion of the trajectory is relatively unimportant for aiming accuracy (Carlton, 1981; Chua & Elliott, 1993; Temprado et al., 1996). However, in contrast to the 50%V condition, the presentation of visual feedback over the first 75% of the movement did result in significantly better performance compared to the NV condition. In the past, it has been assumed that visual information over the first 75% of the movement benefited the error correcting homing in phase of movement (Carlton, 1981). On this basis, it was predicted that over extensive practice, participants would learn to use early sources of visual feedback to produce effective error corrections and hence would exhibit performance similar to that of the FV group. However, the advantage of the 75%V condition over the NV condition seemed to be primarily in the production

of the initial impulse. Although the effectiveness of the error correction phases was slightly better for the 75%V group compared to the NV group, error corrections were still not near as effective as the FV group. Being able to see the cursor for the entire movement allowed participants to reduce error following the initial impulse by 70 %. In contrast, participants who practiced with vision for the first 75% of the movement reduced error by only 20 %. With such low success in minimizing error it is not surprising that participants did not rely on error corrections as did participants in the FV group. In fact, the extent to which error corrections were produced was not different between the 75%, 50% and NV conditions, even after extensive levels of practice.

Evidence from previous work on manual aiming (Elliott et al., 1994) and ball catching (Elliott, Zuberec & Milgram, 1994; Sharp & Whiting, 1974) has shown that, within certain limits, both the length of the visual sample and the occlusion time are important factors in movement control. Typically, increasing the duration of visual samples provided the necessary information to extrapolate the spatio-temporal trajectory over occluded portions as long as the duration of occlusion intervals did not exceed 80 msec. In the present study, the cursor was visible for approximately 165 msec in the 75%V condition and the interval from 75% displacement to the end of the initial impulse was approximately 105 msec. Therefore, the visual sample was long enough to extract dynamic changes in the movement trajectory. However, the occlusion time appears to have been too long to extrapolate this information over the remaining trajectory and uncertainty about where the initial impulse ended negated the production of error corrections.

The advantage of the FV group over the 75% group highlights the importance of the last 25% of the movement in the production of both the initial impulse and error corrections. The finding that initial impulse endpoints were less variable for the FV compared to the 75% condition indicated that the 105 msec visual sample between 75% of the movement and the end of the initial impulse was processed via a visuomotor feedback loop with a relatively short delay. Error

corrections were likely prepared on the basis of this information and possibly on information obtained from within the error correction phases themselves. The latter possibility is reasonable given that error correction movement times for the FV group were over 200 msec throughout acquisition.

4.3.2. Kinetic and static visual channels

Paillard and Amblard (1985) have postulated that aiming movements are under the control of two semi-independent visual systems. The kinetic channel operates in the visual periphery, is tuned to code continuous motion at high velocities (10 - 200 deg/sec) and has high temporal acuity. It is said to play an important role in controlling the direction of movement. The static channel operates in central vision and codes location information for stimuli moving below visual angle velocities of 15 deg/sec. It is thought to be primarily responsible for the homing in phase where limb velocities are relatively low. Here, the location of the limb can be compared to the location of the target thereby enabling the appropriate corrections to be made to the limb's position.

The results of the present experiment have several implications for the two channel model proposed by Paillard and Amblard (1985). On one hand, a visual angle of 6.8 deg between the home position and the target implies that the kinetic channel was not involved. However, peak velocities were approximately 50 deg/sec. This suggests that the static channel may be capable of processing stimuli moving at higher velocities than that posited by Paillard and Amblard (1985). Further support for this position has also been provided by Abahnini, Proteau and Temprado (1997) who have shown that velocities up to 50 deg/sec can be processed in central vision.

On the other hand, it is possible that the kinetic channel did play an important role in controlling the amplitude of the high velocity initial impulse phase. Neurophysiological studies on

the cat (areas 17 and 18) (Orban, Kennedy & Hayes, 1981) and macaque monkey (middle temporal visual area) (Maunsell & Van Essen, 1983) have shown evidence for direction selective as well as velocity sensitive cells with a shift in eccentricity to higher velocities with increasing eccentricity (Orban, Kennedy & Bullier, 1986). Also, Proteau and Masson (1997) have reported that the amplitude of force pulses were affected by perturbing the perceived velocity of movement. Hence, the kinetic channel may benefit the control of movement amplitude as well as direction. Indeed, the finding that peripheral vision improves directional but not amplitude accuracy (Bard et al., 1990) may be because the dynamic changes in the movement trajectory towards the end of the movement are more drastic in the direction of movement than orthogonal to the direction of movement. Peripheral vision likely benefited directional accuracy because direction is determined early in the movement whereas central vision was critical for amplitude control since most of this control takes place during the later stage of movement (Fleury, Bard, Audiffren, Teasdale, & Blouin, 1994). Therefore, it may be more a question of where in the trajectory information is needed for directional versus amplitude control rather than the angle of eccentricity at which visual information is most relevant for the respective components.

If the kinetic channel played a role in controlling the initial impulses, this would imply that it is not limited to eccentricities greater than 10 degrees of visual angle. Maunsell and Van Essen (1983) have shown that neurons in the middle temporal visual area of the macaque monkey subserving eccentricities below 10 degrees have preferred speeds between 8 and 64 deg/sec which is in line with the velocities produced in the present experiment. Also, Orban (1985) has reported that velocity tuned cells in area 17 of the cat subserving central vision are sensitive to both high and low velocities while velocity tuned cells that subserve peripheral vision are sensitive only to high velocities. Orban indicates that this fits well with evidence from behavioral studies on humans involving just noticeable differences (JNDs) in velocity. In central vision the high

sensitivity velocity range was shown to span between 2 to 260 deg/sec. As eccentricity increased, the upper limit of the high sensitivity range remained relatively constant while the lower limit progresses towards higher velocities. In other words, central vision is sensitive to velocity changes at both high and low velocities while peripheral vision is only sensitive to changes at high velocities. Therefore, while the static channel may be limited to central vision, the kinetic channel seems to span over both central and peripheral visual fields.

At 75% of the movement, velocities were on average 38 deg/sec. Therefore, it is possible that corrective submovements were not effective with vision of the first 75% of the movement because velocities over this interval were outside the operational range of the static channel. Only when participants were given vision over the last 25% of the movement were they able to make discrete modifications which were effective in reducing error. This speaks to the functional independence of these two channels in the control of rapid aiming movements. The kinetic channel operates during the high velocity phase of movement and codes velocity information which can be used to regulate the deceleration of the limb. On the other hand, the static channel can only effectively come into play when velocities are below some criterion. Possibly, only at low velocities can the position of the limb be assessed in relation to the target so that the appropriate adjustments can be made.

4.3.3. Specificity of learning hypothesis

The transfer data indicated that removal of vision from the 50%V, 75%V and FV groups adversely affected performance. This was the case after 100 and 1500 trials of practice. Therefore, consistent with Experiments I and II and the work of Proteau and colleagues, learning did not result in a decreasing reliance on visual feedback but the importance of vision remained after extensive practice. Particularly interesting is the finding that, although vision of the first half

of the movement did not reliably benefit movement accuracy during acquisition, its removal caused a significant decrement in performance. This suggests that participants processed early visual information. It is possible that the processing of visual feedback from early in the movement distracted participants from processing intrinsic sources of information such as proprioception or efference copy. Thus, they could not rely on these sources of information when KR was removed in the transfer tests. Alternatively, participants may have attempted to use the early visual information purposefully to extrapolate the spatiotemporal trajectory over the remainder of the movement, but this did not lead to reliably better performance compared to when no vision was available. In any event, regardless of whether vision over the first half of the movement acted as an irrelevant perceptual distractor or was processed to the level of motor output, the evidence suggests that participants still processed this information after 1500 trials of practice, despite the fact that it had no reliable effect on performance. Hence, consistent with the specificity of learning hypothesis, changing the sources of feedback that were available during practice, albeit minor, had an adverse affect on performance. It appears that the available sources of sensory information remained specific to the task after extensive practice and thus were important for maintaining performance when KR was removed.

However, in contrast to the specificity of learning hypothesis (Proteau, 1992), the dependence on visual feedback did not significantly increase as a function of practice. In Experiment II, initial impulse MTs ranged from 450 msec early in practice to 250 msec late in practice. We had proposed that the long initial impulse MTs enabled participants to become dependent on visual feedback at the early stages of practice. This may not have been the case in Experiment I where initial impulse movement times were about 210 msec early in practice. In the present experiment, movement amplitude was decreased from 45 degrees (Experiment II) to 25 degrees in an attempt to obtain similar initial impulse MTs to that of the wrist rotations in

Experiment I. While this was somewhat successful in reducing the time spent in the initial impulse phase, especially early in practice, movement times were still between 250 and 300 msec. Given the high moment of inertia of the forearm participants were not able to reduce initial impulse MTs to the level of that of wrist rotations. Since movement times over 250 msec are quite adequate for visual information processing, participants appear to have become reliant on vision early in practice. Hence, similar to Experiment II, the decrement in performance when vision was removed was likely subject to a ceiling effect.

4.3.4. Online versus offline control

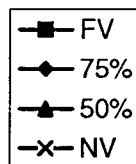
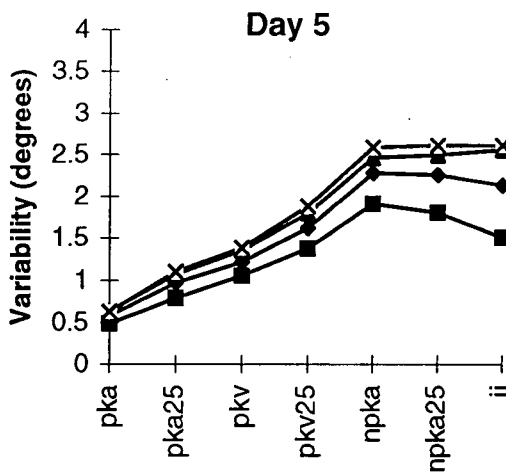
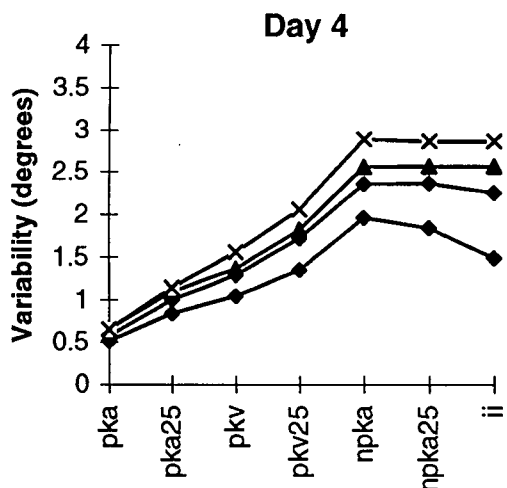
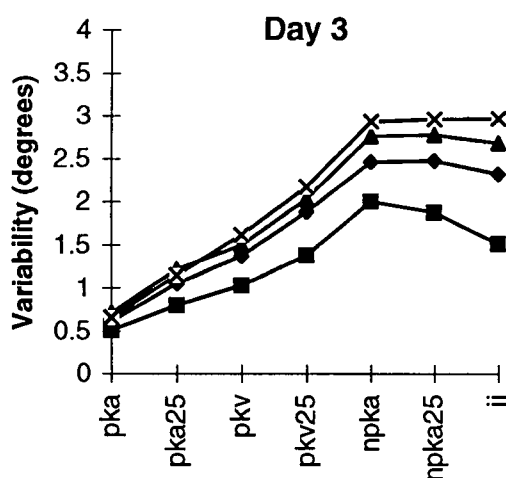
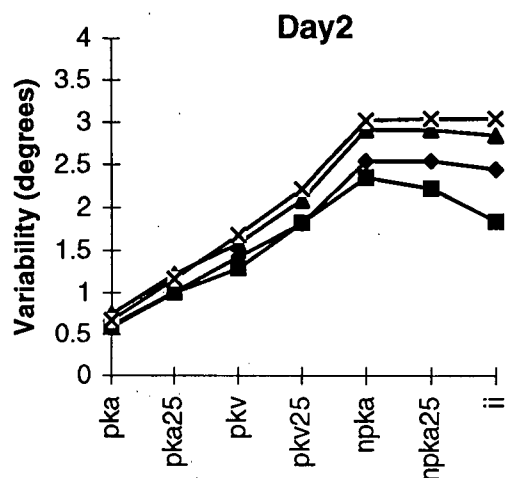
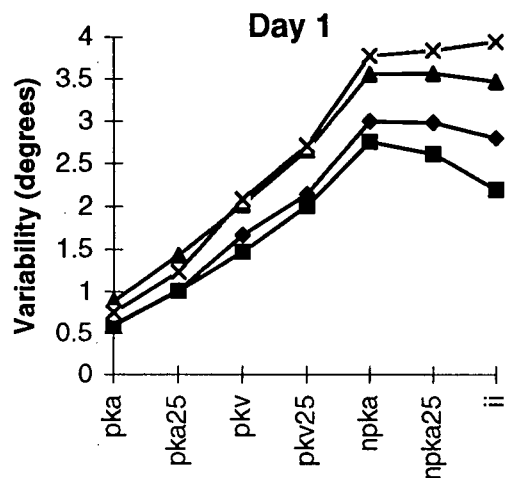
Typically, research which has involved the manipulation of visual feedback has focused on the role of vision in the detection and correction of errors during the execution of movement. A prerequisite for online processing of visual feedback is that movement times are long enough to encompass visuomotor delays. However, it is likely that the effect of these manipulations is not limited to online processing and that visual feedback from a completed movement is used offline as an enriched form of KR to accurately program movements on upcoming trials (Hay & Beaubaton, 1986; Proteau & Marteniuk, 1993). Offline processes would likely predominate in situations in which movement time is relatively short or in situations in which visual feedback is presented too late during a movement to allow corrections to be made online.

Typically, online control has been inferred from the presence of discrete adjustments in the movement trajectory. In the present study, the extent to which error corrections were produced and the effectiveness of these error corrections were greater when full visual feedback was available compared to the partial and no vision conditions. However, the role of vision was not limited to the production of error corrections. Visual feedback had an impact on the production of initial impulses in both acquisition and transfer. It is possible that participants used visual

feedback from a previous trial to improve programming of the initial impulse on a subsequent trial. This offline account is consistent with assumptions in the literature that initial impulses are programmed and therefore not affected by online processes (Meyer et al, 1988; Woodworth, 1899). Along these lines, the effect of transfer on the initial impulse phases implies that visual feedback provided an immediate and enriched form of KR which prevented processing of intrinsic sources of feedback (Abahnini, Proteau & Temprado, 1997). That is, participants became reliant on visual feedback from a previous trial for the programming of upcoming trials and therefore were not able to accurately program movements when this information was removed.

Since the initial impulse, by definition, does not contain movement modifications it is more difficult to find kinematic evidence for online control. Further, other kinematic variables such as time to peak acceleration, time to peak velocity, time from peak acceleration to the end of the initial impulse, and time from peak velocity to the end of the initial impulse were all unaffected by visual condition ($p > .05$). Given that the variability of initial impulse endpoints was influenced by visual condition, it was reasoned that by examining how these variability differences unfolded as the movement progressed, the potential contribution of online and offline control processes could be assessed. Towards this end, the standard deviation of distance traveled at various kinematic landmarks throughout the initial impulses was calculated. Figure 4.6 illustrates the variability in distance traveled at peak acceleration, peak acceleration + 25 msec, peak velocity, peak velocity + 25 msec, negative peak acceleration, negative peak acceleration + 25 msec and the end of the initial impulse for the four visual conditions over five days. Evidence for offline control comes from the difference between conditions in the variability of the distance traveled at peak velocity, $F(3, 36) = 14.4$, $p < .001$. Post hoc tests indicated that spatial variability was lower for the FV compared to the other three groups while the 75%V group was less variable compared to the 50%V and NV groups. Since peak velocity occurred at about 50% displacement, the lower

Figure 4.6. Variability in distance traveled at peak acceleration, peak acceleration + 25 msec, peak velocity, peak velocity + 25 msec, negative peak acceleration, negative peak acceleration + 25 msec, and at the end of the initial impulse on Days 1 to 5 for the FV, 75%V, 50%V and NV conditions.



variability of the FV and 75%V groups compared to the 50%V group at peak velocity must have been a result of information obtained after peak velocity. Hence, the information provided after peak velocity in 75% and the FV groups could only have been used offline in order to have an effect at peak velocity. That is, participants saw more of their movement trajectory in the 75%V and FV conditions and used this information to improve programming on subsequent trials.

Figure 4.6 also provides evidence for online control during the production of initial impulses. The rationale here is that if movements are programmed and not altered online, there should be some lawful relationship between movement variability and distance traveled. Evidence would be gained for online control if these functions differ between visual conditions over and above multiplication by a scalar factor. This is based on the assumption that the differences in motor programming variability between conditions caused by offline processes is multiplicative. Note that in Figure 4.6, kinematic landmarks are represented on the x-axis instead of mean distance traveled. It was believed that this was justified since the mean distance traveled did not differ significantly between visual conditions at any of the kinematic landmarks that were used. Also, the relationship between conditions is not altered by placing these kinematic landmarks at equal spacings on the x-axis. A 4 visual condition x 7 kinematic index x 5 day ANOVA revealed significant main effects of visual condition, $F(3, 36) = 16.7, p < .001$, kinematic index, $F(1, 36) = 1162.9, p < .001$ (linear) and day, $F(3, 36) = 117.6, p < .001$ (linear), as well as a significant interaction between visual condition and kinematic index, $F(3, 36) = 16.2, p < .001$ (linear). In order to breakdown this interaction, separate 2 visual condition x 7 kinematic index x 5 day trend analyses were performed to compare the increase in variability of the FV, 75%V, 50%V groups with that of the NV group. Significant linear visual condition x kinematic index interactions between the FV and NV groups, $F(1, 18) = 27.4, p < .001$, and between the 75%V and NV groups, $F(1, 18) = 7.4, p < .01$, indicated that the increase in variability as the movement

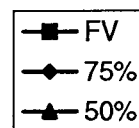
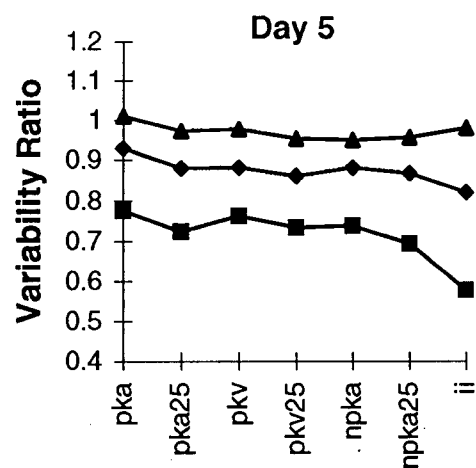
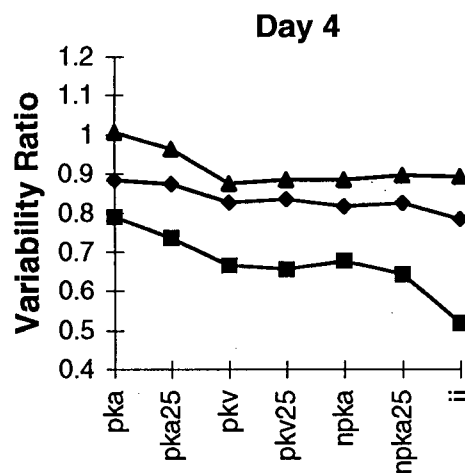
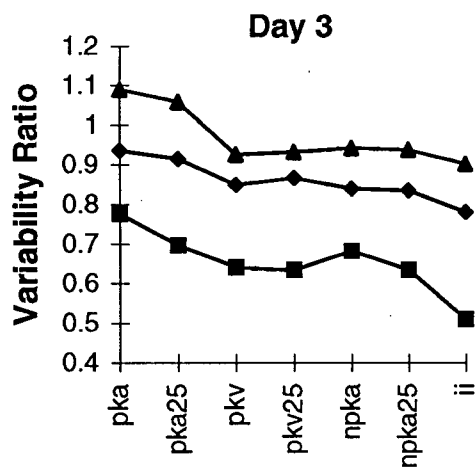
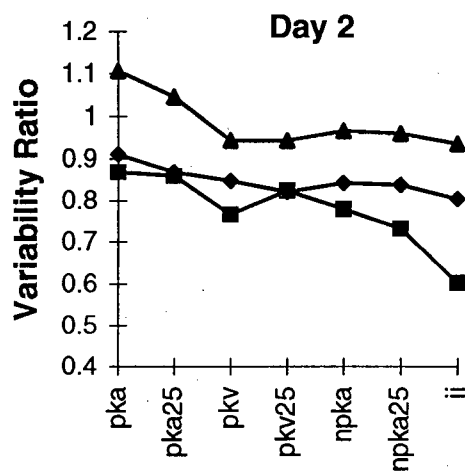
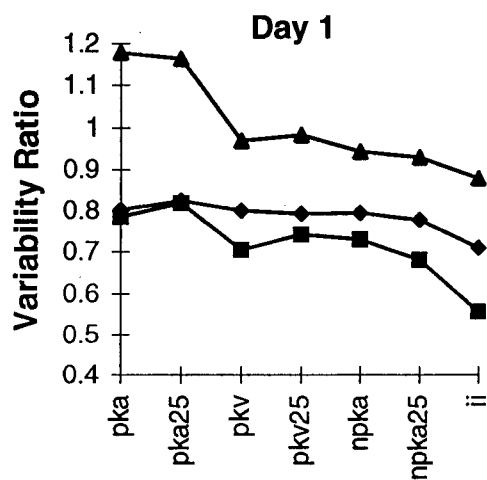
progressed was less for the 75%V and FV conditions compared to the NV condition. Notable is that there was even a tendency for variability to decrease in the FV condition from negative peak acceleration to the end of the initial impulse. There was no interaction between the 50%V and NV groups, $F(1, 18) = 2.6$, $p > .05$. Therefore, the visual information provided in the FV and 75%V groups provided a basis upon which the increase in movement variability as the movement progressed deviated from that of the NV condition.

Figure 4.7 shows the ratios in spatial variability between the FV and NV conditions, 75%V and NV conditions and 50%V and NV conditions at each of the kinematic landmarks for Days 1 to 5. If these were horizontal lines, it would have implied that the functions shown in Figure 4.6 were scalar multiples of each other. However, in Figure 4.7 it can be seen that there was a tendency for the ratios in spatial variability between visual conditions to decrease from the early to late phases of the initial impulse.⁴ These trends seem to be more consistent for the FV compared to the 75% and 50% conditions throughout the five days of practice. This indicates that the increase in spatial variability as the movement progressed was greater in the NV condition than in the other visual conditions by more than a scalar multiple. Hence, using the NV condition as a baseline for programmed movement, or at least movement that is not influenced by visual feedback, there is evidence to suggest that online processing occurred during the production of the initial impulse phases when visual feedback was available.

Finally, a non-significant three way interaction between visual condition, kinematic index and day, $F(3, 36) = 2.0$, $p > .05$, suggests that the relative contribution of offline and online processes did not change as a function of practice.

⁴ Since visual condition was a between participant factor, it was not possible to perform an ANOVA on the ratios in spatial variability.

Figure 4.7. Ratios (FV:NV; 75%V:NV; 50%V:NV) of variability in distance traveled at peak acceleration, peak acceleration + 25 msec, peak velocity, peak velocity + 25 msec, negative peak acceleration, negative peak acceleration + 25 msec, and at the end of the initial impulse on Days 1 to 5.



4.3.5. Distance versus position control

In order to perform goal directed movements, an individual must code and translate spatial information into the appropriate motor commands needed to achieve the task goal (Abrams, Van Dillen & Stemmons, 1994; Bock & Eckmiller, 1986). However, there has been considerable debate in the motor control literature concerning which features are coded in sensory space and transformed into corresponding parameters in motor space. According to one viewpoint, the hypothetical central controller specifies movement distance by programming the timing and amplitude of force pulses (i.e., distance control) (Schmidt et al., 1979; Wallace, 1981). Alternatively, it has been argued that the control system codes positions in space by specifying equilibrium points in the length-tension relationships of the agonist and antagonist muscles (i.e., position control) (Feldman, 1986; Polit & Bizzi, 1978).

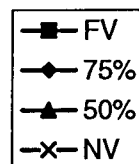
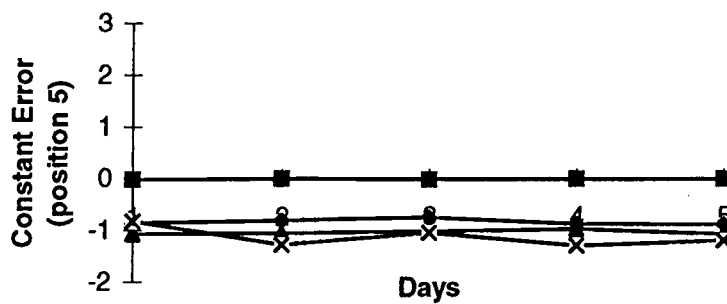
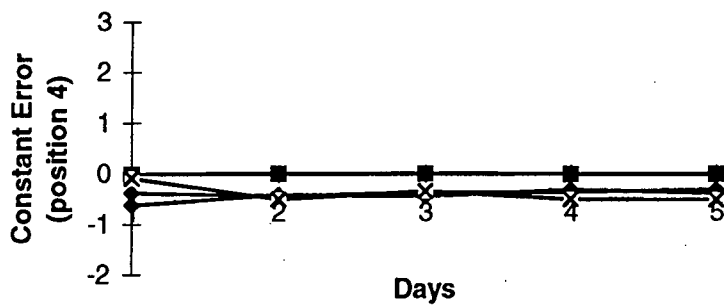
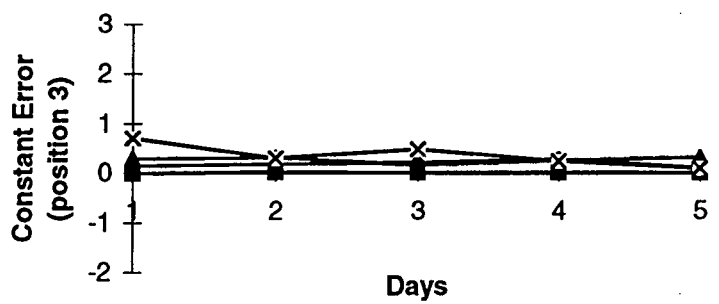
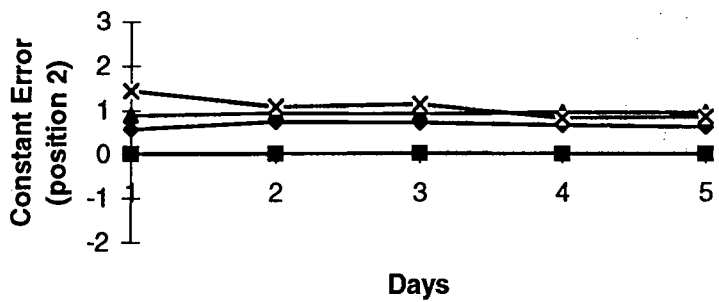
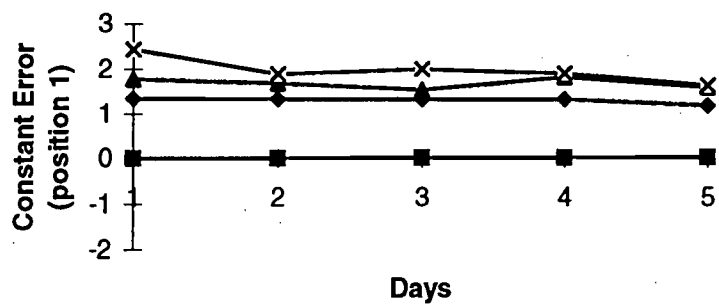
Both viewpoints give rise to different predictions. If amplitude is controlled, an unexpected change in starting position or inertial load would cause systematic biases in movement endpoints. On this basis, Bock and Eckmiller (1986) have argued in favor of amplitude control by showing that errors in a pointing sequence accumulated throughout the sequence and that these errors were biased in the direction of the error made in the previous segment. They claimed that if final position was coded it should not be influenced by variations from within the sequence.

On the other hand, support for a position control viewpoint stems from studies which have shown that desired endpoint location is attained despite perturbations in starting position or inertial load (Polit & Bizzi, 1978; Schmidt, 1980). Further support for position control has recently been obtained from studies which have compared the effect of practice on movement distance and final position reproduction. In a study by Jaric, Corcos, Gottlieb, Ilic and Latash (1994), one group of participants practiced a distance control task in which they were required to produce right arm elbow flexion movements of the same amplitude from different starting

positions. A second group practiced a location control task in which they were required to produce movements to the same location from different starting positions. Following acquisition, both groups were first tested in the task they had practiced but without visual feedback. The tasks were then unexpectedly switched. The distance control group was required to perform the location task while the location group was required to perform the distance task. Results showed that both groups reproduced movement endpoints relatively well when tested on the location task. However, a strong relationship existed between distance traveled and initial position when participants were tested on the distance task. That is, instead of producing movements of the same amplitude, participants increased the distance traveled when initial positions shifted towards the right while they decreased the distance traveled when initial positions shifted to the left. This was the case even for participants who practiced the distance reproduction task. Therefore, regardless of which task participants practiced, they were strongly biased towards final position reproduction. Further work by Ilic, Corcos, Gottlieb, Latash and Jaric (1996) has shown that participants who practiced movements having the same initial and final positions but with varying inertial loads had larger reductions in variable error compared to participants who practiced movements over different distances but with a fixed inertial load. This was taken as support for the equilibrium point hypothesis since both tasks required a change in the force requirements of the task but the load task required movements to be made to a fixed endpoint. Hence, only a single parameter corresponding to the final position needed to be learned.

In the present experiment, starting position was randomly varied from trial to trial but participants were told that the required movement amplitude was constant. Figure 4.8 shows mean constant errors for each of the five starting positions as a function of visual condition and practice. A 4 visual conditions x 5 starting position x 5 days ANOVA revealed a significant main effect of starting position, $F(4, 144) = 480.2$, $p < .01$, and a significant interaction between

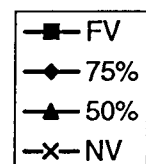
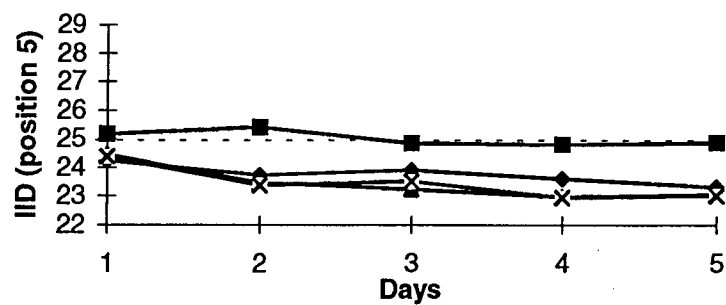
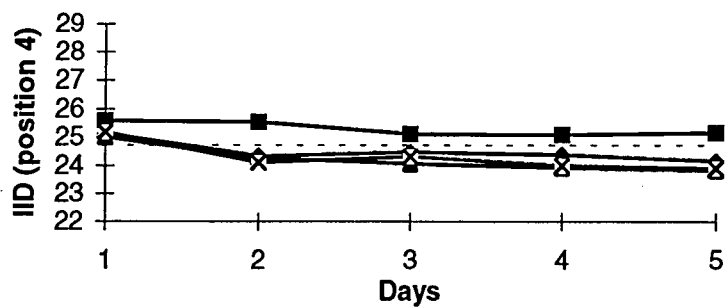
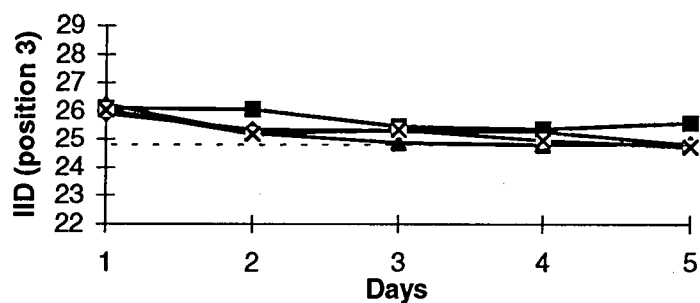
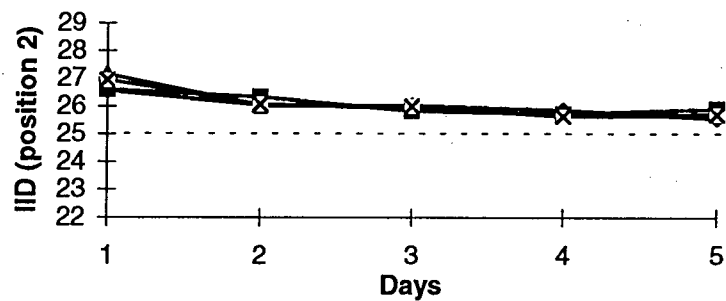
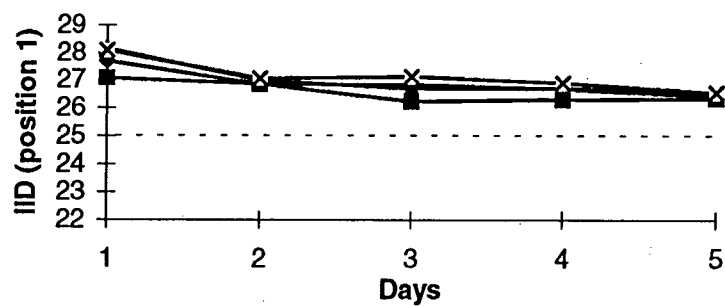
Figure 4.8. Constant error for the five starting positions (positions 1-5 (leftmost-rightmost)) as a function of practice for the FV, 75%V, 50%V and NV conditions.



starting position and visual condition, $F(12, 144) = 56.1, p < .01$. As shown in Figure 4.8, movement endpoints were biased depending on starting position for the 75%V, 50%V and NV groups but not the FV group. Participants overshoot the target for starting positions to the left (i.e., at elbow angles closer to full extension) while they undershot the target for starting positions to the right (i.e., at elbow angles closer to full flexion). Examination of the distance traveled in the initial impulse phases (see Figure 4.9) revealed a similar pattern of results. A main effect of starting position, $F(4, 144) = 655.0, p < .001$, indicated that initial impulses tended to overshoot the target from the leftmost starting position while they undershot the target from the rightmost starting position. A starting position \times visual condition interaction, $F(12, 144) = 18.3, p < .001$, indicated that this effect was larger for the 75%V, 50%V and NV conditions compared to the FV condition. Therefore, it appears that there was a strong disposition to code spatial location which caused movement endpoints to be biased depending on starting position. While participants with visual feedback were able to correct these errors, this information was not available for participants in the other three groups. Also noteworthy is that even after 1500 trials of practice, participants still showed this tendency although they were given KR regarding their constant error after each trial. For both constant error and the distance traveled in the initial impulse, the effects of practice did not interact with starting position or visual condition ($p < .05$). It may be that the range of starting positions (2.5 degree increments over 10 degrees) was too small for participants to consciously perceive (Jaric, Corcos & Latash, 1992) and therefore they did not make the necessary adjustments from trial to trial. At any rate, despite participants being told that movement amplitude was constant regardless of starting position, it was clearly difficult to produce movements of the same distance from the different starting positions.

There is an important distinction between the experimental setup and task used in the present study and that used in other studies (Bock & Eckmiller, 1986; Ilic et al., 1996; Jaric et al.,

Figure 4.9. Initial impulse distance (IID) for the five starting positions (positions 1-5 (leftmost-rightmost)) as a function of practice for the FV, 75%V, 50%V and NV conditions.



1994). In the present experiment, a video aiming task was employed in which movement of the limb was translated to movement of a cursor on an oscilloscope screen. Furthermore, the location of the home position and the target on the oscilloscope screen was always constant, but the actual starting location of limb movement was varied randomly. As a result, the spatial mapping between the visual display and the limb movement changed from trial to trial. In previous work, conventional aiming tasks were employed in which the home position and target area were in the same sensory space as the limb movement. Therefore, the spatial mapping between the initial and target positions and limb movement was always constant. It is possible that by changing the transformations from sensory space to motor space from trial to trial, the mapping from a previous trial interfered with the sensorimotor transformations on a subsequent trial. Perhaps, participants would have been less affected if changes in limb position were matched by changes in the location of the visual display on the oscilloscope screen. This would decrease the complexity of sensorimotor transformations and increase the compatibility between position and distance codes.

Given the evidence supporting both amplitude and position control, Abrams et al. (1994) have proposed a control scheme which postulates that the control of the initial impulse and error correction phases are governed by separate spatial codes. The initial impulse was said to be programmed based on the perceived distance between the home position and the target whereas error corrections are based on the coding of final position. In support of their hybrid model, they showed that initial impulse endpoints, but not final endpoints, were affected by manipulating the perceived distance from the home position to the target through the use of an induced motion illusion. However, the results from the present experiment are somewhat at odds with this viewpoint. Since the display on the oscilloscope screen did not vary from trial to trial, the perceived distance between the home position and the target should not have been affected.

Given the finding that the distance traveled in the initial impulse was affected by manipulating starting location, it seems that the initial impulses were not prepared on the basis of the perceived distance between the home position and the target but rather a spatial code of final position.

4.3.6. Summary

The results of the present experiment indicated that vision played a role in the production of both the initial impulse and error correction phases. The evidence suggests that visual feedback from the first half of the movement was processed but it had no reliable effect on performance during acquisition. Vision of the first 75% of the movement did benefit performance but its role seemed to be limited primarily to the control of the initial impulse. Even after extensive levels of practice, vision of the last 25% of the movement was still crucial for the control of the later stages of the initial impulse and in particular, the effectiveness of the error correction phases. These findings are consistent with models which have posited the existence of separate but semi-independent visuomotor channels for the processing of high velocity and spatial information (Paillard & Amblard, 1985).

5. General Discussion

The present experiments were designed to investigate how the visual control of a particular class of aiming movements in which participants are required to move as fast and as accurately as possible changes with practice. The importance of visual feedback was assessed by manipulating the amount of vision that participants had during acquisition as well as by examining the cost of removing visual feedback at different stages of practice. Also, by parsing movements into their initial impulse and error correction phases, we were able to document how changes in visual control were related to the planning/programming of rapid aiming movements.

The stochastic optimized submovement model put forth by Meyer et al. (1988) is perhaps the most comprehensive account of speed-accuracy tradeoffs to date. It is based on the premise that noise exists in the neuromotor system which leads to systematic relationships between the velocity and endpoint variability of component submovements. Optimal performance is said to be achieved by adjusting the velocity of submovements such that the combined duration of the initial impulse and error correction phases is minimized under the required accuracy demands of the task. Based on their finding that vision had no impact on the tradeoff between the durations of the initial impulse and error correction phases, Meyer et al. claimed that the underlying mechanisms that cause neuromotor noise are independent from those that mediate sensory-based control. Hence, visual feedback was not taken into account in the basic assumptions of the stochastic optimized submovement model regarding the spatio-temporal properties of submovements. In contrast to this viewpoint, Experiment I indicated that after extensive levels of practice, the location of initial impulse endpoints depended on visual feedback while in Experiment II, the effect of practice on the time spent in the initial impulse phases differed between visual conditions. Also, the results of all three experiments indicated that the extent to which error corrections were produced was greater when visual feedback was available even

though initial impulses were more variable when visual feedback was not available. These results are clearly at odds with the underlying assumptions of the stochastic optimized submovement model regarding the effect of vision on the mean and standard deviation of submovement endpoint locations, submovement durations, and the frequency of corrective submovements.

We have proposed that with practice an interdependency develops between programming and feedback processing. On one side, improvements in the production of initial impulses lead to reductions in the variability of initial impulse endpoints and consequently, the extent to which error corrections are produced. Also, uncertainty about the amplitude of the required adjustment is decreased thereby increasing the rate of error identification and correction processes. Further, biasing initial impulse endpoints to one side of the target reduces uncertainty regarding the required direction of corrective movements. Barrett and Glencross (1989) have referred to this as the production of a deliberate error whereby certain features of a corrective response (e.g., direction) can be programmed in advance. The final corrective response, however, is confirmed and refined based on sensory information.

On the other side of the interdependency, the ability to use sensory feedback to detect and correct errors plays an important role in the planning and programming of rapid aiming movements. In performing aiming movements, several strategies are at the participants' disposal. For example, they can produce fast, highly variable initial impulses and then rely on error corrections to home in on the target. Alternatively, they can produce slower, less variable initial impulses in order to reduce the reliance on feedback based error corrections. Meyer et al. (1990) have shown through computer simulation that movements comprising of a single submovement (i.e., the initial impulse) are characterized by a linear speed-accuracy tradeoff while movements with multiple submovements approximate a logarithmic function. This implies that for high index of difficulties, it is more beneficial to produce fast initial impulses and rely on corrective

submovements than to reduce initial impulse velocities to the extent that error corrections are not needed. While this multiple submovement strategy may be preferred when effective feedback processing is available, the present results indicated that when effective feedback processing was not available, it was more beneficial to produce low velocity initial impulses thereby decreasing the reliance on error corrections. When participants had visual feedback, they planned their movements to use this effective source of sensory information. As a consequence, the reliance on visual feedback remained even after extensive levels of practice. However, when visual feedback was not available, movements were planned to minimize the need for discrete error corrections.

Along these lines, we believe that the relationship between the initial impulse and error correction phases is optimally suited to meet the constraints of the task and the instructions given to participants. In the present experiments, participants were instructed to move as fast as possible and to achieve high levels of accuracy. Consistent with past research (Corcos, Jaric, Agarwal, & Gottlieb, 1993; Elliott et al., 1995), our results indicated that with practice, participants tended to increase the velocity of initial impulse phases while also being able to reduce the variability of initial impulse endpoints. However, even after extensive practice, initial impulse variability was high relative to the size of the target. In Experiment I, the size of the target was 2.25 degrees and the standard deviation of initial impulse endpoints in the FV condition was approximately 3.0 degrees after extensive practice. In Experiment II, the target size was 1.5 degrees and initial impulse variability was above 2.0 degrees. Due to noise in the neuromotor system, it appears that reductions in initial impulse variability reached asymptote. Therefore, participants had to adopt strategies that optimized their performance given the inherent limitations caused by motor output variability. The results of the present experiments indicated that these strategies depended on the ability to make effective error corrections.

In Experiment III, the amplitude of the movement was 25 degrees as opposed to 45 degrees in Experiments I and II. As a consequence, peak velocities were lower and initial impulses were less variable (1.5 deg) relative to the size of the target (1.5 deg) than in the first two experiments. It is noteworthy that in the first two experiments, the difference between visual conditions in the extent to which error corrections were produced increased as a function of practice. The pattern of results from Experiment III differed from those of the first two experiments in that, although there were differences between visual conditions, these differences did not increase as a function of practice. Since the ratio of the standard deviation of initial impulse endpoints to target size was smaller in Experiment III than in the first two experiments, participants produced initial impulses which hit the target on a higher percentage of trials. It is likely that in cases where initial impulses hit the target on the majority of trials, differences in strategies between feedback conditions would not be expected since the reliance on error correction would be relatively low. This explanation is consistent with Klapp (1975) who showed that reaction times depended on target size when movement amplitudes were small but were independent of target size when movement amplitudes were large. He proposed that the short amplitude movements were prepared in advance while the larger amplitude movements involved online processing (also see Lajoie & Franks, 1997). However, as will be discussed below, the absence of discrete error corrections does not necessarily imply that movements were programmed in advance and therefore were not altered by sensory feedback (Keele, 1968).

When visual feedback was available, participants progressed towards control strategies which made optimal use of vision to perform discrete error corrections. Hence, the role of visual feedback in producing corrective submovements remained after extensive levels of practice. These findings are consistent with work by investigators who have shown that part of learning involves the development of effective feedback processing procedures to optimize the use of

visual feedback (Elliott et al., 1995). The results are also in agreement with the specificity of learning hypothesis (Proteau, 1992) in that participants remained heavily reliant on the sources of information that were available during acquisition. However, specificity of learning and the importance of visual feedback was not limited to the production of error corrections. Initial impulses were less variable when visual feedback was available and the removal of vision had a significant impact on the production of initial impulses. Furthermore, removal of visual feedback from the first 50% and 75% of the movement caused a significant decrement in performance, even though the extent to which error corrections were produced in these conditions was not significantly different from the no vision condition.

From one standpoint, the effect of visual feedback on the production of initial impulses questions the longstanding belief that initial impulses are programmed and therefore not influenced by sensory feedback (Abrams et al., 1990; Meyer et al., 1988; Woodworth, 1899). However, Experiment III provided evidence that the benefit provided by vision in the production of the initial impulse phase was due in part to offline processing. Indeed, an account based on offline processing is consistent with the notion that initial impulses are programmed. Here, vision is not used during movement execution but provides detailed information about a completed movement which can be used to improve programming on subsequent trials.

Investigators have used several different methods based on the analysis of movement trajectories to provide evidence for online processing of visual feedback. Perhaps the most common technique involves the detection of discrete adjustments in kinematic profiles. However, since the initial impulse by definition does not contain discrete modifications, other methods needed to be considered. Based on the assumption that visual control predominates in the later stages of movement, Elliott and colleagues (Chua & Elliott, 1993; Elliott et al., 1991) have examined the symmetry of velocity profiles to detect online processing. Lengthening of the

absolute and relative time spent after peak velocity was taken as evidence of online control. However, because these modifications can be very rapid and the nature of the adjustment depends on the direction of the error from the early part of the movement, the time spent after peak velocity may not necessarily reflect the presence of visuomotor processing. On this basis, Elliott, Binstead and Heath (1998) have recently proposed a novel method from which online processing can be inferred. On each trial, the distance traveled at peak velocity was correlated with the distance traveled at the end of the movement. The rationale here was that if participants adjusted their movements during the latter part of the trajectory to compensate for variability early in the trajectory, then the distances traveled at peak velocity and the end of the movement would be negatively correlated. A positive correlation would exist if no adjustment was made. Elliott et al. showed that negative correlations existed for both vision and no vision conditions but stronger correlations were evident when visual feedback was available, thereby providing evidence for the important role of vision during movement execution. In Experiment III, we proposed another method to investigate online control. It involved examining the relation between spatial variability and the distance traveled at particular landmarks in the kinematic profiles. Our reasoning was somewhat similar to that of Elliott et al. If compensations for variations in the movement trajectory are made online, then variability versus displacement functions would deviate from those that describe movement which is programmed in advance and not modulated online. The results indicated that, during the production of initial impulses, the increase in variability as the movement unfolded was curtailed when visual feedback was available. Hence, there is evidence to suggest that adjustments to the initial impulse were made online.

Although we have suggested that visual feedback was used online, it could be argued that visual information was used to calibrate proprioceptive or efference copy stores which then provided the basis upon which online adjustments were made. Vision feedback conveys real time

(dynamic) information about the movement trajectory and may provide a basis upon which intrinsic information stores can be accurately calibrated (Hale, Hodges, Khan, & Franks, 1998). The adverse effect of removing vision would be explained if one assumes that these sensory stores are short lived and quickly decalibrated in the absence of visual feedback (Proteau & Marteniuk, 1993). However, this alternative seems unlikely given that visual feedback provides an immediate and detailed form of KR. This would presumably have guidance like qualities (Salmoni et al., 1984) which prevents the development of other sensory stores (Abahnini et al., 1997).

A final issue concerns the nature of visuomotor control during the production of the initial impulse and error correction phases. In the past, the initial impulse and error correction phases have been dichotomized based on the role of sensory information during the two phases of movement. Initial impulses were said to be ballistic while error corrections were under feedback based control. Given the evidence for the use of vision during the production of the initial impulse phases, at least for initial impulses with sufficiently long durations (> 200 msec), the question remains as to whether these two phases of movement are distinct in terms of the processes which underly their control. Typically, it has been envisaged that error corrections are prepared on the basis of the current or predicted position of the hand relative to the target. However, another way of conceptualizing the aiming tasks used in the present work is that the velocity of the limb must be controlled such that it is zero when the limb reaches the target. Evidence for movement control based on velocity information stems from studies which have shown that the acceleration of the hand is continuously modified based on the actual (Brenner & Smeets, 1998) or perceived velocity (Smeets & Brenner, 1995) of a moving target. Also, manipulating the perceived velocity of a limb moving towards a stationary target influences final position (Proteau & Masson, 1997). In these studies, perceived velocity was manipulated by moving background information relative to motion of the target or limb, an illusion that is said to

affect perceived velocity but not position (Smeets & Brenner, 1995). It is therefore plausible that during the initial impulse phase, velocity information from various points in the trajectory serves to specify the level of motor output and in doing so, regulates the decelerative phase of the movement by specifying time to contact with the target (Lee & Young, 1985). Adjustments during this phase may involve visuomotor loops which are prepared in advance of movement initiation (Elliott et al., 1998) and therefore, visual feedback processing during this high velocity stage is extremely rapid and requires little conscious effort (Pélisson, Prablanc, Goodale, & Jeannerod, 1986). Along these lines, we propose that the high velocity initial impulse phase is prepared by specifying the transformation between visual input (velocity as a function position in the trajectory) and motor output. Once the initial impulse is initiated, movement progresses according to the rules specified by the transformation and without intervention from higher cognitive centers. However, due to variations in visuomotor processing, errors will arise in the production of the initial impulse. Once the velocity is below a certain level, spatial errors can be detected and discrete adjustments are prepared based on a comparison between limb and target positions. During this stage, positional information is sampled intermittently via a relatively long visuomotor loop involving conscious effort.

In conclusion, the present research demonstrated that with practice an interplay developed between movement planning and feedback processing. Participants progressed towards control strategies which depended on their ability to make effective error corrections. When visual feedback was available, movements were planned to make optimal use of this effective source of information. Hence, the reliance on visual feedback remained after extensive levels of practice. In the absence of visual feedback, corrective submovements were not effective in minimizing error and the extent to which discrete error corrections were produced steadily declined throughout practice. We posit that the interdependency between movement planning and feedback

processing is contingent upon limitations due to neuromotor noise and the accuracy demands of the task. Finally, the evidence presented for online processing of visual feedback during the production of the initial impulse questions the ballistic nature of this high velocity phase of movement. Future research will be directed towards establishing the limits of online processing and the nature of error signals derived during the production of initial impulses.

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