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The planning and execution of target directed movement

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THE PLANNING AND EXECUTION OF TARGET DIRECTED MOVEMENT

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Contents

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Published work from this thesis

Khan, M.A., Lawrence, G.P., Buckloz, E., & Franks, I.M. (2004). Programming strategies for rapid aiming movements under simple and choice reaction time conditions. *Quarterly Journal of Experimental Psychology* (in press). (Chapter 3).

Khan, M.A., Lawrence, G.P., Fourkas, A., Franks, I.M., Elliott, D., & Pembroke, S. (2003). Online versus offline processing of visual feedback in the control of movement amplitude. *Acta Psychologica, 113*, 67-81. (Chapter 4).

Khan, M.A., Lawrence, G.P., Franks, I.M., & Elliott, D. (2003). The utilisation of visual feedback in the control of movement direction: evidence from a video aiming task. *Motor Control, 7*, 290-303. (Chapter 5).

Khan, M.A., Lawrence, G.P., Franks, I.M., & Buckolz, E. (2004). The utilisation of visual feedback from peripheral and central vision in the control of direction. *Experimental Brain Research, 158*, 241-251. (Chapter 6).

CHAPTER 1
THESIS OVERVIEW

1.1. Background

Aiming movements such as pointing, reaching, touching, and grasping form the basis of numerous everyday activities. Tasks such as moving a computer mouse, pressing the keys on a computer keyboard, or reaching for a glass of water require accurate and efficient control of movements. It is therefore hardly surprising that the research in this field dates back over one hundred years to the work of Woodworth (1899). In this early period of human motor control investigation, Woodworth was interested in what processes were involved in aiming movements, such as pointing, reaching, touching, and grasping. He proposed that movements of this type consist of two phases; an initial impulse and a current control phase. The initial impulse is assumed to be a centrally programmed 'ballistic' movement intended to end at the location of the target. It is characterised by a fairly rapid, continuous change in the position of the limb. If the programming of the initial impulse is such that a discrepancy between its endpoint and the target location occurs, the limb movement may enter a current control or error correction phase. In this second phase, adjustments to the movement trajectory, based on visual or proprioceptive information about limb position relative to the target, are made in order to reduce this discrepancy so that the original goal of bringing the limb to rest on the target can be achieved.

Woodworth's (1899) model still provides a viable explanation of how goal directed movements are controlled. It has been frequently adopted as a framework for investigation over the past century (e.g., Abrams, Meyer, & Kornblum, 1990) and can be regarded as the foundation for many of the most influential theories describing limb control (e.g., Meyer, Abrams, Kornblum, Wright, & Smith, 1988) and speed-accuracy tradeoffs (e.g., Fitts, 1954). An issue which has been at the forefront of much theorising is the extent to which movement outcome is dependent on the relative contributions of central planning and online sensory feedback.

1.2. Outline of the thesis

This thesis attempts to investigate issues relating to the programming of movements and the use of visual feedback in two series of experiments. The first series of experiments focus on movement planning and examine the influence of response complexity on both simple and choice reaction time (RT). The aim here was to test whether differences in the response complexity effect between simple and choice RT tasks depend on the extent to which movements are programmed during RT versus during execution. The second series of experiments were designed to investigate the use of visual feedback in both the planning and execution of movements. The control of direction and amplitude components of aiming movement tasks were investigated at different movement times. Also of interest was the extent to which the utilisation of central and peripheral vision depended on where in the visual field information was presented or the time available to use this information. Theories developed from past research in this area are both expanded and re-examined using a new methodology whereby the variability in limb trajectories are analysed at various points during the movement in order to assess the relative contributions of online and offline visual feedback in movement control.

1.3. Thesis Format

This thesis consists of a review of the literature, five research papers and a general discussion. All five manuscripts are written as stand alone research articles and have been published or accepted in international psychology and motor control journals, with the exception of chapter 7. For consistency all manuscripts are written in the style adopted by the School of Sport, Health and Exercise Sciences, University of Wales, Bangor which is described in the American Psychological Association Publication Manual (2001) and the current recommendations of the University of Wales thesis preparation. For the same reason all citations are included in a single section and the end of this thesis and illustrations are numbered consecutively. However, to facilitate reading, abbreviations are defined at their first appearance within each chapter of the thesis. The contributions to each original manuscript of the co-authors are detailed in the 'acknowledgements' and 'published work from this thesis' sections. As all the manuscripts included in this thesis are independent but linked, at times there is a necessary overlap in the content between chapters.

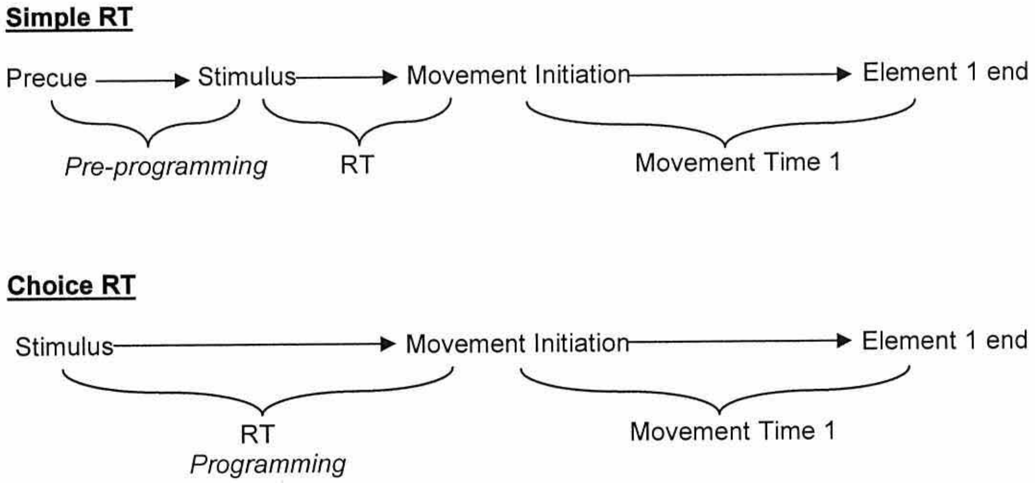
CHAPTER 2

INTRODUCTION: REVIEW OF LITERATURE.

2.1. Motor Programming

In their classic study, Henry and Rogers (1960) demonstrated a direct relationship between reaction time (RT) and response complexity with RT increasing as the number of elements in a response increased. This slowing of RT as response complexity increased was attributed to the greater time needed to program more complex movements. According to Henry and Rogers, the programming of complex responses involves 'a larger amount of stored information, ... and thus the neural impulses will require more time for coordination and direction into the eventual motor neurons and muscles' (p. 450).

The influence of complexity on RT has stimulated a great deal of interest within the field of motor control. One question that has frequently been debated is whether response complexity has the same effect on simple and choice RT. In simple RT tasks, a precue is presented in which the required response is identified to the participant (see Figure 1). Following a foreperiod, an imperative stimulus informs the participant that the response should be produced. In contrast, a choice RT condition contains no precue so the participant is unaware of the required response until the presentation of the imperative stimulus. With these differences in mind, it is reasonable to suggest that some programming might be completed prior to stimulus presentation in the simple RT condition. This suggests that programming may not be a component of simple RT. In contrast, pre programming cannot be performed in the choice RT paradigm since the required response is not known in advance. Consequently, programming is a necessary component of the measured RT. Klapp, Wyatt, & Lingo (1974) therefore suggested that choice RT is a more desirable paradigm when investigating the effect of response complexity on RT. By comparing RTs between two single element morse code responses that differed in complexity (dit versus dah), Klapp, et al., showed that both simple and choice RT increased as the complexity of a response increased. However, following practice only choice RT increased as a function of response complexity. It was therefore concluded that the effects of response complexity on choice RT was a robust phenomenon. However, experiments showing consistent effects of complexity on simple RT were reported to have involved little practice (Klapp et al., 1974; Henry & Rogers, 1960) and that following practice, participants' learn to adopt strategies involving pre programming which eliminates the response complexity effect.


Simple RT

Choice RT

Figure 1. Critical differences between the events involved in simple and choice RT paradigms depicting where response programming may be occurring.

Increases in choice but not simple RT as a function of response complexity have been demonstrated in a number of different research articles (Carlton, Carlton, & Newell, 1987; Klapp, 1975, 1995, 2003; Klapp & Rodriguez, 1982; Klapp & Wyatt, 1976; Vidal, Bonnet, & Macar, 1991). However, in contrast to these findings, researchers have also shown increases in simple RT as a function of response complexity for both aiming movements (Canic & Franks, 1989; Franks & Van Donkelaar, 1990; Henry & Rogers, 1960) and speech articulation (Sternberg, Monsell, Knoll, & Wright, 1978; Sternberg, Knoll, & Turock, 1990).

The contrast between the response complexity findings raises an empirical challenge; when and why will response complexity influence (a) choice RT but not simple RT and (b) simple RT but not choice RT? In order to address such issues, Klapp (1995) compared RTs between two single element key press responses (dit, dah) and two four element responses (dit-dah-dah-dit, dah-dit-dit-dah) under both simple and choice RT conditions. As previously described, the rationale for using both simple and choice RT conditions was to investigate how the sequence of events prior to the imperative stimulus influences the relationship between response complexity and RT. This experimental design allowed an investigation into how the number of elements and response duration may have different effects on simple and choice RT depending on which response features may be programmed in advance of the stimulus. By comparing RTs between the two single element responses (dit versus dah), Klapp showed that choice RT increased as the duration of a response increased but not simple RT. On the other hand, simple RT was greater for the four compared to single element responses while there was no effect of number of elements on choice RT.

Klapp (1995) accounted for these results by proposing a two process model of response programming in which he referred to the programming of internal features (e.g., duration) of individual elements as INT and the ordering of elements as SEQ. In simple RT, INT was said to be performed prior to the presentation of the stimulus whereas processes involved in SEQ occur during the RT interval. Therefore, simple RT is influenced by the number of elements in a response since the greater the number of elements the greater the time to program SEQ. In choice RT, pre-programming is not possible and therefore both INT and SEQ must occur during RT. Klapp assumed that both processes occurred in parallel and that INT takes longer than SEQ, consequently the processing of SEQ was consumed within the processing of INT. Based on this assumption, it is the duration of individual elements that influences choice RT and not the number of elements in a response (also see Immink & Wright, 2001).

Recently, Klapp (2003) offered a revised version of his two process model of response programming based on findings from a series of experiments involving speech articulation. He showed that choice RT increased as a function of the number of syllables (elements in the response) when the number of syllables was precued in advance of the stimulus. This finding was inconsistent with the original two process model of response programming as it suggested that the number of elements in a response does influence choice RT. Therefore, the assumption that INT and SEQ occur in parallel and that INT determines choice RT because it takes longer to process than SEQ is questionable. Klapp modified his model by proposing that SEQ involved the scanning of an abstract time frame rather than the sequencing of the actual elements or movements. This time frame specifies the time of initiation of each movement without specific reference to their content. In simple RT, the time frame is loaded into a buffer prior to the presentation of the stimulus. During the RT interval, the time frame is activated and scanned to locate the starting point. This scanning process takes longer as the number of elements increase. Hence, simple RT increases as a function of the number of elements. Similarly, in a choice RT condition when the number of elements but not the nature of the elements is precued, the abstract time frame can be loaded into a buffer prior to the presentation of the stimulus. In such experimental conditions, choice RT increases as the number of elements and the time to perform the scanning process increases. However, in choice RT conditions in which the number of elements is not precued, the time frame is retrieved immediately prior to responding and therefore does not have to be scanned. Hence, in conditions such as these, choice RT does not increase as a function of number of elements in a sequence.

Although Klapp's (1995, 2003) two process model of response programming offers an elegant account for the differential effects of the number of elements and response duration on simple and choice RT, it has been suggested that not all response programming occurs during the RT interval and that programming can be continued during movement execution (i.e. online) (Glencross, 1980; Smiley-Oyen & Worringham, 1996). An alternative interpretation to that of Klapp's two process model of response programming is that participants distribute the programming of response elements differently under simple and choice RT situations. There are several lines of evidence to support this interpretation and the notion of online programming. For example, the effect of the number of elements on RT is not linear but decreases as the number of elements increases (Canic & Franks, 1989; Henry & Rogers, 1960; Klapp, Abbott, Coffman, Greim, Snider, & Young, 1979). Movement times for initial elements have been shown to be longer for multiple element responses than single element responses (Chamberlin & Magill, 1989). Also, there is a larger effect of response complexity on RT when movements are performed as fast as possible compared to when they are performed at less than maximal speeds (Van Donkelaar & Franks, 1991). From these findings it is possible to conclude that for relatively complex responses, participants program the initial elements during RT but then delay the programming of latter elements until after the RT interval, provided that movement time is sufficient for online programming to occur. In situations where movements are programmed online it is possible that the effect of response complexity on RT would be reduced or even eliminated as fewer elements are programmed during the RT interval.

Assuming that response preparation involves the storage of elements in a short term buffer (Henry & Rogers, 1960) it may be that only a limited number of elements can be programmed at any point in time. In simple RT, as it is possible to prepare responses during the foreperiod, there is the potential that more elements can be held in short term memory prior to movement initiation. Participants may use this strategy as a way of minimising RT by reducing the amount of programming required during the RT interval. However, more complex responses will result in longer RTs if one assumes that the translation of movement commands to the neuromotor centres cannot take place until stimulus presentation (Henry, 1980). In contrast, a choice RT paradigm contains no precue and therefore any programming performed before the initiation of movement will result in increases in RT. As a result, participants may adopt a strategy in order to minimise RT whereby fewer elements are programmed in advance of movement initiation (Chamberlin & Magill, 1989; Klapp et al., 1979). Consequently, if the differences in the sequence of events prior to the RT interval lead participants to adopt these different strategies, then choice RT would be influenced less by the number of elements in a response compared to simple RT because the extent to which movements are programmed in advance of movement initiation versus online is less.

Klapp (1995) argued against the hypothesis that online programming occurred in choice but not simple RT based on the finding that inter-response intervals did not vary between the RT tasks. However, it may be possible that online programming was occurring in parallel with the actual execution of response elements rather than during the pause times between key-presses. The required durations of the dit and dah key-presses were 150 and 450 msec respectively, while there was also a required inter-response interval of 100 msec between key presses in the four element responses. Since these durations were requirements of the task and were sufficiently long for processing to occur during movement execution, the presence of online programming was unlikely to be detected by variations in either key-press or pause times.

The degree to which responses are programmed in advance of movement initiation versus during execution also has implications for the one-target movement time advantage. It has been suggested (Adam, Nieuwenstein, Huys, Paas, Kingma, Willems, & Werry, 2000; Helsen, Adam, Elliott, & Buekers, 2001) that when a rapid aimed hand movement is allowed to stop on a target it is performed quicker than when it must proceed to a second target. This phenomenon is known as the one-target advantage and can be explained by the 'movement integration hypothesis'. This hypothesis suggests that both elements are programmed in advance of movement initiation and that the response characteristics of the second element are held in a buffer. These characteristics are then implemented when necessary during the first element to ensue optimal integration of the elements (Adams et al., 2000). It is crucial to point out that the control process of the second element may be implemented before the termination of the first element. When this occurs an overlap in the control processes involved in the first and second element is created which interferes with the execution of the first element, leading to the one-target advantage. The one notable exception to the one-target advantage is when the second element involves a reversal in direction. In this case, a two target advantage arises where movement times to the first target are shorter for the two compared to one element response. This is said to be due to an integration of muscular forces which is mediated by the mechanical characteristics of the reversal. The integration occurs as the forces used to decelerate the first element are also used to propel the limb back towards the second target. Consequently, the first element in a two element reversal task only requires a biphasic pattern of muscle activity (agonist-antagonist) which simplifies the control process and allows the first and second elements to be optimally integrated.

2.2. Visual Feedback Processing

Estimations of Visual Feedback Processing Time

The use of vision when performing accurate aiming movements has received much attention throughout the motor control literature. It is commonly accepted that the availability of visual feedback improves movement accuracy over those situations where vision is not available. This finding has typically been accredited to the utilisation of visual feedback during movement execution (i.e. online). An important issue regarding this notion is the length of time that vision is available during movement execution. If movement durations are too short or vision is presented too late during a movement then the differences in accuracy between the vision and no vision conditions is reduced. The question of how long it takes to process visual feedback dates back more than a century ago to the classic study of Woodworth (1899). Woodworth's experiments consisted of horizontal aiming movements performed with a pencil on paper attached to a drum which was rotating at a constant speed. Participants were instructed to produce reciprocal movements between lines a fixed distance apart or to match the amplitude of a movement to the previous trial. This allowed Woodworth to asses the accuracy of movement end-points as well as the spatial-temporal characteristics of trajectories. From the data, Woodworth concluded that aiming movements consisted of two phases; the initial impulse phase and the error correction phase. The initial impulse phase was described as a fairly rapid, centrally programmed movement designed to bring the limb into the vicinity of the target. Once the limb entered the target vicinity the second phase or error correction phase took effect. In this 'homing in' phase, movements are performed slower such that visual information about the limb and target can be used to make any adjustments to the trajectory to enable the limb to finish on the target. In order to investigate the time at which visual information could be processed, Woodworth had participants perform the experiment under different movement time conditions. In addition to the different temporal constraints, participants made the movements in both an eyes open and eyes closed condition. Woodworth discovered that as the movement time decreased the error in the eyes open condition approached that of the eyes closed condition. Specifically, at movement times of 450 msec there was no difference in error between the two visual conditions. Therefore Woodworth estimated the time for visual feedback processing to be approximately 450 msec. However, this estimation has not been without criticism. Since Woodworth employed reciprocal aiming movements, the duration of individual aiming movements included both the time required to slide across the paper and the time required to make a reversal in movement direction (Vince, 1948). Consequently, Woodworth may have over estimated the time required for visual feedback processing. More recent research concerning this issue, utilising discrete aiming movements, has estimated visual feedback processing time to be $\leq$ 135 msec (Carlton, 1981; Zelaznik, Hawkins & Kisselburgh, 1983). However, it is possible that the accuracy benefits associated with the use of vision in these recent studies may not solely be due to the utilisation of visual feedback online. It is possible that visual feedback from a completed movement is used as an enriched form of knowledge of results to improve the programming of movements on subsequent actions (i.e. offline) (Abahnini, Proteau & Temprado, 1997; Blouin, Bard, Teasdale & Fleury, 1993; Zelaznik et al., 1983). These offline processes would likely lead to accuracy improvements in situations where movement durations are too short or where visual feedback is presented too late in a movement to allow visually based corrections to be performed during movement execution.

Online versus Offline Processing of Visual Feedback

In the past, researchers have attempted to establish the contributions of online and offline processing of visual feedback by manipulating the scheduling of visual conditions within a block of trials (Blouin et al., 1993; Zelaznik et al., 1983). The rationale being that when visual conditions are randomised or alternated within a block of trials, visual feedback from a vision trial could be processed offline as an enriched form of knowledge of results to improve the programming on a subsequent no vision trial. Consequently, accuracy in the no vision condition would exhibit closer accuracy to that of the full vision condition when compared to situations in which visual conditions are separated and presented in blocks. However, Zelaznik et al., reported that substantial accuracy differences did exist between visual conditions when vision and no vision trials were alternated within a block of trials. Likewise, Blouin et al., showed that the scheduling of visual feedback had little effect on accuracy differences between vision conditions. These results suggest that the contribution of offline processing was minimal and the principal role of visual feedback was in the online regulation of movement trajectories.

Movement Kinematics

Typically, the use of vision during movement execution has been inferred from the presence of discrete corrections in the movement trajectory marked by discontinuities in kinematic profiles i.e. reversals in the direction of movement (see Figure 2), zero line crossings in accelerations (see Figure 3), and significant deviations in acceleration profiles (see Figure 4). These discontinuities are said to be based on sensory information obtained during the production of the initial impulse, and thus reflect the presence of online adjustments to movements. A reversal in movement direction, going from a forward to a backward direction, corresponds to a positive to negative zero line crossing in the velocity profile. This is typical of a movement which overshoots a target and is then corrected back towards the target in the opposite movement direction. A movement which initially undershoots a target but is then reaccelerated to move the limb forwards is depicted by a zero line crossing in the acceleration profile. Significant deviations in the acceleration profile represent subtle changes in acceleration without any increase in velocity. They correspond to a decrease in the net breaking force of the limb which has the effect of lengthening the amplitude of the movement. The use of discrete corrections in the movement trajectory to infer online visual control was based on the assumption that visual feedback processing is intermittent in so much that the initial impulse or ballistic phases of movement are run to completion before visual control can take effect (Vince, 1948; for a review see Elliott, Helsen & Chua, 2001). Research has shown that when receiving visual information of the limb movement trajectories contain more discrete corrections, which result in better accuracy compared to situations where vision is unavailable (Chua & Elliott, 1993; Khan & Franks, 2000; Khan, Franks & Goodman, 1998). However, it has also been shown that movements yield higher accuracy through the availability of vision even where no significant differences in the number of discrete corrections between visual conditions is observed (Elliott, Carson, Goodman, & Chua, 1991; Khan, Elliott, Coull, Chua & Lyons, 2002). On one hand, it is possible that visual information was not being processed during movement execution but rather offline to improve movement programming. These offline processes would result in significant differences in end-point accuracy between visual conditions without any kinematic evidence for online control. On the other hand, Elliott and colleagues (Elliott, Binsted & Heath, 1999; Elliott et al., 1991; Elliott, Chua, Pollock & Lyons, 1995) have suggested that visual guidance may be continuous rather than intermittent in nature taking the form of "graded adjustment of muscle activity during deceleration" (Elliott et al., 1995, p. 80). If this is the case then visual regulation will not be reflected in discrete corrections to kinematic profiles[1].

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[1] Continuous visual processing may still result in movements being executed with discrete corrections. However, these may not be evident in the data due to the conservativeness of the criteria for assessing significant deviations.

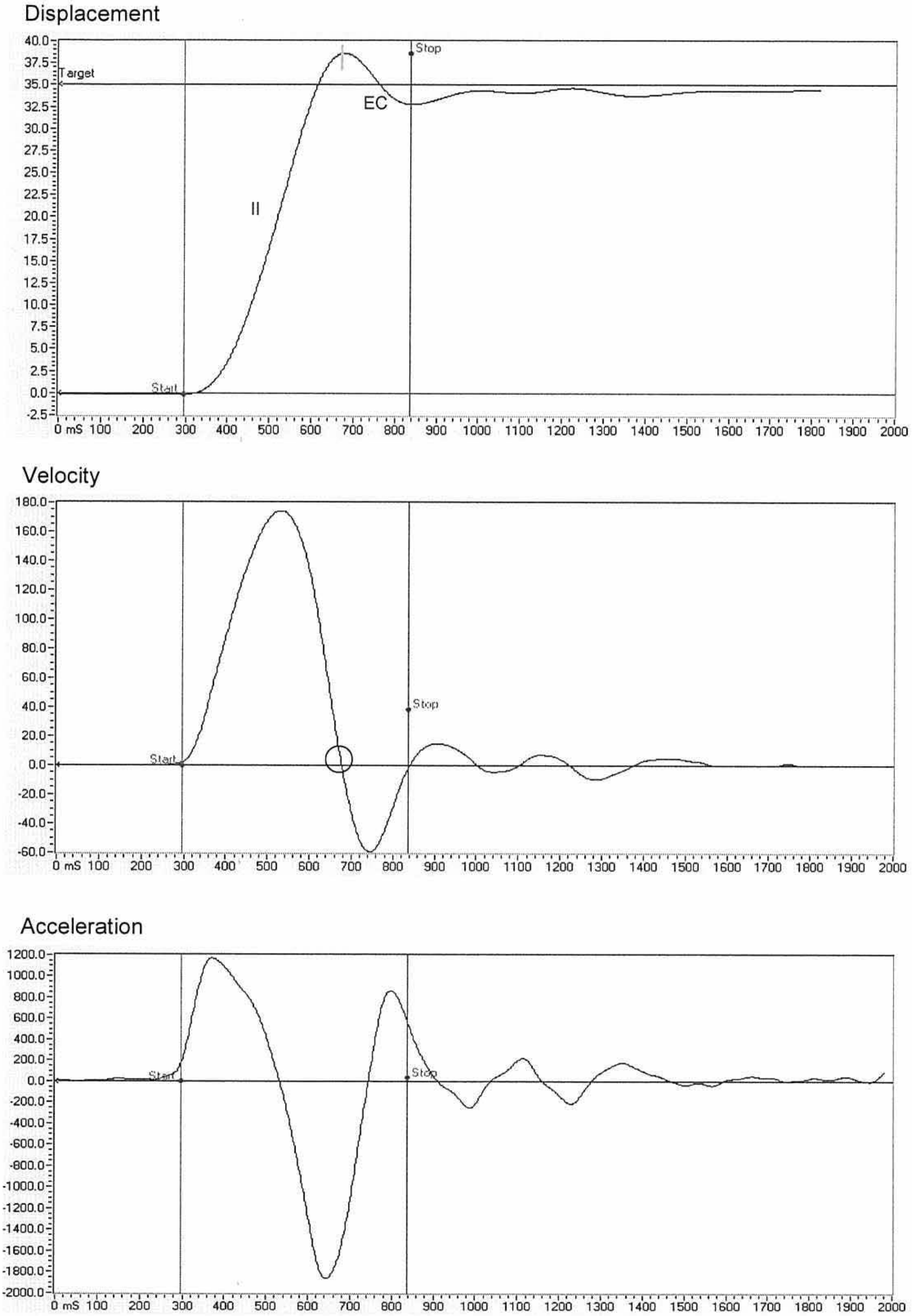

Figure 2. Sample displacement, velocity, and acceleration profiles, showing parsing of the movement into the initial impulse and error correction phase, for a movement containing a zero line crossing in velocity (II = initial impulse, EC = error correction).

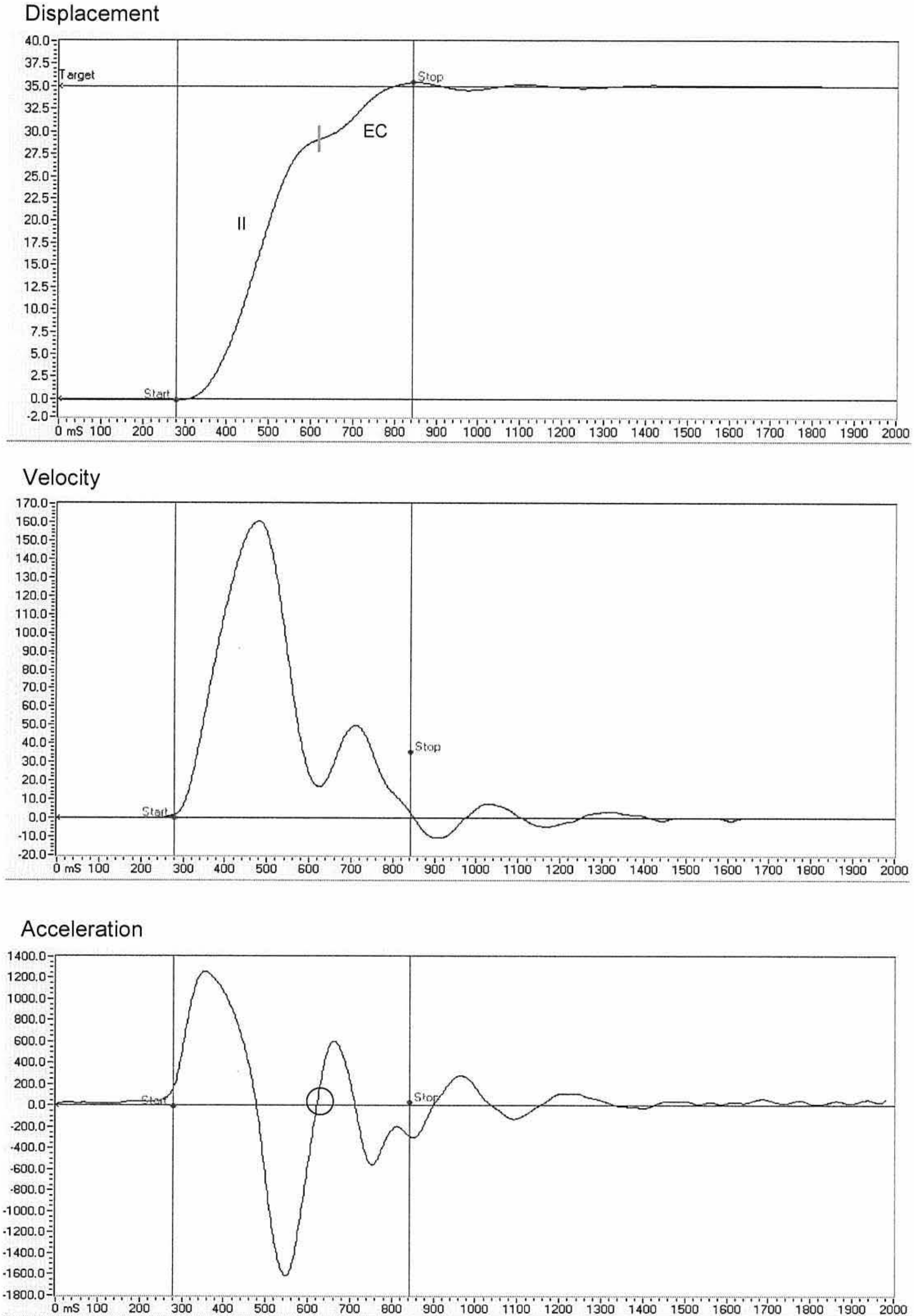

Figure 3. Sample displacement, velocity, and acceleration profiles, showing parsing of the movement into the initial impulse and error correction phase, for a movement containing a zero line crossing in acceleration (II = initial impulse, EC = error correction).

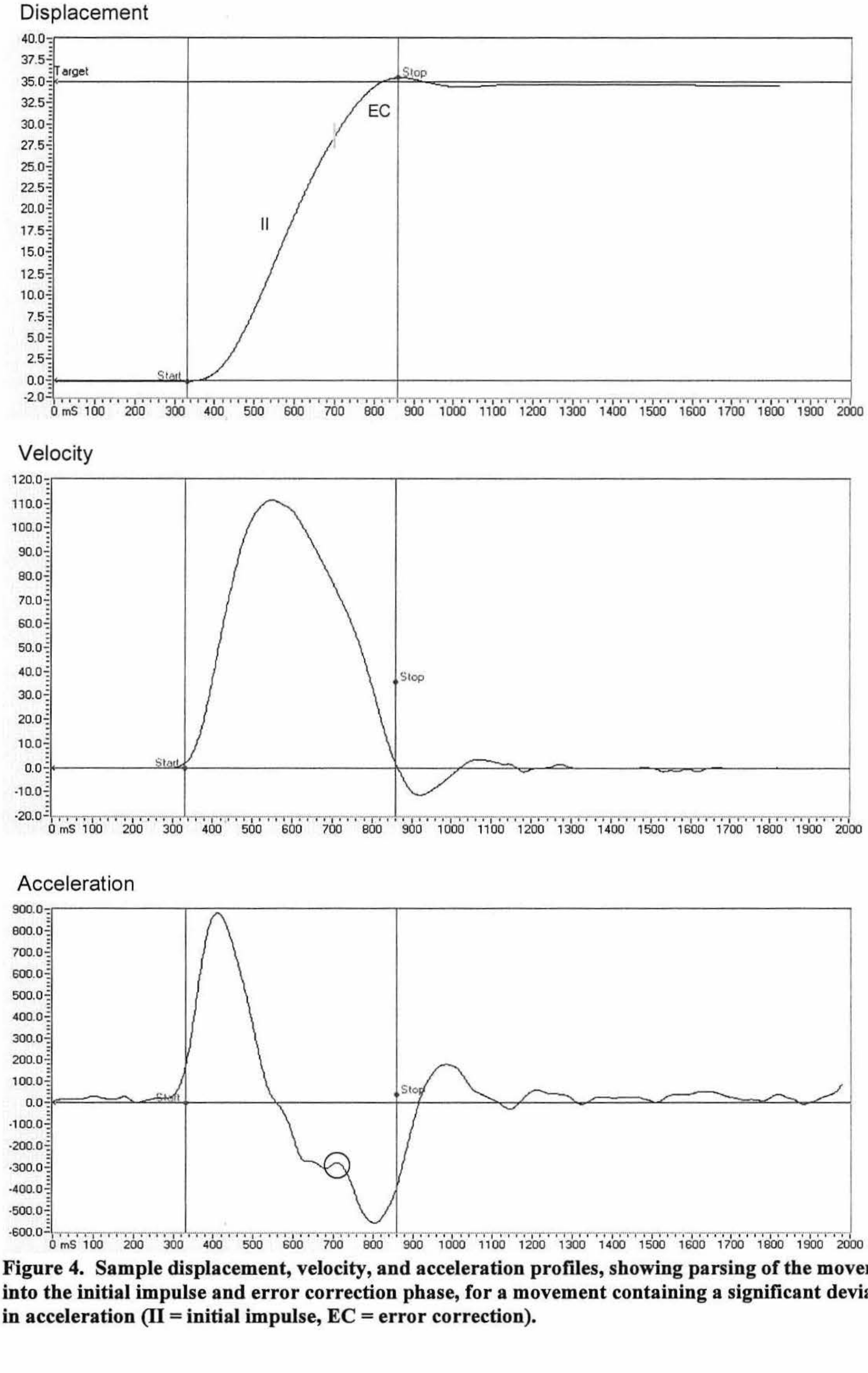

Figure 4. Sample displacement, velocity, and acceleration profiles, showing parsing of the movement into the initial impulse and error correction phase, for a movement containing a significant deviation in acceleration (II = initial impulse, EC = error correction).

Using Variability Profiles and Correlation Analysis to Infer Online and Offline Visual Feedback Processing

Given the problems associated with inferring the utilisation of vision from discrete corrections, researchers have recently devised an alternative method to investigate the relative contributions of online and offline processing of visual feedback (Khan et al., 2002; Khan & Franks, 2002). This method involves examining the variability in distance travelled at various stages throughout the movement trajectory by calculating the within participant standard deviations in the distance travelled at several kinematic markers (e.g. peak acceleration, peak velocity and peak negative acceleration and movement end) (also see Darling & Cooke, 1987; Messier & Kalaska, 1999) (see Figure 5). The rationale here is that if movements are programmed and not altered online then variability should increase according to some function as the movement progresses i.e. errors that occur early in the movement trajectory are not corrected and hence will be magnified as the movement distance increases. If however, corrections for variations in the movement trajectory are made during movement execution, then variability profiles would deviate from those that describe movement which is programmed in advance and not modulated online. However, it is important to note that the variability profiles must differ in form, that is by more than multiplication of a scalar factor, in order for the presence of online processing of visual feedback to be inferred. Consequently, if variability profiles differ in magnitude but not form then only the presence of offline processing can be inferred. For example, if vision is being used offline to increase the programming of subsequent actions then variability at early kinematic markers, namely peak acceleration and peak velocity, would be reduced due to more accurate response programming. This would cause spatial variability to rise at different rates compared to situations where vision is unavailable. However, if vision was not being used during movement execution then this rise would occur without any effect on the form of the variability profile. Therefore, in order to determine if variability profiles differ in form between visual conditions, the ratios in spatial variability between the vision and no vision conditions at each kinematic marker must be analysed. If the ratios in variability between the visual conditions differ significantly between the kinematic markers, then evidence for online processing of visual feedback would be revealed.

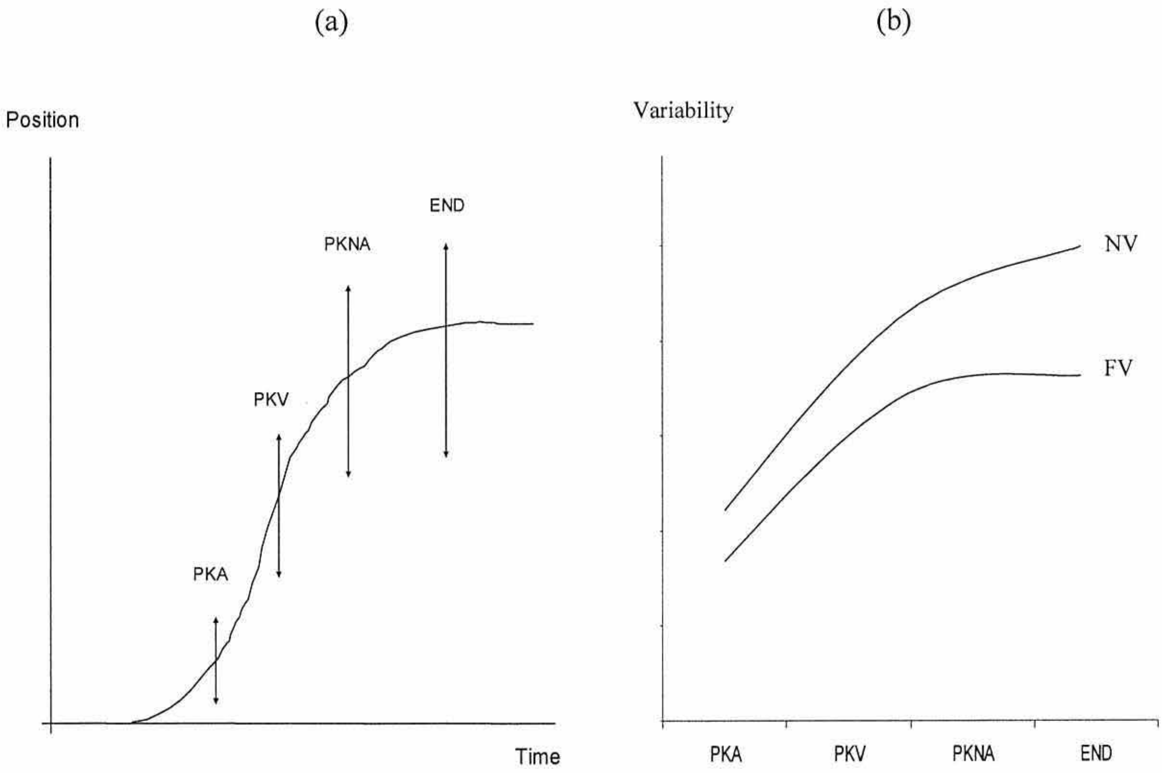

Figure 5. (a) Schematic diagram of an amplitude constrained displacement profile with the calculation of the within-subject standard deviations in the distance travelled at peak acceleration (PKA), peak velocity (PKV), peak negative acceleration (PKNA) and movement end (END) with (b) the typical corresponding variability profiles for a full vision (FV) and no vision (NV) condition.

In order to complement the analysis of spatial variability, one can correlate the distance travelled at early kinematic markers with the distance travelled at the end of the movement (also see Carlton, Newell & Carlton, 1984; Elliott et al., 1999; Gordon & Ghez, 1987; Messier & Kalaska, 1999). If accuracy at the end of the movement is predominantly due to programming processes, then the proportion of the variance at the movement end-point that can be explained by the distance travelled at early kinematic markers (i.e., coefficient of determination (r^2)) will be high. On the other hand, if movements are modulated online then the relation between the distance travelled at the end of the movement and the distance travelled at early kinematic markers will be lower. Therefore, evidence for online processing of visual feedback would be gained if spatial variability is lower in the vision compared to no vision condition and the proportion of the variance in the distance travelled at the end of the movement that is determined by the distance travelled early in the movement varies between visual conditions. However, if spatial variability is lower in the vision compared to the no vision condition but there are no significant differences between the coefficients of determination then this would imply that visual feedback was processed offline.

Peripheral versus Central Vision

As well as the accuracy benefits of vision being dependent on movement duration, another important issue relates to where in the visual field vision is presented. Abrams et al. (1990) demonstrated that individuals usually fixate on the target location before movement initiation or relatively early in the movement trajectory. This places the limb in the peripheral visual field during the initial stages of movement and the central visual field in the latter stages of movement when the limb is approaching the target vicinity. Paillard and Amblard (1985) proposed that information from peripheral and central vision is processed via two semi-independent visual channels, each mediating a specific role in the control of goal directed movement. The kinetic channel operates in the visual periphery, processes high speed visual information and is said to play an important role in the control of movement direction. The static channel operates in central vision, when the limb enters the relatively slow 'homing in' phase of its' trajectory, and is thought to be primarily responsible for controlling the amplitude of movements.

In support of Paillard and Amblard's (1985) model, research has shown that the accuracy of tasks in which participants are required to move a particular amplitude is improved through the availability of central vision (Bard, Paillard, Fleury, Hay, & Larue, 1990; Carlton 1981; Temprado, Vieilledent, & Proteau, 1996). Further, in experimental tasks requiring only a directional constraint, accuracy is improved through the use of peripheral vision (Abahnini et al. 1997; Abahnini and Proteau 1999; Bard, Hay, Fleury, 1985; Bard et al., 1990). However, in contrast to Paillard and Amblard's model, these latter studies also revealed improvements in directional accuracy through the use of central vision. One explanation for this finding was that central vision was not used to adjust movement trajectories online. Rather it was said to provide feedback on the accuracy of movement end-points which was then used as a form of knowledge of results to improve the programming of subsequent actions (Abahnini and Proteau 1999; Abahnini et al., 1997). In support of this explanation, it was noted that for movement times of < 500 msec visual feedback in the central vision condition was typically only available for < 100 msec and hence it was unlikely that sufficient time was available to use this information to correct limb trajectories online.

2.3. Purpose of Experiments

The first empirical chapter of this thesis was designed to test Klapp's (1995; 2003) two process model of response programming through a series of three experiments that use rapid goal directed movements without any temporal constraints. Experimental procedures required participants to perform manual aiming movements, consisting of one or two elements to either small or large targets, under both simple and choice RT paradigms. A dual task procedure was used in order to asses the attention demands during both RT and movement execution. This consisted of participants performing the procedure described above with the right hand whilst simultaneously responding to an auditory signal by making a key press with the left hand. An alternative explanation to that of Klapp's two process model is offered, in that the response complexity effect depends on the extent to which movements are programmed during RT and integrated during movement execution.

Chapters 4 and 5 of this thesis were designed to investigate the relative contributions of online and offline processing of visual feedback in both amplitude and direction tasks. The experiments control for the problems associated with inferring the utilisation of vision from discrete corrections by adopting the method of comparing variability profiles between visual conditions. Both experiments adopt methodologies similar to that of Woodworth (1899). Participants performed aiming movements in full vision and no vision under four different movement time constraints. The variability of movement trajectories were analysed and conclusions are drawn about the relative role of online and offline visual feedback processing for both amplitude (Chapter 4) and direction (Chapter 5) tasks. Chapters 6 and 7 test work by Paillard and Amblard (1985) by investigating the role of peripheral and central vision during goal directed movement. Participants performed aiming movements under four different visual conditions (full vision, peripheral vision, central vision, no vision) at movement speeds sufficient for online visual feedback processing to occur. In addition, Chapter 6 addresses the question of whether the accuracy benefits in direction control that are associated with the availability of peripheral vision are actually due to 'where' in the visual field information is available or 'when' visual feedback is available. It may be possible that peripheral vision is processed online because it is presented early in the movement trajectory and therefore participants have sufficient time to utilise this information. On the other hand, central vision may be presented too late in the movement trajectory for online processing of visual feedback to occur.

CHAPTER 3

PROGRAMMING STRATEGIES FOR RAPID AIMING MOVEMENTS UNDER SIMPLE AND CHOICE REACTION TIME

In the past, researchers have revealed that response complexity has different effects on simple and choice RT. On one hand, it has been shown that response complexity influences choice RT but not simple RT (Carlton et al., 1987; Klapp, 1975, 1995, 2003; Klapp & Rodriguez, 1982; Klapp & Wyatt, 1976; Vidal et al., 1991) while other studies have revealed a greater effect of response complexity on simple compared to choice (Canic & Franks, 1989; Franks & Van Donkelarr, 1990; Henry & Rogers, 1960; Sternberg et al., 1978, 1990). Klapp (1995) compared RT's between two single element responses and two four element responses under both simple and choice RT conditions in an attempt to explain the previous conflicting results. He showed that for the single element responses choice RT increased as the duration of the response increased but simple RT did not. However, only simple RT increased as the number of elements increased from one to four. Klapp accounted for these results by proposing a two process model of response programming where the programming of the internal features (duration) of individual elements was referred to as INT and the timing of elements as SEQ. Klapp's model assumes that, in a simple RT condition the time frame specifying when the initiation of each element occurs (SEQ) is loaded prior to stimulus presentation then scanned to locate its starting point during the RT interval. This scanning process is said to take longer as the number of response elements increases. Hence, simple RT increases as a function of the number of elements in a response. In choice RT, since there is no precue, the time frame is loaded immediately prior to responding therefore eliminating the scanning process. As a result, choice RT is not influenced by increases in the number of response elements.

The purpose of the present experiments was to test Klapp's (1995; 2003) two process model of response programming using rapid aiming movements without any temporal constraints. Movement responses comprised of one or two elements to either small or large targets. According to Klapp's model, simple RT should be greater for the two compared to one element response whereas there should be no effect of number of elements on choice RT. Also, if choice RT is influenced by the programming of response duration, it was expected that choice RT should be greater for the small compared to large target conditions since movement time increases as the accuracy of a response increases (Fitts, 1954)[2]. This is based on the assumption that speed accuracy trade-offs can be accounted for in terms of the timing of force pulses (Schmidt, Zelaznik, Hawkins, Frank & Quinn, 1979). However, since simple RT is said not to depend on the duration of response elements, there should be no effect of target size on simple RT[3]. Of particular interest, was the extent to which the RT pattern of results could be explained by the hypothesis that participants distribute the programming of response elements differently under simple and choice RT paradigms. It is possible that participants in the choice RT paradigm adopted a strategy in which online programming was more prevalent than in the simple RT paradigm. If this was the case, it was expected that the additional processing requirements during movement execution would result in longer movement times or pause times between elements (Chamberlin & Magill, 1989).

The degree to which responses are programmed in advance of movement initiation versus during execution also has implications for the one-target advantage.

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[2] This maybe considered a more indirect manipulation of duration compared to Klapps (1995) experiments in which duration was explicitly manipulated.

[3] It may also be argued that more accurate responses contain more submovements and that simple RT could increase as the number of submovements increase.

Typically, in sequential aiming movements, movement durations to the first target are shorter in single element compared to two element responses (Adam et al., 2000; Helsen et al., 2001). This phenomenon is said to be due to interference in the production of the first element. In order to enhance the integration between response elements, the control processes associated with the production of the second element are implemented during the execution of the first. This 'overlap' in the control processes increases the executive control of the first element and leads to the one-target advantage. However, the current experiment adopts a methodology whereby the second element is in the opposite direction to that of the first. In these reversal movements the antagonist muscle forces used to decelerate the first element also act as the agonist on the second element. This results in a biphasic pattern of muscle activity which simplifies the control process and leads to an optimal integration between response elements. As a result the one-target advantage is reduced and typically a two-target advantage arises. The present experiments will investigate the extent to which online processes enhance or disrupt the integration between the first and second elements in a reversal movement.

3.1. EXPERIMENT 1

3.1.1. Method

Participants. Thirty self declared right-handed undergraduate students (18 males and 12 females) between the ages of 18 and 35 yrs volunteered to participate in the experiment. All reported normal or corrected to normal vision and were naïve with regard to the purpose of the experiment. Participants gave their informed consent prior to taking part and the experiments were carried out according to the ethical guidelines laid down by the Ethics committee of the School of Sport, Health and Exercise Sciences, University of Wales, Bangor, for research involving human participants.

Apparatus. Participants held a pen with their right hand and made movements on a Calcomp III digitizing tablet (size = 122 cm x 91.5 cm, sample rate = 200 Hz, accuracy = ± 0.125mm) positioned horizontally in front of them. Movements of the pen were constrained along a track-way in the left to right direction. The position of the pen was represented by a cursor (1 cm in diameter) on a 37" Mitsubishi Diamond Pro computer monitor situated 40 cm in front of the participants and 20 cm above the tablet. Visual displays of the start position, target regions, and a cursor representing pen position appeared on the monitor screen (see Figure 6). The start position was located on the left of the monitor and consisted of a vertical line 0.4 cm wide and 4 cm long. Directly above the start position was a 2 cm x 1.5 cm rectangle where the stimulus appeared. Two target regions (1 and 2) were situated to the right of the start position and each consisted of a 4 cm target box within which was a smaller 2 cm target box. Target 1 was located 15 cm from the start position (centre to centre) and target 2 was located 7.5 cm from the start position (centre to centre). To minimise head movements participants placed their chin on a chin rest that was adjusted so that the start and target boxes were at eye level. The participants arm was occluded by an opaque shield throughout the experiment.

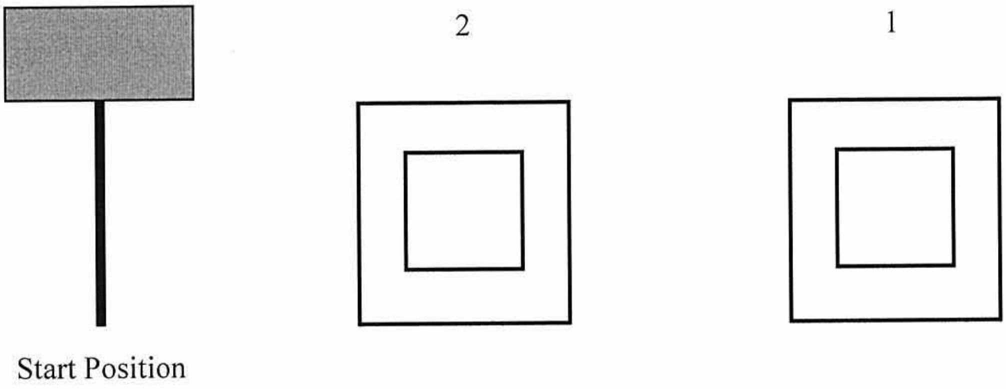

Figure 6. Diagram of monitor display in Experiment 1 showing locations of home position, stimulus display box, small and large targets at positions 1 and 2.

Task and Procedure. Participants were randomly assigned to one of two reaction time tasks: simple RT or choice RT. Each group contained an equal number of males and females (9 males and 6 females). In both RT tasks there were four possible stimuli: 1S, 2S, 1L, and 2L. A "1S" represented a single element response to the small far right target. A "2S" represented a two element response, in which participants were required to move to the far small target and then back to the near small target. "1L" and "2L" represented corresponding single and two element movements to the large targets.

At the beginning of each trial, the start position, target regions, and the cursor representing limb position appeared on the monitor. Participants were required to move the cursor to the centre of the start position. In the simple RT condition, a precue was presented for 2000 ms. This precue was identical to the stimulus which was to follow and hence informed the participant with a 100% certainty which response was required. Following the precue, an audio tone was presented signalling the start of the variable foreperiod (1500 ms to 2500 ms). This was followed by the presentation of the stimulus which remained visible throughout the trial. The choice RT procedure was identical to the simple RT procedure with the exception that no precue was presented. Therefore, participants in the choice RT condition did not have any prior knowledge of which response was required. At the end of each trial, participants received feedback about their RT (msec) and constant error (mm) at each target.

Participants in each RT condition received 128 trials with the four stimuli occurring in random sequence. The first 8 trials were disregarded as familiarisation. All trials in which participants made the wrong response or in which RTs were less than 100 msec or greater than 800 msec were rejected and repeated within the sequence of trials. This accounted for less than 5% of the trials.

Data Reduction, Dependent Measures and Analyses. The displacement data for each trial were filtered using a second-order dual-pass Butterworth filter with a low-pass cut-off frequency of 10 Hz. Instantaneous velocity data were obtained by differentiating the displacement data using a two-point central finite difference algorithm. In order to locate the beginning of the movement, peak velocity was first obtained. The velocity profile was then traversed backwards in time until the velocity fell below 2 cm/sec. The end of the movement to the first target was defined as the first point in time following peak velocity in which the absolute angular velocity of the pen fell below 2 cm/sec. If the movement consisted of two elements, the beginning of the movement to the second target was determined by first locating peak velocity in the reversal direction. The velocity profile was then traversed backwards in time until the absolute velocity fell below 2 cm/sec. The end of the movement was then defined as the point in time following peak velocity at which the absolute velocity fell below 2 cm/sec. If the absolute velocity between the end of the first element and the beginning of the second element remained below 2 cm/sec, the movement was said to contain a pause. Pause time was then calculated as the interval between the end of the first element and the start of the second element.

The dependent measures consisted of reaction time (RT), movement time 1 (MT1) and movement time 2 (MT2), pause time (PT), target hit rate 1 (THR1) and target hit rate 2 (THR2). Also, based on the assumption that the kinematics of limb trajectories up to peak velocity represent the programmed phase of movement whereas online processes take effect after peak velocity (for a review see Elliott, Helsen & Chua, 2001), MT1 was partitioned into time to peak velocity (TPKV) and time after peak velocity (TAPKV). RT was the interval between the presentation of the stimulus and the initiation of movement. MT1 was the interval from the start of the movement to when the pen reached the first target while MT2 was the interval from the first to the second target. PT was the interval between the termination of the first element and the initiation of movement to the second target. Target hit rates where the percentage of trials in which the movements ended within the respective targets.

RT, MT1, TPV, TAPKV and THR1 were analysed using separate 2 reaction time task (simple RT, choice RT) x 2 number of elements (1, 2) x 2 target size (small, large) ANOVAs with repeated-measures on the last two factors. Since PT, MT2 and THR2 were recorded only for movements with two elements, these data were analysed using separate 2 reaction time task (simple RT, choice RT) x 2 target size (small, large) ANOVAs with repeated-measures on the last factor. All post hoc analyses were performed using Tukey's HSD ($p < .05$) procedures.

3.1.2. Results

The group means and standard deviations for each dependant variable are reported in Table 1. As would be expected, RTs were longer in the choice compared to the simple RT condition, *F* (1, 28) = 12.04, *p* < .01. A significant main effect for number of elements revealed that overall, RTs were longer in the two element compared to single element conditions, *F* (1, 28) = 12.16, *p* < .01. There was also a significant RT task x number of elements interaction, *F* (1, 28) = 6.05, *p* < .05. A breakdown of this interaction indicated that choice RT was not influenced by the number of elements, whereas simple RT was longer in the two element compared to single element condition (see Figure 7). No significant main effect or interactions involving target size were revealed (*p* > .05).

	SRT				CRT			
	1		2		1		2	
Dependent Measure	L	S	L	S	L	S	L	S
RT (ms)	251.27	256.38	270.76	276.49	313.14	315.09	318.16	316.91
	28.72	*33.05*	*44.03*	*47.21*	*41.26*	*51.82*	*46.95*	*45.64*
MT1 (ms)	382.65	418.04	351.02	388.73	367.55	391.00	317.60	329.91
	43.10	*46.79*	*49.25*	*63.25*	*39.95*	*45.89*	*52.06*	*59.45*
THR1	0.97	0.86	0.90	0.77	0.95	0.84	0.91	0.72
	0.03	*0.11*	*0.06*	*0.12*	*0.05*	*0.07*	*0.08*	*0.10*
MT2 (ms)	----------	----------	310.83	353.47	----------	----------	295.03	327.18
	----------	----------	*32.65*	*37.07*	----------	----------	*48.86*	*52.94*
PT (ms)	----------	----------	4.02	38.02	----------	----------	25.00	44.36
	----------	----------	*8.13*	*41.57*	----------	----------	*64.26*	*76.51*
THR2	----------	----------	0.97	0.92	----------	----------	0.94	0.89
	----------	----------	*0.04*	*0.05*	----------	----------	*0.05*	*0.06*
TPKV(ms)	169.07	178.53	183.93	189.93	167.25	166.63	168.92	170.12
	26.14	*26.25*	*25.41*	*27.60*	*30.70*	*28.76*	*26.87*	*28.80*
TAPKV(ms)	178.85	201.36	169.58	199.74	163.15	173.19	152.73	162.52
	31.16	*35.72*	*28.63*	*38.88*	*25.87*	*29.48*	*28.24*	*34.40*

Table 1. Mean, *standard deviations*, of reaction time (RT), movement time to the first target (MT1), target hit rates at the first target (THR1), movement time to the second target (MT2), target hit rates at the second target (THR2), time to peak velocity (TPKV), and time after peak velocity (TAPKV) for the simple and choice RT conditions as a function of number of elements (1, 2) and target size (L = large; S = small) in Experiment 1.

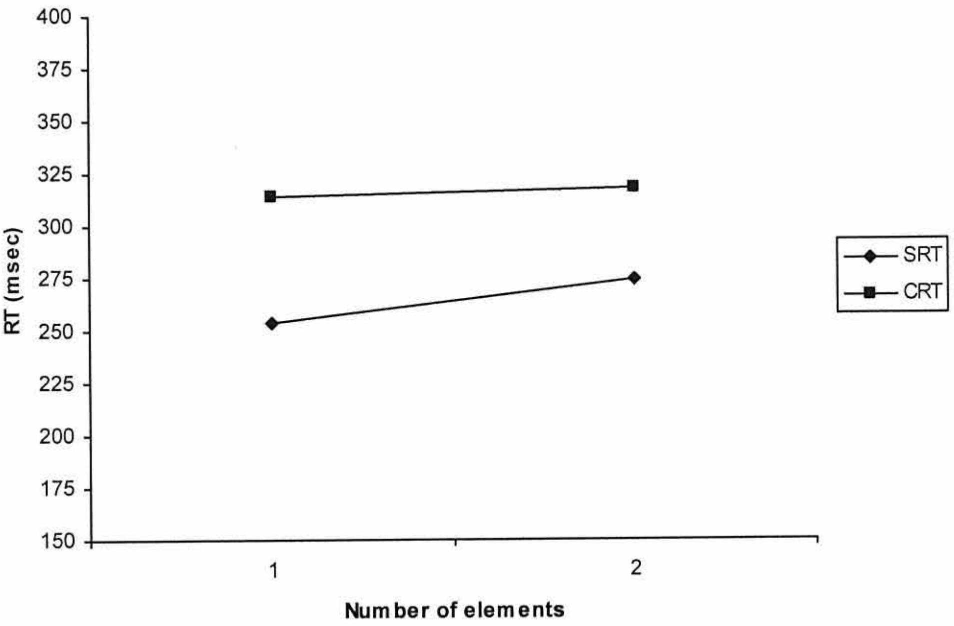

Figure 7. Reaction time (RT) in the simple and choice RT tasks as a function of number of elements in Experiment 1.

The analysis of MT1 revealed that the duration of the first element was longer in the simple compared to choice RT condition, *F* (1, 28) = 3.90, *p* < .05. Also, movement times to the first target were slower when participants were required to end their response on that target compared to when they were required to reverse direction to the second target, *F* (1, 28) = 70.28, *p* < .001. A significant RT task x number of elements interaction revealed that the difference in MT1 between the simple and choice RT conditions was greater in the two element compared to the single element responses, *F* (1, 28) = 5.97, *p* < .05 (see Figure 8). Consistent with Fitts Law (1954), movement times in the large target condition were faster compared to those in the small target condition, *F* (1, 28) = 54.40, *p* < .001. A RT task x target size interaction revealed that the effect of target size on MT1 was greater in the simple compared to choice RT condition, *F* (1, 28) = 6.40, $p < .05$.

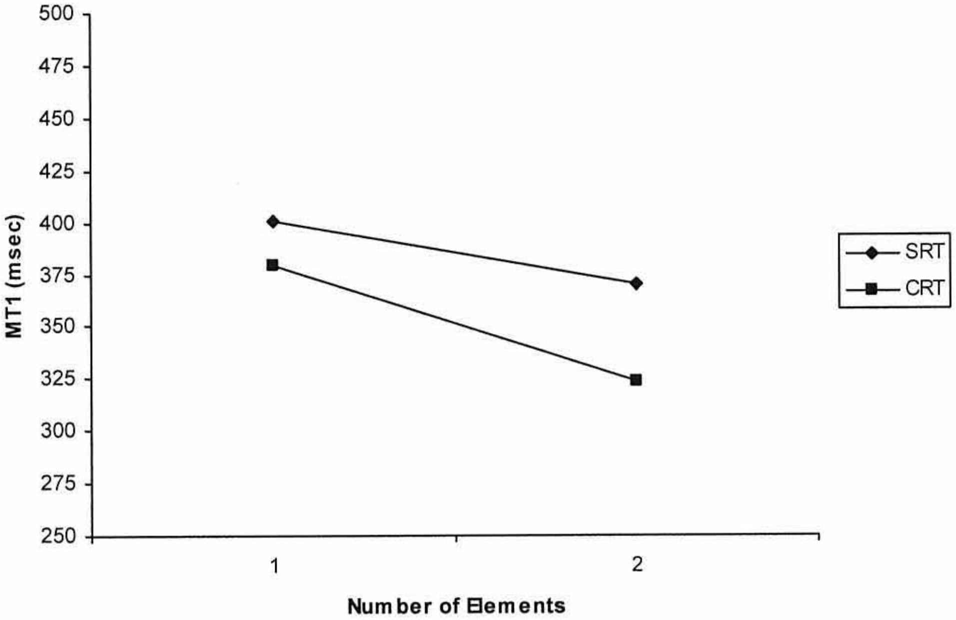

Figure 8. Movement time to the first target (MT1) in the simple and choice RT tasks as a function of number of elements in Experiment 1.

The analysis of TPKV revealed significant main effects for number of elements, *F* (1, 28) = 71.90, $p < .001$, and target size, *F* (1, 28) = 11.5, $p < .01$. There was also a significant interaction between RT task and number of elements, *F* (1, 28) = 32.4, $p < .001$. A breakdown of this interaction revealed that participants took longer to get to peak velocity in the two element compared to single element condition in the simple RT task. However, there was no effect of number of elements on choice RT. A significant interaction between RT task and target size also revealed that TPKV increased as target size decreased in the simple but not choice RT task.

There were significant main effects for RT task, F (1, 28) = 5.01, $p < .05$, number of elements, F (1, 28) = 10.70, $p < .01$, and target size, F (1, 28) = 56.52, $p < .001$, on the TAPKV. Overall, participants spent more TAPKV in the simple compared to choice RT task, in the single versus two elements conditions, and when movements were made to the small versus large targets. There was also a significant interaction between RT task and target size, F (1, 28) = 11.61, $p < .01$. A breakdown of this interaction revealed that the effect of target size on TAPKV was greater in the simple compared to choice RT task.

PT and MT2 were longer in the small compared to large target condition, F (1, 28) = 15.39, $p < .001$, and, F (1, 28) = 66.88, $p < .001$, respectively. There were no significant effects of RT task on PT or MT2 ($p > .05$).

The analysis of THR1 revealed main effects for element, F (1, 28) = 30.24, $p < .001$, and target size, F (1, 28) = 76.46, $p < .001$. Participants were more accurate at the first target when they were required to end their response on that target compared to when they were required to continue their movement to the second target. Also, THR1 was greater in the large target conditions compared to small target conditions. No other effects were significant on THR1 ($p < .05$).

A significant main effect for RT task on THR2 revealed that participants were more accurate in the simple compared to the choice RT condition, F (1, 28) = 4.25, $p < .05$. Also, THR2 was greater for movements to the large target compared to small target, F (1, 28) = 49.23, $p < .001$.

3.1.3. Discussion

The results of the present experiment indicated that simple RT increased as the number of elements in a response increased, whereas there was no effect of number of elements on choice RT. These results were consistent with Klapp's (1995; 2003) two process model of response programming, whereby the processes involved in scanning the time frame that specifies where the initiation of each response element occurs (SEQ) influences simple but not choice RT. According to Klapp, the programming of the internal features of individual response elements (INT) is performed in advance of stimulus presentation in simple RT tasks, whereas SEQ is loaded prior to stimulus presentation then scanned to locate its starting point during the RT interval. Since this scanning process takes longer as the number of elements increases, simple RT is influenced by the number of elements in a response. However, because pre-programming is not possible in choice RT tasks, both INT and SEQ are performed during the RT interval. As the time frame is retrieved immediately prior to responding this eliminates the scanning process, therefore it is the duration of response elements and not the number of elements in a response that influences choice RT.

Although the present results were consistent with Klapp's (1995; 2003) two process model of response programming, of further interest was the extent to which the pattern of RT results could be attributed to differences in the distribution of programming between the simple and choice RT conditions. Before discussing this further it may first be useful to consider the two-target movement time advantage observed in the present experiment (i.e., faster movement times to the first target in the two compared to one element responses). Although this finding is opposite to the one-target advantage that has been observed in sequential aiming movements (i.e., faster movement times for single compared to dual element responses), it is typical of movement sequences involving a reversal in direction (Adam et al., 2000). It has been suggested that in reversal movements, the antagonists muscle groups which decelerate the first element also act as the agonists in the second element. Hence, because of the mechanical characteristics of reversal movements, the two-target advantage arises due to the high integration between the first and second elements.

It was hypothesised that one possible reason choice RT did not increase as a function of the number of elements was that participants programmed only the first element prior to movement initiation and then programmed the second element online. If this was the case, it was expected that movement times would be longer in the choice compared to simple RT condition. However, the opposite effect was observed. That is, movement times to the first target were greater in the simple RT condition compared to choice RT condition with this difference being larger for responses involving two compared to one element. In other words, the two target movement time advantage was reduced in the simple compared to choice RT condition[4]. One interpretation of these findings is that online programming was occurring in both the simple and choice RT conditions but the nature of the programming was different. Recall that simple RT increased as a function of the number of elements, suggesting that participants were programming both response elements in advance of movement initiation. Adams et al., (2000) suggested that when both response elements are programmed in advance of movement initiation the response characteristics of the second element are held in a

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[4] This effect does not appear to be due to a speed-accuracy trade-off since there were no differences in target hit rates at the first target between simple and choice RT conditions.

buffer. These characteristics are then implemented when necessary during the first element to ensure optimal integration of the response elements. However, when the control processes of element two are implemented before the termination of element one an overlap in the control processes involved in the first and second element is created. This increase in executive control interferes with the execution of the first element and leads to the one-target advantage. If participants in the simple RT condition were attempting to optimally integrate the response elements then they may have programmed movements with longer durations so that they could visually monitor the execution of the first element to enhance the timing of the second element online (Ketelaars, Khan & Franks, 1999). Consistent with the movement integration hypothesis, the visual feedback during the first element could be used to mediate the integration between the first and second elements (Helsen et al., 2001). If this was the case, then the increase in executive control associated with these processes would result in a reduction to the two-target movement time advantage or a move towards the one target advantage in these reversal movements[5].

Although movement times were slower to the smaller targets there was no effect of target size on RTs. A breakdown of movement times into time before and after peak velocity revealed that time to peak velocity was influenced by target size in the simple but not the choice RT condition. Since time to peak velocity has been said to be representative of the programmed phase of the movement (Elliott et al., 1999), a separate 2 number of elements x 2 target size ANOVA was performed on just the simple RTs.

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[5] It is also possible that visually based online corrections in the simple RT condition disrupted the integration between the first and second elements and that this lead to a reduction in the two target advantage. Such a disruption would likely have lead to an increase in pause times between the first and second elements. However, since pause times did not differ between simple and choice RT conditions, it seems that movements were integrated during execution of the first element in the simple RT condition.

This analysis did reveal a significant effect of target size with RTs to the small target being greater than those to the large target, $F(1, 14) = 6.10, p < .05$. Therefore, it seems that in the simple RT task, movements were programmed with longer durations in the small compared to large target conditions resulting in an influence of target size on simple RT. In the choice RT condition, participants may have adopted a 'safety' strategy of programming movements to the small target and then made any necessary adjustments during movement execution. This strategy may have been facilitated by the same location of the small and large targets as well as the relatively long distance between the home position and the first target. Consistent with this explanation is the finding that time to peak velocity was not influenced by target size in the choice RT condition but time after peak velocity was greater in the small compared to large target conditions. Klapp (1975) has reported that target size had an effect on RTs when movement amplitudes were relatively short, whereas there was no effect when movement amplitudes were long. It may be that the distance between the home position and the first target was too long in the present experiment to elicit an effect of target size on choice RT.

3.2. EXPERIMENT 2

The results of the first experiment indicated that the number of elements had no effect on choice RT, whereas simple RT increased as the number of elements increased. It was expected that if movements were programmed online in the choice RT condition, movement times would have been longer in the choice compared to simple RT condition. In contrast to expectations, movement times to the first target were greater in the simple compared to choice RT condition. It was reasoned that since participants in the simple RT condition knew in advance of the stimulus whether they had to perform a one or a two element response, they programmed the first element of the response with a longer duration relative to the choice RT condition. This strategy facilitated online programming and the integration between elements since it allowed participants to utilise visual feedback to accurately time the implementation of the second element.

In the present experiment, a dual task procedure was employed to test the possibility that participants were integrating elements online in the simple RT condition[6]. Participants performed a task similar to that in Experiment 1 with their right hand (primary task) while simultaneously reacting to a tone by making a key-press response with their left index finger (secondary task). An underlying assumption of the movement integration hypothesis is that longer movement times to the first target in multiple element responses are due to increased executive control during the first element (Adam et al., 2000). Hence, the integration between elements would be susceptible to interference when two tasks are performed simultaneously.

One advantage of using a dual-task procedure is that by examining the nature of the dual-task interference, inferences can be made about the various processes involved in online control and movement integration. If participants are programming movements online, it was expected that RTs to the secondary task would be greater in the two compared to single element responses when the secondary task stimulus was presented during movement execution. Furthermore, in reversal movements where the two elements are highly integrated, the endpoint of the first element is determined by when

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[6] The following chapter also investigates similar issues under a choice RT paradigm. Experiments 2 and 3 were presented and analysed separately in order that a more detailed examination of performance under simple and choice RT conditions could be offered.

the second element is initiated. Hence, if participants are visually regulating the execution of the first element to facilitate the integration between elements, one would expect a heightened degree of spatial errors at the first target due to interference caused by the secondary task.

3.2.1. Method

Participants. Ten self declared right-handed undergraduate students (8 male, 2 female) between the ages of 18 and 24 volunteered to participate in the study. None of the participants had taken part in Experiment 1. All of the participants reported normal or corrected to normal vision and were naïve with regard to the purpose of the experiment. Participants gave their informed consent prior to taking part and the experiment was carried out according to the ethical guidelines laid down by the Ethics committee of the School of Sport, Health and Exercise Sciences, University of Wales, Bangor, for research involving human participants.

Apparatus. The experimental setup for the primary task was similar to that in Experiment 1 with the exception that movements were performed on a smaller SummaSketch III Professional digitizing tablet (size = 450mm x 310mm, sample rate = 120 Hz, accuracy = ± .02mm). Movements of the pen were represented by a cursor on a 19" Dell Trinitron computer monitor situated 40 cm in front of the participant and raised 30 cm from the tablet surface. The target and stimulus display on the monitor was similar to that in Experiment 1 with the exception that only the small targets (2 x 2 cm) were used. For the secondary task, participants placed their left index finger on a micro switch that was mounted to left of the digitizing tablet and within easy reach of the participants' left hand.

Task and Procedure. The primary task consisted of a simple RT task. The procedures were similar to the simple RT task in Experiment 1 with the exception that there were only two possible stimuli since only the small targets were used: "1" and "2" denoting single and two element responses, respectively. At the end of each trial, participants received feedback about their RT (msec) and constant errors (mm) at both targets.

For the secondary, or probe task, a computer generated tone was presented and participants were required to react as quickly as possible by making a finger press response with their left index finger that was positioned on the micro-switch.

For the primary task in the single task condition, the secondary task stimulus was presented at various positions throughout the movement, but participants were instructed not to respond to this stimulus. On any particular trial, the probe could either not be presented (i.e., no probe) or occur at one of five possible positions; (1) 50 ms after the onset of the primary task stimulus i.e. during RT of the primary task (RT), (2) at the initiation of movement in the primary task (MI), (3) 50 ms after the initiation of movement (MI + 50), (4) at peak velocity (PKV), and (5) 50 ms after peak velocity (PKV + 50). These probe positions were chosen so that processing demands associated with both programming and online regulation of movement could be assessed. Also, tying the probes to key positions in the primary task has the advantage that despite trial-to-trial variations in movement times, processing demands at specific stages of the movement can be examined with high temporal precision (Ketelaars et al., 1999). Participants received 60 trials with both the primary and secondary task stimuli occurring in random order.

For the secondary task in the single task condition, the sequence of events on the monitor screen was identical to that of the primary task. However, participants were instructed not to perform any movements associated with the primary task. They were required to hold the pen so that the cursor on the monitor screen was located on the start position throughout the trial. On any particular trial, secondary task stimuli were either not presented or were presented at 50, 200, 250, 350, and 400 msec following onset of the primary task stimulus. Participants received 30 trials with the order of the probe positions and primary task stimuli occurring in random.

For the dual task condition participants were required to respond to both the primary and secondary task stimuli. They were instructed to minimise RT and make arm movements as quickly and accurately as possible in the primary task while reacting to the secondary task stimulus as rapidly as possible. However, performance on the primary task was said to be a priority. Participants were only given feedback on their performance in the primary task (i.e., RT (msec) and constant error (mm)). Participants performed 120 trials comprising of 60 single element responses and 60 two element responses which were randomised. On each trial, there was either no probe or the probe occurred at one of the five positions mentioned previously. Probe positions were randomised in a pseudorandom order. That is, each probe position occurred before any was repeated. In both the single and dual task conditions, any trials in which participants made the wrong response or in which RTs were less than 100 msec and greater than 800 msec were rejected and repeated. This accounted for less than 5% of the trials.

Dependent Measures and Analyses. For the primary task in the single task condition, RT, MT1 and THR1 were analysed using separate 2 element (1, 2) x 6 probe position (no probe, RT, MI, MI + 50, PKV, PKV +50) repeated measures ANOVAs. PT, MT2 and THR2 were analysed using a 6 probe position (no probe, RT, MI, MI + 50, PKV, PKV +50) repeated measures ANOVA. For the secondary task in the single task condition, probe RTs were analysed using a 2 element (1, 2) x 5 probe position (50, 200, 250, 350, 400msec) repeated measures ANOVA.

For the dual task condition, analyses of primary task RT, MT1, and THR1 were conducted using separate 2 number of elements (1, 2) x 6 probe position (no probe, RT, MI, MI + 50, PKV, PKV + 50) repeated measures ANOVAs. PT, MT2 and THR2 were analysed by performing separate 6 probe position (no probe, RT, MI, MI + 50, PKV, PKV + 50) repeated measures ANOVAs. Secondary task RTs were analysed using a 2 number of elements (1, 2) x 5 probe position (RT, MI, MI + 50, PKV, PKV + 50) repeated measures ANOVAs. All post hoc analyses were performed using Tukey HSD ($p < .05$) procedures.

3.2.2. Results

Single Task Condition

Primary Task. Consistent with the results of Experiment 1, simple RT was shorter in the single element (237 msec) compared to the two element condition (250 msec), $F(1, 9) = 14.16, p < .01$. There was a tendency for primary task RTs to be quicker when the probe occurred during primary task RT (230 msec) compared to the other probe positions (mean = 246 msec). Although participants were instructed not to respond to the auditory probe stimulus, they may have tended to initiate a primary task movement in response to the tone. However, this does not seem to be the case as RT did vary between the one and two element conditions. Hence participants were processing the primary task stimulus. Also, a non significant interaction between number of elements and probe position, *F* (5, 45) = .50, $p > .05$, revealed that the effect of number of elements was not influenced by probe position.

MT1 was faster in the two element (412 msec) compared to single element responses (502 msec), *F* (1, 9) = 57.51, $p < .001$. Also, the two element condition was associated with lower target hit rates (0.80) compared to the single element condition (0.95), *F* (1, 9) = 29.08, $p < .001$.

No other significant effects were observed ($p > .05$).

Secondary Task: There were no significant effects of probe position or the number of elements on probe RT in the single task condition (mean = 229 msec) ($p > .05$).

Dual Task Condition

Primary Task. Consistent with the primary task in the single task condition, RT in the single element condition (238 msec) was shorter than in the two element condition (251 msec), *F* (1, 9) = 10.63, $p < .01$. Primary task RTs were shorter when the probe occurred during primary task RT (214 msec) compared to the other probe positions (251 msec), *F* (5, 45) = 22.88, $p < .001$. However, a non significant interaction between number of elements and probe position revealed that the effect of number of elements was not influenced by probe position, *F* (5, 45) = .391, $p > .05$.

The analysis of MT1 revealed a significant main effect for element, *F* (1, 9) = 65.63, $p < .001$, with movement times involving a two element response (393 msec) being faster compared to those requiring only a single element response (498 msec).

Analysis of THR1 revealed that participants were more accurate at the first target in the single element (0.94) compared to two element responses (0.78), *F* (1, 9) = 17.15, $p < .01$. Particularly interesting was the finding that there was a significant main effect of probe position, *F* (5, 45) = 4.09, $p < .01$, as well as a significant interaction between number of elements and probe position, *F* (5, 45) = 4.26, $p < .01$. A breakdown of this interaction revealed target hit rates were not affected by probe position in the single element condition (see Figure 9). However, in the two element condition, there was a significant reduction in target hit rates when the probe occurred 50 msec after movement initiation compared to all other probe positions.

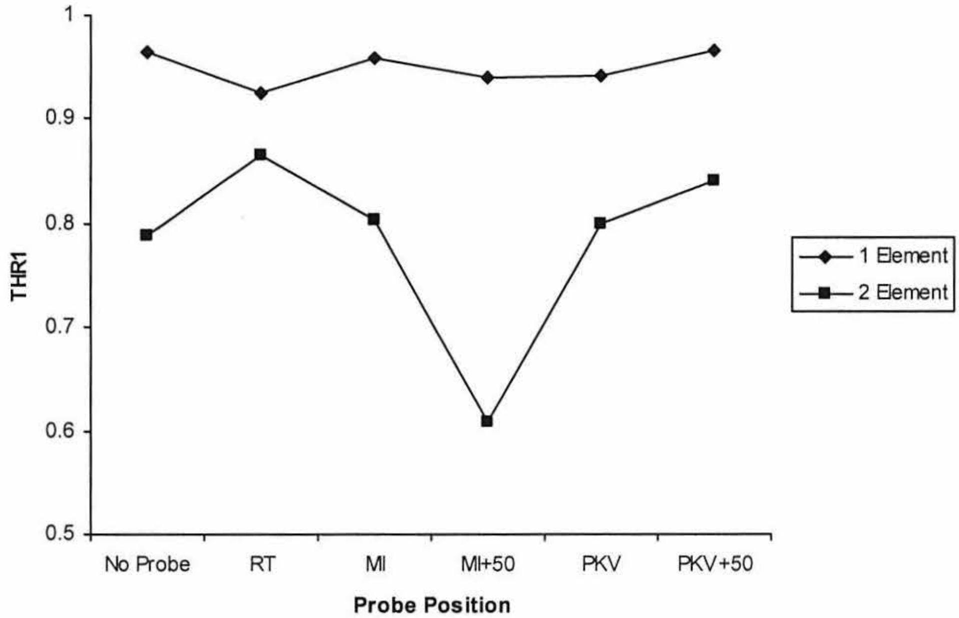

Figure 9. Target hit rates at the first target (THR1) for the single and dual element responses as a function of probe position in the dual task condition in Experiment 2 (reaction time = RT; movement initiation = MI; peak velocity = PKV).

There were no significant effects for either PT or MT2 ($p > .05$).

Secondary Task. Probe RTs were shorter in the single compared to two element responses, $F(1, 9) = 15.33, p < .01$. This was the case when the probe occurred during RT of the primary task and during movement execution (see Figure 10). There was also a main effect of probe position, $F(4, 36) = 28.89, p < .001$. Post hoc tests revealed that probe RTs were greater when the probe occurred during RT of the primary task compared to all other probe positions.

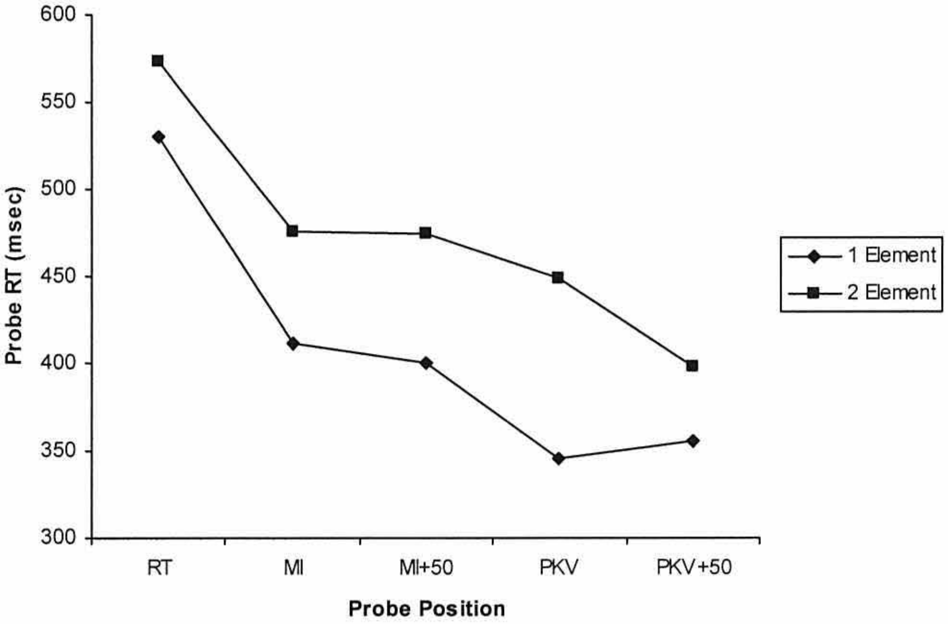

Figure 10. Probe RTs for the single and dual element responses as a function of probe position in Experiment 2 (reaction time = RT; movement initiation = MI; peak velocity = PKV).

3.2.3. Discussion

Secondary task RTs were greater when the primary task involved two elements compared to one element. This was the case when the secondary task stimulus occurred both during RT of the primary task and during execution of the first element. This heightened degree of interference during the production of the first element, when a second element was required, suggests that online programming occurred in the simple RT condition. More importantly, when the secondary task stimulus occurred at probe position 3 (i.e., movement onset + 50 msec) there was a significant drop in target hit rates in the primary task. It should be noted that this decrease in target hit rates occurred when the probe stimulus was presented during acceleration of the primary task. This early phase of movement has been assumed to be ballistic (Meyer, Abrams, Kornblum, Wright & Smith, 1988). However, since probe RT was 490 msec when the probe occurred at position 3 in the two element condition, the actual interference was likely due to processes during deceleration of the primary task where visual control is said to take effect (Elliott et al., 2001). This finding supports the hypothesis that participants in the simple RT condition were visually guiding the execution of the first element and that diverting attention away from this process by employing a dual task procedure resulted in a decline in spatial accuracy. Consistent with the movement integration hypothesis (Adam et al., 2000), participants may have enhanced the integration between elements by using visual feedback to time the implementation of the second element (Helsen et al., 2001). In a reversal movement where the antagonist of the first element also acts as the agonist of the second element, the endpoint of the first element would be determined by the accuracy of the timing of the second element. Based on the assumption that the use of visual feedback to integrate elements involved executive control, the additional attention demands of the probe task would have interfered with the timing of the second element resulting in increased error rates at the first target.

3.3. EXPERIMENT 3

The results of Experiment 2 implied that online programming was occurring in the simple RT condition. The present experiment tested whether online programming was also occurring in the choice RT condition. It was suggested in Experiment 1 that participants in the choice RT task programmed the first element during the RT interval but delayed the programming of the second element until movement execution. Hence, choice RT did not increase as a function of number of elements since programming of the second element occurred outside the RT interval. In the present experiment, participants performed a similar task to that in Experiment 2, but the primary task was a choice RT task. It was expected that evidence for online programming would be gained if secondary task RTs were greater in the two compared to one element responses when the secondary task stimulus occurred during execution of the primary task.

3.3.1. Method

Participants. Ten self declared right-handed undergraduate students (8 male, 2 female) between the ages of 18 and 24 volunteered to participate in the study. None of the participants had taken part in Experiment 1 or 2. All of the participants reported normal or corrected to normal vision and were naïve with regard to the purpose of the experiment. Participants gave their informed consent prior to taking part. The experiment was carried out according to the ethical guidelines laid down by the Ethics committee of the School of Sport, Health and Exercise Sciences, University of Wales, Bangor, for research involving human participants.

Task and Procedure. The apparatus was identical to that used in Experiment 2. Also the procedures were similar to Experiment 2 with the exception that the primary task consisted of a choice RT task. That is, participants were not informed which response would be required in advance of the stimulus. At the beginning of each trial, a non-informative tone was presented signalling the start of a variable foreperiod (1500ms to 2500ms). This was followed immediately by the presentation of the stimulus. All other procedures were similar to Experiment 2.

3.3.2. Results

Single Task Condition

Primary Task. Consistent with the results of Experiment 1, choice RT was not influenced by the number of elements in a response (single element: 279 msec; two element: 285 msec), $F\ (1, 9) = 1.26, p > .05$. However, there was a significant main effect of probe position on primary task RTs, $F\ (5, 45) = 5.23, p < .01$. Post hoc tests revealed that primary task RTs were faster when the probe stimulus occurred 50 ms after the primary task stimulus (259 msec) compared to the other probe positions (mean = 287 msec). Similar to the simple RT task in Experiment 2, it appears that although participants were instructed not to respond to the auditory probe stimulus, they may have tended to initiate a primary task movement in response to the tone. Therefore, the null effect of number of elements could be due to participants not fully processing the visual stimulus of the primary task. However, this does not appear to be the case since there was a non-significant interaction between number of elements and probe position, F $(4,36)=1.13$, $p > .05$. Hence, the number of elements had no effect on primary task RTs regardless of probe position.

MT1 was shorter in the two element responses (342 msec) compared to the single element responses (415 msec), $F(1, 9) = 21.60$, $p < .001$. Also, hit rates at the first target were less in the two (0.79) compared to single element responses (0.94), $F(1, 9) = 14.13$, $p < .01$.

No other significant effects were observed ($p > .05$).

Secondary Task. As would be expected, there were no significant effects of probe position or the number of elements on probe RT in the single task condition (mean = 237 msec) ($p > .05$).

Dual Task Condition

Primary Task. The analysis of primary task RT again revealed a non-significant main effect for the number of elements on choice RT (single element condition = 281 msec, two element condition = 283 msec), $F(1, 9) = .92$, $p > .05$. Similar to the single task condition, primary task RTs were shorter when the probe stimulus occurred during RT of the primary task $F(5, 45) = 21.35$, $p < .001$. A non-significant interaction between number of elements and probe position *F* (5,45)=1.34, $p > .05$, revealed that primary task RTs were not influenced by number of elements regardless of probe position.

The analysis of MT1 revealed only a significant effect of number of elements with movements to the first target being quicker in the two (319 msec) compared to single element responses (408 msec), *F* (1, 9) = 68.41, $p < .001$. Also, THR1 was lower in the two (0.74) compared to single element responses (0.92), *F* (1, 9) = 18.41, $p < .01$ (see Figure 11). However in contrast to the results for the simple RT task in Experiment 2, there was no effect of probe position on THR1 ($p > .05$).

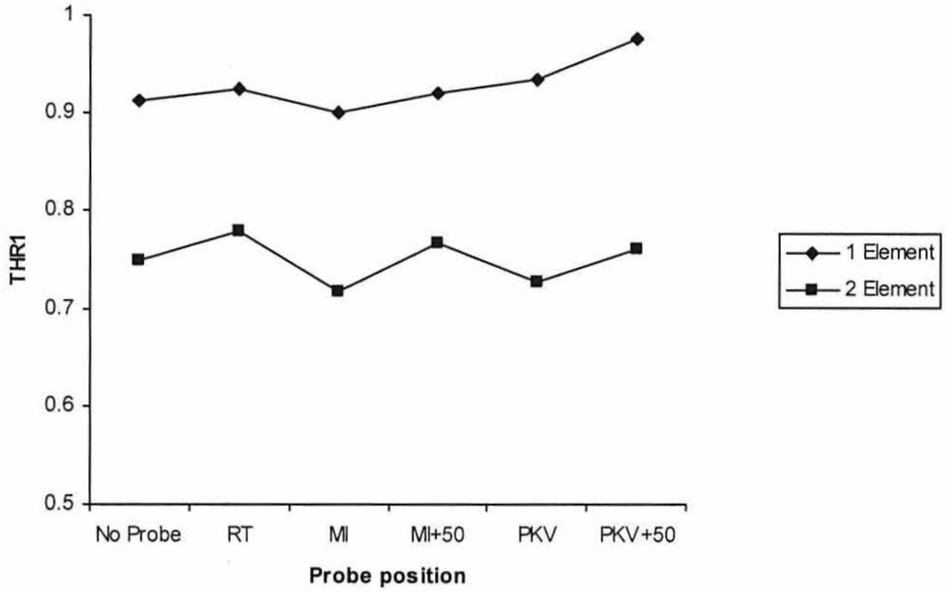

Figure 11. Target hit rates at the first target (THR1) for the single and dual element responses as a function of probe position in the dual task condition in Experiment 3 (reaction time = RT; movement initiation = MI; peak velocity = PKV).

The analyses of PT, MT2 and THR2 revealed no significant effects ($p > .05$).

Secondary Task. The probe RT analysis revealed a significant main effect for number of elements, *F* (1, 9) = 23.86, $p < .001$. As shown in Figure 12, probe RTs were greater in the two compared to the single element condition. This was the case when the probe occurred during both RT and execution of the primary task. There was also a main effect of probe position, *F* (4, 36) = 213.06, $p < .001$. Post hoc tests revealed that probe RT was greater when the probe occurred during RT of the primary task compared to all other probe positions.

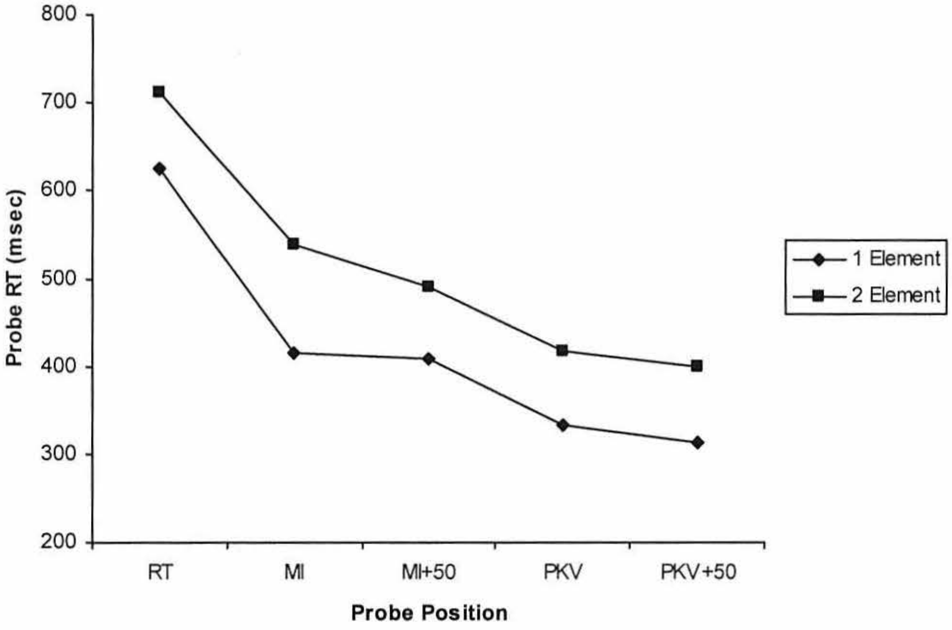

Figure 12. Probe RTs for the single and dual element responses as a function of probe position in Experiment 3 (reaction time = RT; movement initiation = MI; peak velocity = PKV)

3.3.3. Discussion

Similar to the results of the choice RT task in Experiment 1, the number of elements in the response had no effect on RT. Of particular interest in the present experiment, was whether this null effect of number of elements on choice RT was due to online programming. The results of the secondary task revealed that RTs to the probe were greater when the primary task response involved two elements compared to one.

This was the case both when the secondary task stimulus occurred during RT of the primary task and during execution of the primary task. Hence, increasing the number of elements increased the processing demands of the primary task both during the RT interval and during movement execution. The increased attention demands during movement execution in the two element condition, suggests that programming of the second element was occurring during execution of the first element. Interestingly however, is that although choice RT did not vary as a function of number of elements, probe RTs were greater for the two compared to one element responses when the probe occurred during the RT interval of the primary task. It was suggested that the null effect of number of elements on choice RT may be due to participants programming only the first element during RT and then programming the second element online. If participants were only programming one element during RT regardless of the number of elements required, one would not expect a greater attention demand during RT for the two compared to one element response. Perhaps the realisation that a two element response was required had a greater attention capture even though the programming of the second element did not occur until during movement execution.

3.4. General Discussion

The results of all three experiments revealed that simple RT was greater for the two compared to single element responses whereas there was no effect of number of elements on choice RT. These results are consistent with the two process model of response programming proposed by Klapp (1995; 2003) in which the time it takes to sequence response elements influences simple but not choice RT. According to the latest version of the two process model (Klapp, 2003), programming in the simple RT paradigm involves the loading of an abstract time frame, specifying the initiation time of each element. During the RT interval, the time frame is activated by scanning for the location of the first element. This scanning process takes longer for responses involving more elements, hence RT increases as the number of elements increases. In Choice RT, the time frame cannot be loaded prior to the RT interval as pre-programming is not possible. Therefore, choice RT does not increase as the number of elements increase since response initiation follows immediately from the specification of the time frame, thus eliminating the scanning process.

An alternative interpretation of the present results is that participants adopted different programming strategies in the simple and choice RT conditions. Analysis of probe RTs in Experiments 2 and 3 revealed that attention demands during the first element were greater in the two compared to single element responses in both simple and choice RT tasks. This suggests that online programming was occurring in both RT tasks. However, when participants knew in advance of the stimulus that they were required to perform a two element response (i.e., simple RT), they programmed the first element with a longer duration compared to when the required response was not known prior to stimulus presentation (i.e., choice RT). When these movement time results are looked at in conjunction with the RT results, one possible interpretation of the findings is that the nature of the online programming was different between the two RT conditions. In the choice RT condition, it is believed that it was the actual movement commands of the second element that were programmed online. Support for this interpretation is provided by the null effect of the number of elements on RT and the longer secondary task RTs in the two compared to the single element condition. However, in the simple RT condition, the nature of the online programming is thought to reside in the visual guidance of the first element and the timing of initiation of the second element. Consistent with the movement integration hypothesis (Adams et al., 2000), it is believed that the visual guidance of the first element facilitated the timing of initiation of the second element so that response elements could be optimally integrated. The longer movement times to the first target in the two element responses and the dramatic decrease in target hit rates when the secondary task appeared during movement execution support this interpretation. In the two element conditions, it seems that participants were programming movements to the first target with longer durations in order to provide sufficient time for online visual guidance to be effective. In addition, it is believed that the visual feedback was utilised to time the initiation of the second response element. This produced an increase in the executive control during the first element, and resulted in increased error rates at the first target when the additional attention demands of the probe task were present. This can be explained further by looking at the nature of the integration between the response elements. In a reversal movement the antagonist muscle groups of the first element also act as the agonist muscle groups of the second element. Thus the endpoint of the first element is determined by the accuracy of the timing of the second element. Therefore, the heightened degree of spatial errors at the first target that were observed when the probe occurred during movement execution implied that the integration process was disrupted by the attention demands of the probe. The influence of the probe task on the accuracy of the primary task was not present in the choice RT condition which provides further support to the notion that the nature of the online programming was different between the RT conditions.

It was suggested that the nature of the online programming observed in the simple RT condition involved the visual guidance and the timing of initiation of the second element. Since RT increased as a function of the number of elements, it was assumed that participants programmed both elements in advance of movement initiation. The characteristics of the second element were then held in a buffer and implemented when necessary during the first element to facilitate the integration between response elements. However, an alternative interpretation of the current results is that, as suggested in the choice RT condition, participants were programming the actual characteristics of the second element online. Hence, one possible reason for the increase in RT as a function of number of elements observed in the simple RT condition is that, in contrast to the model proposed by Klapp (1995; 2003), the programming of movement durations influenced simple RT. Overall, movement times to the first target were faster in the two compared to single element response. However, this decrease in movement time as a function of number of elements was less in the simple compared to choice RT condition. It was reasoned that participants programmed movements with longer durations in the simple RT condition in order to utilise visual feedback online, and in doing so, facilitate the timing of the second element to enhance the integration between response elements. Therefore, the effect of the number of elements on simple RT could be a function of the processes associated with the programming of movement duration. In support of this, the results of Experiment 1 revealed that target size had an effect on simple RT. Since time to peak velocity was longer for the small compared to large target conditions, it appears that the increase in simple RT as target size decreased was due to the programming of movements with longer durations to meet the accuracy demands of the task[7]. However, if the nature of the online programming was the same between the two RT conditions then it is difficult to explain why the introduction of a second attention demanding task influenced performance in the simple and choice RT tasks differently.

In both the single and two element responses, the first element was always to the same target. This may have promoted an online programming strategy, especially in the choice RT condition, since there was no uncertainty involving the first element. Research has revealed that choice RT decreased when the unknown element in a movement sequence occurred later in the response (Garcia-Colera & Semjen, 1988; Rosenbaum, Inhoff & Gordon, 1984). It was reasoned that when the early elements were known in advance, participants programmed later elements online. Therefore, in order to minimise choice RT in the present experiments, participants may have prepared the first element in the same manner regardless of the required number of elements and then relied on online programming in the two element conditions. In the simple RT condition, participants knew in advance of the stimulus whether they would be required to perform a one or two element response. This would have provided the opportunity to prepare two element responses to a greater extent prior to movement initiation compared to the choice RT condition. Hence, simple RT was influenced more by response complexity than choice RT.

Although the distribution of programming in simple and choice RT tasks may have depended on the certainty of early response elements, it is also possible that the

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[7] It was difficult to make similar inferences in the choice RT task since time to peak velocity was not influenced by target size.

relative difficulty of responses was a critical factor in determining the extent to which responses were programmed prior to movement initiation. In past research, simple RT has generally been shown to be independent of response complexity when responses were relatively simple (e.g., one versus two syllables in a word (Klapp, Anderson & Berrian, 1973); dit versus dah morse code responses (Klapp, Wyatt & Lingo, 1974; Klapp 1995)) but increase as a function of response complexity for more complex responses (e.g., number of words in a sequence (Sternberg, Monsell, Knoll, & Wright, 1978); one versus four morse code elements (Klapp, 1995)). On the other hand, choice RT seems to increase as a function of response complexity when responses are relatively simple (e.g., one versus two syllables in a word (Klapp et al., 1973); dit versus dah morse code responses (Klapp et al., 1974)) but not when responses are more complex (e.g., one versus four morse code elements (Klapp, 1995); aiming movements (Chamberlin & Magill, 1989). Similarly, Klapp (2003) has shown that choice RT but not simple RT increased as a function of number of syllables in a pseudoword when the syllables were easily integrated. Under conditions in which the syllables were less integrated, simple RT increased but choice RT was unaffected by the number of syllables. It appears that when responses are on the lower end of the complexity scale or elements can be easily chunked, participants program the entire response prior to movement initiation in choice RT tasks and hence RT increases as a function of response complexity. When the responses are more complex, such as in the present experiments, participants are more likely to program the initial elements during RT and later elements online. The underlying factor that determines whether participants distribute the programming of response elements differently in simple and choice RT conditions may be the time available to load response elements into short term memory. In simple RT, elements can be loaded during the foreperiod and hence there is the potential that simple RT would increase for more complex responses. In choice RT it may be difficult to load and activate complex responses during the RT interval without drastically increasing RT. Hence, participants program the first element during RT and then delay the programming of other elements until during movement execution.

In conclusion, the results of the present experiments revealed that the greater effect of response complexity on simple compared to choice RT was due to differences in the distribution of programming during RT and movement execution. It has been suggested that the distribution of programming may depend on factors such as the certainty of early response elements and the relative complexity of responses. Although the present results do not allow a differentiation between these two possibilities, both imply that the effect of response complexity on simple and choice RT depends on how participants distribute programming to deal with limitations in short term memory for movement.

CHAPTER 4

ONLINE VERSUS OFFLINE PROCESSING OF VISUAL FEEDBACK IN THE CONTROL OF MOVEMENT AMPLITUDE.

It is commonly accepted that the availability of visual feedback improves movement accuracy provided that movement durations are long enough to encompass visuomotor delays. However, researchers have also acknowledged that the benefit of vision may not solely be due to online processing of visual feedback whereby adjustments to the trajectory occur during movement execution. It is possible that visual feedback from a completed movement is processed offline as an enriched form of knowledge of results (KR) to adjust movement programming on subsequent movements (Abahnini et al., 1997; Blouin et al., 1993; Zelaznik et al., 1983). These 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.

In the past, the utilisation of vision during movement execution has been inferred from the presence of discrete adjustments in the movement trajectory. However, if vision is continuous rather than intermittent in nature as suggested by Elliott and colleagues (Elliott et al., 1991, 1995, 1999) then the use of vision during movement execution will not be reflected in discrete corrections to kinematic profiles. Given this potential problem with inferring the utilisation of vision from discrete corrections, the variability of movement trajectories are analysed in the present experiment to investigate the relative contributions of online and offline visual feedback processing. Specifically, this entails calculating the within participant standard deviations in the distance travelled at several kinematic markers (e.g., peak acceleration, peak velocity and peak negative acceleration). The rationale here is that errors which occur early in the movement would be magnified as the movement progresses. Therefore, if movements are programmed and not altered online, variability should increase according to some function as the movement progresses. If compensations for variations in the limb trajectory are made online, then variability profiles would deviate in form (i.e. more than a multiplication of a scalar factor) from those that describe movement which is programmed in advance and not modulated online.

The present experiment adopted a paradigm that was originally developed by Woodworth (1899) and subsequently used by numerous other investigators to investigate the duration of visuomotor delays (Keele & Posner, 1968; Zelaznik et al., 1983). Participants performed manual aiming movements under full and no vision conditions over a range of different movement times. The proposal was that visual feedback would have an influence on performance when movement times are long enough to encompass visuomotor delays. However, it is possible that at short movement times, visual feedback may have an influence that is due to offline processing. It should be emphasized that the goal of the current experiment was not to provide an estimate of visual feedback processing time. This has been shown to be dependent on a number of factors such as the task that is used and the certainty of the feedback condition (see Carlton, 1992, for a review). The aim was to establish the presence of online and offline processing of visual feedback through the analysis of movement variability throughout the movement. It was expected that at short movement times, significant differences in spatial variability profiles would exist between vision and no vision conditions. If these differences are due only to offline processing, the form of the variability profile would be similar for both visual conditions. The minimum movement time at which the variability profiles for the full and no vision conditions deviate by more than a scalar multiple would indicate the presence of online processing.

In order to complement the analysis of spatial variability, the distance travelled at both peak acceleration and peak velocity was correlated with the distance at the end of the movement. The rationale here was that if variability at the end of the movement is determined by planning processes, the proportion of the variance at the end of the movement that is explained by variability at early kinematic markers (i.e., coefficient of determination, r^2) will be high (Gordon & Ghez, 1987; Messier & Kalaska, 1999; also see Carlton et al., 1984 and Elliott et al, 1999, for similar analyses). If adjustments are made online, then the extent to which variability at the end of the movement is determined by variability earlier in the movement will be low. Therefore, if visual feedback is used offline to improve movement planning, it was expected that there would be variability differences between visual conditions but the proportion of the variance in the variability at the end of the movement that is explained by variability earlier in the movement would not differ between visual conditions. Lower coefficients of determination between the distance travelled early in the movement and at the end of the movement in the vision compared to no vision condition would reveal that visually based adjustments occurred during movement execution.

4.1. Method

Participants. Twenty four self declared, right hand dominant, university students served as participants in the study (16 males, 8 females, ages 18-35 yrs). All were naive to the hypothesis being tested and inexperienced at the experimental task. Participants gave their informed consent prior to taking part and the experiment was carried out according to the ethical guidelines laid down by the Ethics Committee of the School of Sport, Health and Exercise Sciences, University of Wales, Bangor for research involving human participants.

Apparatus. The aiming movements were performed with a pen on a SummaSketch III Professional digitizing tablet (size = 45 x 31 cm, sample rate = 120 Hz, accuracy = ± .02 mm) positioned horizontally in front of the participants. Movements were performed with the right hand in the left to right direction along a track way. The position of the pen was illustrated by a round cursor .5 cm in diameter on a Dell Trinitron 19" monitor located 33 cm in front of the participants and 30 cm above the tablet. There was a one to one mapping between the movement of the pen and the movement of the cursor. The home position and target were presented on the monitor and were located 12 cm to left and right of the participants' midline, respectively. Both consisted of vertical bars 2 cm in height and .2 cm in width. The distance of 24 cm between the home and target markers yielded a visual angle of 40 degrees. The participants' chair and chin rest were adjustable in height so that the participants' eyes were at the same level as the home and target markers. The arm and hand were hidden from the participants' view by an opaque shield thus preventing vision of the arm at all times.

Task and Procedure. At the beginning of each trial, the home and target positions and the cursor representing the position of the pen appeared on the monitor. Participants were required to place the cursor on the home position and then fixate on the target. A tone was then presented. Participants were required to move from the home position to the target as smoothly as possible and come to a complete stop[8]. It was explained to participants that RT was not important. Each participant performed the task under two visual conditions (full vision [FV], no vision [NV]) and four movement times (225, 300, 375, 450 msec). In the full vision condition, the cursor was visible throughout the movement. In the no vision condition, the cursor disappeared as soon as it left the home position and did not reappear until it was time to get ready for the next trial. The home and target markers were visible throughout the trial in both visual conditions. For each movement time, participants performed one block of trials under the full vision condition and one block under the no vision condition. Half of the participants performed the full vision condition first while the order was reversed for the other participants. The four movement time conditions were counterbalanced across participants. Each block of trials consisted of 25 trials giving a total of 200 trials per participant. Knowledge of results regarding accuracy (constant error) and movement time were presented on the monitor after each trial. At the beginning of each block of trials, participants were given approximately ten to fifteen practice trials to familiarise themselves with the movement time requirements. Only those trials that were within ±10% of the criterion movement time were accepted for analysis[9].

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[8] The requirement to move as smooth as possible was to minimise the occurrence of discrete modifications in the kinematic profiles. Also, Khan et al. (2002) have shown that for aiming movements in which participants are instructed to minimise movement time, peak negative acceleration is reached earlier in the vision compared to no vision condition. Since this difference in time to peak negative acceleration would have an influence on variability profiles, it was important that participants did not modify their control strategy depending on whether or not visual feedback was available.

[9] Three participants were replaced on the basis that more than 10% of their movement times in any one condition fell outside the criterion bandwidth. All other participants had 22 to 25 acceptable trials in each condition.

Data Reduction, Dependent Measures and Analyses. The displacement data for each trial were filtered using a second-order dual-pass Butterworth filter with a low-pass cut-off frequency of 10 Hz. Instantaneous velocity data were obtained by differentiating the displacement data using a two-point central finite difference algorithm. This process was repeated to obtain acceleration data. In order to locate the beginning of the movement, peak velocity was first obtained. The velocity profile was then traversed backwards in time until the velocity fell below 1 cm/sec. The end of the movement was defined as the first point in time following peak velocity in which the absolute velocity of the pen fell below 1 cm/sec. This criteria for the end of the movement meant that trajectories could not contain a reversal in direction.

Dependent measures included the time and distance travelled at peak acceleration, peak velocity, peak negative acceleration and at the end of the movement. In order to investigate spatial variability throughout the movement the within participants standard deviation in distance travelled at peak acceleration, peak velocity, peak negative acceleration and at the end of the movement were calculated. Also recorded, were any discontinuities in the acceleration trace such as negative to positive zero line crossings and significant deviations (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 40 msec of the relative minimum (see Chua & Elliott, 1993).

4.2. Results

Discrete Discontinuities in the Kinematic Profile

Examination of the acceleration profiles revealed that there were no zero line crossings or significant deviations in the 225 and 300 msec conditions. Also, there were no zero line crossings at any of the movement times. A 2 visual condition (FV, NV) x 2 movement time (375, 450) repeated measures ANOVA performed on the percentage of movements that contained a significant deviation in acceleration revealed a main effect for movement time, F (1, 23) = 33.1, $p < .001$ (FV375 = 2%, NV375 = 1%, FV450 = 8%, NV450 = 7%). No other effects were significant ($p > .3$). Since we were primarily interested in visual feedback processing that was not associated with discrete modifications in the kinematic profiles, movements that did contain significant deviations were removed from the following analyses.

Means of Movement Time and Distance Travelled

The mean movement time and distance travelled at the kinematic markers and at the end of the movement were analysed using separate 2 visual conditions (full vision, no vision) x 4 criterion MT (225, 300, 375, 450 msec) x 4 kinematic markers (peak acceleration, peak velocity, peak negative acceleration, movement end) repeated measures ANOVAs. The analysis of movement times revealed significant main effects of criterion MT, F (3, 69) = 1479.7, $p < .001$, kinematic marker, F (3, 69) = 6656.9, $p < .01$, and an interaction between criterion MT and kinematic marker, F (9, 207) = 93.5, $p < .001$. As expected, movement times increased as criterion MT increased and movement times to each kinematic marker increased as the movement progressed. The increase in movement times as the movement progressed was greater for longer criterion MTs. There were no significant effects of visual condition ($p > .05$). Hence, there were no differences in movement time between visual conditions at any of the kinematic markers.

The analysis of the distance travelled at each kinematic marker revealed a significant main effect of kinematic marker, $F\ (3, 69) = 21021.1, p < .001$ and an interaction between criterion MT and kinematic marker, $F\ (9, 207) = 3.3, p < .01$. Breakdown of this interaction using Tukey HSD ($p < .05$) revealed that the distance travelled at peak acceleration was greater in the 225 msec compared to 450 msec condition (see Table 2). No other effects were significant ($p > .05$).

		Movement Time (msec)			
Dependent Measure	Visual Condition	225	300	375	450
TPKA (msec)	FV	62 *6*	76 *13*	86 *18*	96 *23*
	NV	62 *7*	74 *10*	84 *18*	96 *20*
TPKV (msec)	FV	119 *9*	153*12*	185 *17*	222 *20*
	NV	118 *9*	150 *11*	185 *16*	224 *21*
TPKNA (msec)	FV	178 *10*	225 *12*	280 *19*	343 *25*
	NV	175 *10*	222 *12*	282 *18*	344 *19*
MT (msec)	FV	234 *5*	302 *9*	371 *7*	446 *8*
	NV	234 *6*	305 *9*	374 *6*	446 *12*
DPKA (mm)	FV	24.8 *3.6*	24.2 *5.6*	21.9 *7.1*	19.9 *7.3*
	NV	24.8 *3.2*	23.2 *4.1*	20.9 *6.6*	19.8 *6.6*
DPKV (mm)	FV	121.5 *6.7*	122.5 *5.2*	120.8 *6.9*	119.3 *7.1*
	NV	121.6 *7.2*	121.4 *5.6*	120.9 *6.6*	121.2 *9.7*
DPKNA (mm)	FV	219.0 *7.9*	216.3 *5.3*	216.5 *7.6*	216.8 *6.6*
	NV	219.1 *9.2*	215.2 *6.4*	218.5 *6.6*	217.9 *8.9*
DEND (mm)	FV	240.8 *5.9*	240.9 *4.7*	241.7 *4.2*	239.6 *3.1*
	NV	242.3 *8.1*	241.9 *5.9*	243.7 *8.9*	241.3 *8.3*

Table 2. Mean, *standard deviation*, times to peak acceleration (TPKA), peak velocity (TPKV), peak negative acceleration (TPKNA), end of movement (MT) and distances travelled at peak acceleration (DPKA), peak velocity (DPKV), peak negative acceleration (DPKNA), end of movement (DEND) as a function of visual condition and criterion MT.

Spatial Variability

The variability in the distance travelled at the various kinematic markers and at the end of the movement were analysed by performing a 2 visual conditions x 4 criterion MTs x 4 kinematic markers repeated measures ANOVA. This analysis revealed significant main effects for visual condition, $F\ (1, 23) = 133.7, p < .001$, criterion MT, $F\ (3, 69) = 8.2, p < .001$, and kinematic marker, $F\ (3, 69) = 576.5, p < .001$. There were also significant two-way interactions between visual condition and criterion MT, F (3, 69) = 4.1, $p < .05$, visual condition and kinematic marker, $F\ (3, 69) = 54.0, p < .001$, criterion MT and kinematic marker, $F\ (9, 207) = 24.3, p < .001$, as well as a three-way interaction between visual condition, criterion MT and kinematic marker, $F\ (9, 207) = 2.7, p < .05$.

Breakdown of the three-way interaction revealed that variability was lower in the full vision compared to no vision conditions at peak negative acceleration and the end of the movement at all movement times while there were also significant differences at peak velocity in the 375 and 450 msec conditions (Tukey HSD, $p < .05$) (see Figure 13).

There were also significant increases in variability from peak acceleration to peak velocity and from peak velocity to peak negative acceleration in both visual conditions at each movement time. While there were no differences in variability from peak negative acceleration to the end of the movement for either visual condition in the 225 and 300 msec movement time conditions, there were significant decreases for both visual conditions in the 375 and 450 msec conditions.

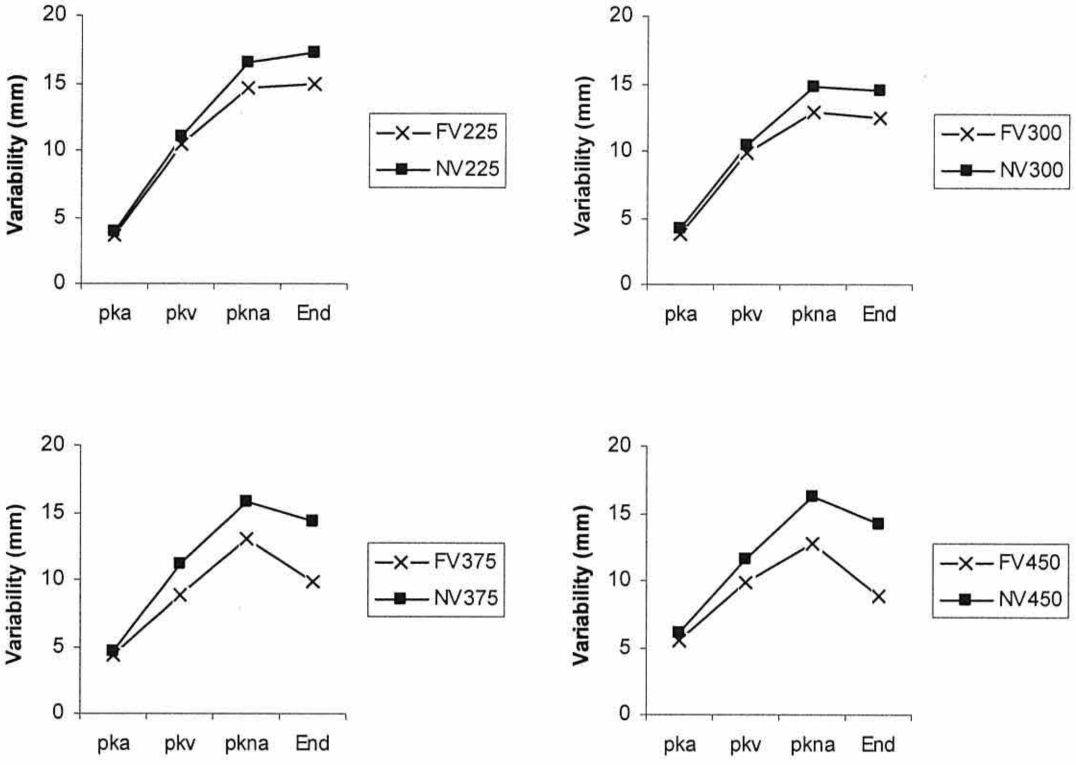

Figure 13. Variability in distance travelled at peak acceleration (PKA), peak velocity (PKV), peak negative acceleration (PKNA) and movement end (END) for the full (FV) and no vision (NV) conditions in the 225, 300, 375, 450 msec movement time conditions.

In order to assess whether the form of the variability profiles differed between the visual conditions, the ratio in spatial variability between the full and no vision conditions at each kinematic marker was calculated for each participant. These ratios were then submitted to a 4 criterion MT x 4 kinematic marker repeated measures ANOVA. This analysis revealed significant main effects of criterion MT, F (3, 66) = 3.4, $p < .05$, and kinematic marker, F (3, 66) = 21.1, $p < .001$, as well as a significant interaction between criterion MT and kinematic marker, F (9, 198) = 2.8, $p < .05$. A breakdown of this interaction revealed that there was no difference in variability ratios between kinematic markers in the 225 and 300 msec conditions (Tukey HSD, $p < .05$) (see Figure 14).

Hence, there was no effect of visual feedback on the form of the variability profiles at these movement times. However, in the 375 msec condition, there was a reduction in the variability ratio from peak acceleration to the end of the movement. Also, in the 450 msec condition, the variability ratio was significantly smaller at the end of the movement compared to peak acceleration, peak velocity and peak negative acceleration. Therefore, the decrease in spatial variability that was observed from peak negative acceleration to the end of the movement in the 375 and 450 msec conditions was proportionally greater in the full than no vision condition resulting in significant differences in the form of the variability profiles.

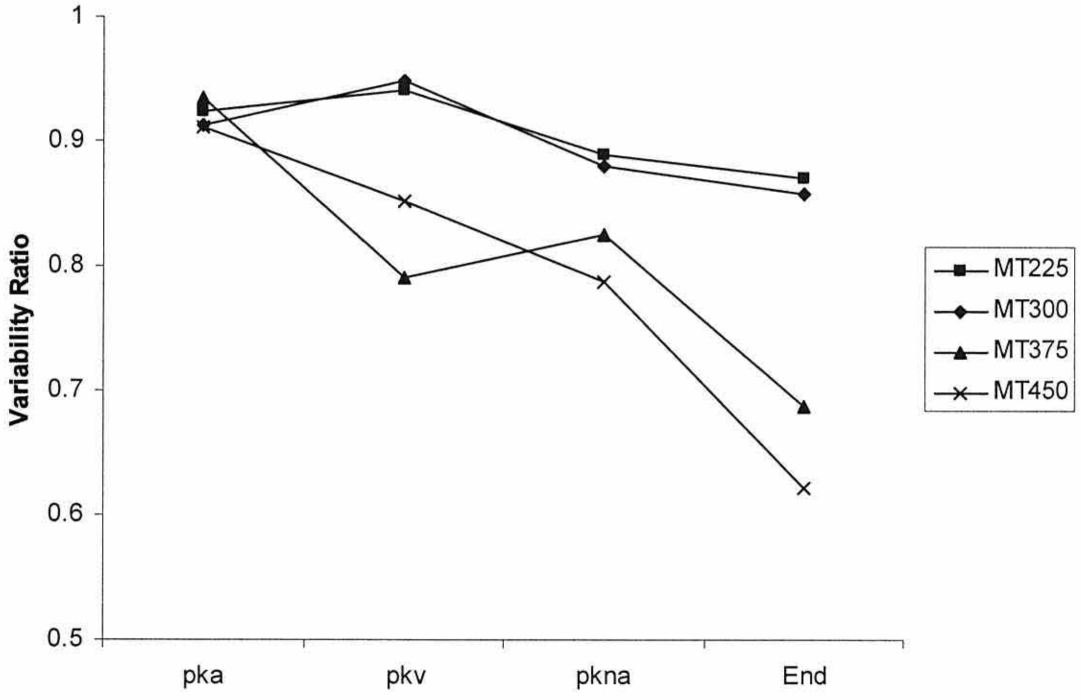

Figure 14. Ratios in variability between the full and no vision conditions at peak acceleration (PKA), peak velocity (PKV), peak negative acceleration (PKNA) and movement end (END) in the 225, 300, 375, 450 msec movement time conditions.

Correlations Between Kinematic Markers and Movement Outcome

The squared within-participant correlation coefficients (r^2) between the distance travelled at peak velocity and the end of the movement are presented in Table 3[10]. Since the number of subjects was equal to 24 and the alpha level was set at .05, any r^2 above .381 was classified as significant (Person and Hartley, 1966). A two visual condition x 4 criterion MT repeated measures ANOVA performed on the squared Fischer Z transformations of the correlation coefficients[11] revealed significant main effects of visual condition, $F(1, 23) = 11.9, p < .01$, criterion MT, $F(3, 69) = 31.3, p < .001$, as well as an interaction between visual condition and criterion MT, $F(3, 69) = 2.9, p < .05$. The proportion of the variance in movement distance explained by the distance travelled at peak velocity was greater in the 225 and 300 msec conditions compared to the 375 and 450 msec conditions (Tukey HSD, $p < .05$). Also, while there were no differences between visual conditions in the 225 and 300 msec conditions, the proportion of the variance in movement distance accounted for by the distance travelled at peak velocity was lower in the full vision compared to no vision condition in the 375 and 450 msec conditions.

Since examination of the variability profiles revealed that variability increased up to peak negative acceleration in all conditions, the relation between the distance travelled at peak negative acceleration and the distance at the end of the movement was also analysed. Examination of mean squared correlation coefficients in Table 3 indicates that the proportion of the variance in movement distance explained by the distance travelled at peak negative acceleration was greater than that accounted for by the distance at peak

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[10] Correlation coefficients (r) were positive for all participants

[11] Fischer Z transformations were performed since correlation coefficients are not normally distributed

velocity. Similar to the analysis of the squared Fischer Z correlations between distance at peak velocity and movement distance, squared Fischer Z correlations between the distance travelled at peak negative acceleration and movement distance were lower in the 375 and 450 msec conditions compared to the 225 and 300 msec conditions, $F(3, 69) = 54.4, p < .01$ (Tukey HSD, $p < .05$). Also, while there were no differences between visual conditions in the 225 and 300 conditions, the proportion of the variance in movement distance explained by the distance travelled at peak negative acceleration was lower in the full vision compared to no vision condition in both the 375 and 450 msec conditions, $F(3, 69) = 6.3, p < .05$ (Tukey HSD, $p < .05$).

Dependent Measure	Visual Condition	Movement Time (msec)							
		225		300		375		450	
		r^2	Z^2	r^2	Z^2	r^2	Z^2	r^2	Z^2
DPKV (mm)	FV	.62	1.04	.52	.90	.40	.74	.25	.54
		.16	*.42*	*.16*	*.92*	*.19*	*.46*	*.13*	*.37*
	NV	.60	1.02	.57	.97	.51	.89	.37	.70
		.18	*.44*	*.15*	*.40*	*.18*	*.44*	*.19*	*.46*
DPKNA (mm)	FV	.91	1.83	.83	1.52	.56	.96	.48	.84
		.06	*.25*	*.13*	*.37*	*.19*	*.46*	*.22*	*.51*
	NV	.90	1.83	.84	1.55	.68	1.17	.62	1.04
		.08	*.28*	*.09*	*.31*	*.22*	*.51*	*.17*	*.43*

Table 3. Mean, *standard deviation*, squared correlation coefficients (r^2) and the square of the Fischer Z transformations (Z^2) between the distance at peak velocity (DPKV) and the distance at the end of the movement and between the distance at peak negative acceleration (DPKNA) and the distance at the end of the movement as a function of visual condition and criterion MT.

4.3. Discussion

It has been well documented that visual feedback improves movement accuracy and researchers have typically attributed this finding to the role of visual feedback in correcting errors in the limb trajectory during movement execution. However, an alternative explanation is that visual feedback is processed after movement execution and utilised to improve programming on subsequent actions. The issue of whether visual feedback is processed online or offline has important implications for the underlying assumptions of numerous models of limb control regarding the relative contributions of central planning and sensory information processing in the control of human movement (e.g., Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Plamondon & Alimi, 1997). The present study analysed spatial variability at various stages throughout the movement to establish the potential contributions of online and offline processing of visual feedback. It was reasoned that evidence for offline processing of visual feedback would be gained if variability was lower in the full vision than in the no vision condition, but the form of the variability profiles did not differ between the visual conditions. The presence of online processing of visual feedback would be inferred only if there was a significant change in the form of the variability profiles between visual conditions.

Consistent with past research, differences in endpoint variability between visual conditions decreased as movement time decreased (Keele & Posner, 1968; Woodworth, 1899, Zelaznik et al., 1983). However, significant differences between visual conditions were still present at movement times of 225 and 300 msec. Although differences in endpoint accuracy between visual conditions at these relatively fast movement times have been attributed to online control in the past, the analysis of movement variability in the present study suggests that the benefit of vision was due to offline processing. The variability profiles for the two visual conditions deviated from each other, but the ratios in spatial variability between the visual conditions remained constant between the kinematic markers. Hence, the variability profiles had the same form and did not differ by more than multiplication of a scalar factor. In addition, the results of the correlation analysis revealed that proportion of variance in movement distance explained by the distance travelled at peak velocity and peak negative acceleration did not differ between the visual conditions. Therefore, the extent to which endpoint accuracy was determined by earlier kinematics was similar under both visual conditions. These findings suggest that differences in variability profiles between visual conditions were not due to processes occurring during the course of the movement but point rather to processes occurring outside of movement execution. It is believed that at these faster movement times, participants used visual information about the trajectory of the limb and the outcome of a completed movement as an enriched form of KR to improve planning on subsequent trials.

It should be noted that although online control was not evident in the 225 and 300 msec conditions, this does not challenge the minimum delays of visuomotor processing reported in other studies. It is well documented that the duration of visuomotor loops, which have been shown to be as fast as 100 msec, depend on the task that is used (Carlton, 1992). In the present study, participants viewed a relatively small cursor on a computer monitor that had a limited refresh rate (85 Hz). Also, the dissociation between visual information on the monitor and actual limb position may have caused the processing of visual feedback to be less efficient compared to when viewing the limb directly as in a conventional aiming task. Nonetheless, with regards to the goal of the present study, the analysis of spatial variability indicated that vision had an impact at fast movement times that was due only to offline processing.

In the 375 and 450 msec conditions, there were decreases in variability from peak negative acceleration to the end of the movement in both visual conditions. However, the proportional decrease was greater in the full vision compared to no vision condition. Hence, variability profiles differed by more than a scalar multiple suggesting that visually based modifications were made during movement execution in the full vision condition. Also, the proportion of the variance in movement distance explained by the distance travelled at peak velocity and peak negative acceleration was lower in the 375 and 450 msec compared to the 225 and 300 msec conditions. It seems that early kinematic variables become a poor predictor of movement outcome at longer movement times where modifications to the movement trajectory can take place (also see Carlton et al., 1984). More importantly, the distance travelled at peak velocity and peak negative acceleration were poorer predictors of endpoint error in the vision compared to no vision condition. This suggests that the degree to which participants modified their limb trajectories to compensate for early variations was greater when visual feedback was available.

It is possible that the decrease in variability towards the end of the movement in the no vision condition was due to the processing of proprioceptive feedback. In the present study, all movements were performed to one target and were constrained in a single dimension. Hence, the processing of proprioceptive feedback may have been enhanced due to the relatively simple nature of the task. Also, it is possible that since participants performed the task in both vision and no vision conditions, visual information was used to calibrate proprioceptive or efference copy stores which then provided the basis upon which online adjustments were made. Visual feedback conveys real time (dynamic) information about the movement trajectory and may provide a basis upon which intrinsic information stores can be accurately calibrated (Ghez, Gordon, Ghilardi, & Sainburg, 1995; Hale, Hodges, Khan, & Franks, 1999; Proteau & Marteniuk, 1993). However, this interpretation should be considered with some degree of caution since it has also been suggested that when visual feedback is available, the processing of this information dominates and therefore prevents the processing of other sources of sensory information (Posner, Nissen, Klein, 1976; Tremblay & Proteau, 1998).

Based on the assumption that visual feedback processing is intermittent in nature, the presence of online control has typically been inferred from the presence of discontinuities in the movement trajectory (see Elliott et al., 2001). The identification of discrete adjustments in kinematic profiles to distinguish sensory based error corrections from ballistic phases of movement has been the basis for some of the most influential models on speed-accuracy tradeoffs (Crossman & Goodeve, 1983; Meyer et al., 1988). In the present study, participants were instructed to produce smooth movements to the target. Consistent with this requirement, over 90% of all movements did not contain discontinuities in acceleration. The analysis of spatial variability on trials which did not contain discontinuities revealed that visual feedback was processed online in the 375 and 450 msec conditions. Therefore, consistent with recent findings in the literature, visual feedback had an effect on movement control in the absence of any discrete adjustments in the kinematic profiles (Elliott et al, 1999; Khan et al., 1998; Proteau & Masson, 1997). This suggests that visual control is continuous rather than intermittent in nature whereby visually based corrections are not susceptible to refractoriness during ballistic phases of movement (Elliott et al., 1995; Pélisson, Prablanc, Goodale, & Jeanerod, 1986).

In summary, the analysis of spatial variability was a viable method to establish the relative roles of offline and online processing of visual feedback. The results indicated that at fast movement times, variability profiles were influenced by the availability of visual feedback but the form of these profiles was not affected. Hence, there was a benefit of vision at the fast movement times but this was due only to offline processing. At longer movement times, the forms of the variability profiles differed significantly between visual conditions with variability in the vision condition decreasing more relative to that of the no vision condition. This suggests that visually based corrections compensated for variations in the movement trajectory during the latter parts of the movement. These online modifications occurred in the absence of any increase in the production of discrete kinematic adjustments suggesting the presence of continuous visual guidance in limb control.

CHAPTER 5

THE UTILISATION OF VISUAL FEEDBACK IN THE CONTROL OF MOVEMENT DIRECTION

In the previous chapter, the analysis of spatial variability to establish online and offline contributions of visual feedback processing was limited to self-terminating movements with a criterion amplitude. In these types of movements, kinematic variables such as peak acceleration and peak velocity can be readily identified. The present experiment, focussed on the role of visual feedback in the control of movement direction. In contrast to amplitude aiming tasks where participants are required to stop on a target, research on direction control has typically involved 'sweeping' like movements in which participants are required to move through the target (Abahnini & Proteau, 1999; Abahnini et al., 1997; Bard et al., 1985; Bard et al., 1990; Blouin et al., 1993; Fleury, Bard, Audiffren, Teasdale, & Blouin, 1994). In directional aiming tasks, the goal is to move towards and follow through past the target in a manner similar to striking a ball. Since kinematic markers are not readily identifiable in these movements, deviations from the longitudinal axis at 25%, 50%, 75% and 100% of the distance from the home position to the target (see Figure 15) were calculated. Spatial variability was then defined as the within-participant standard deviation of these directional errors.

The task used in the present experiment consisted of a video aiming task in which participants performed movements away from the body on a horizontal digitizing tablet that translated to vertical movements of a cursor on a monitor. In previous research using similar types of tasks, it has been shown that directional variability increased as the movement progressed and as movement amplitude increased (Gordon, Ghilardi & Ghez, 1994; Messier & Kalaska, 1997; 1999). However, in these studies, participants did not receive visual feedback during movement execution. The present experiment examined variability profiles for vision and no vision conditions over a range of movement times.

Past research has indicated that differences in endpoint accuracy between vision and no vision conditions increased as movement times increased (Keele & Posner, 1968; Woodworth, 1899; Zelaznik et al., 1983). This finding has been attributed to the utilisation of visual feedback to correct errors in the movement trajectory when movement times are long enough to encompass visuomotor delays. The intention of the current experiment was to investigate the possibility that differences that exist between visual conditions at relatively fast movement times could be due to offline processing. Therefore, it is expected that at the faster movement times, limb trajectories would be more consistent in the vision compared to the no vision conditions but the form of the variability profiles would not be affected. At longer movement times, the variability profiles in the vision condition were expected to deviate in form from the no vision condition indicating that visual feedback was processed online to modify limb trajectories.

Similar to Chapter 4, in order to complement the analysis of spatial variability correlations were calculated between directional error at the target with directional error at 50% of the distance to the target. It was expected that if visual feedback is used offline to improve movement planning, there would be variability differences between visual conditions but the proportion of the variance in directional error at the target that is explained by directional error at 50% of the movement would not differ between visual conditions. Lower coefficients of determination between directional error at 50% and 100% of the movement in the vision compared to no vision would reveal that visually based adjustments occurred during movement execution.

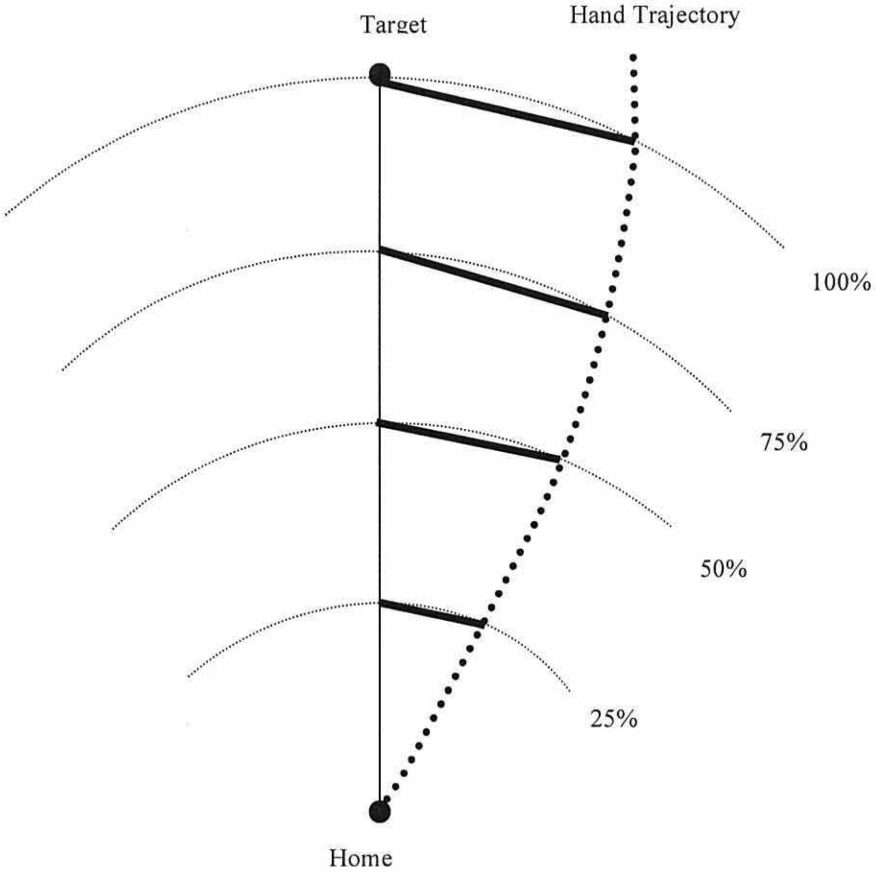

Figure 15. Schematic diagram of a limb trajectory to a target illustrating the calculation of directional errors at 25%, 50%, 75% and 100% of the longitudinal distance to the target.

5.1. Method

Participants. Sixteen self declared, right hand dominant, university students served as participants in the study (ages 18-35 yrs). All were naive to the hypothesis being tested and gave their informed consent prior to taking part in the study. The experiment was carried out according to the ethical guidelines laid down by the Ethics Committee of the School of Sport, Health and Exercise Sciences, University of Wales, Bangor for research involving human participants.

Apparatus. The aiming movements were performed with a pen on a Calcomp III digitising tablet (size =122 x 91.5 cm, sample rate = 200 Hz, accuracy = ± 0.125mm) positioned horizontally in front of the participants. The position of the pen was illustrated by a round cursor 1 cm in diameter on a 37" Mitsubishi Diamond Pro monitor located 33 cm in front of the participants and 20 cm above the tablet. There was a one to one mapping between the movement of the pen and the movement of the cursor. Movements of the pen away from the body on the tablet corresponded to vertical movements of the cursor on the monitor. The home position consisted of a round dot (1 cm in diameter) and was located at the bottom of the monitor. Three circular targets (1 cm in diameter) were located above the home position along an arc of radius of 24 cm. The centre target was located directly above the home position while the other two targets were located 10 degrees to either side of the centre target. The distance of 24 cm between the home and target markers yielded a visual angle of 40 degrees. The participants chair and chin rest were adjustable in height so that the participants' eyes were at a level midway between the home and target markers. The arm and hand were hidden from the participants' view by an opaque shield thus preventing vision of the arm at all times.

Task and Procedure. At the beginning of each trial, the home and target positions and the cursor representing the position of the pen appeared on the monitor. Participants were required to place the cursor on the home position. Once the cursor was steadily aligned, one of the targets changed colour from red to green informing the participants which target to aim for. After a 1500 msec interval a tone was presented. Participants were required to make a sweeping movement from the starting position towards and past the target. Since they were not required to stop on the target, the task had a direction but no amplitude requirement. Participants were told to make their movements as smooth as possible. This was important because past work has shown that when visual feedback was available, participants traversed the early parts of the trajectory quickly and then spent more time in the vicinity of the target to use visual feedback (Elliott et al., 1995; Khan et al., 2002; Khan & Franks, 2000). In the present study, it was preferable that that there were no differences in movement time between visual conditions at any of the longitudinal distances. Hence, any differences in variability between visual conditions could not be attributed to movement time effects. It was also explained to participants that RT was not important.

Each participant performed the task under two visual conditions (full vision [FV], no vision [NV]) and four criterion movement times (150, 250, 350, 450 msec). In the full vision condition, the cursor was visible throughout the movement. In the no vision condition, the cursor disappeared as soon as it left the home position and did not reappear until it was time to get ready for the next trial. The home and target markers were visible throughout the trial in both visual conditions. For each movement time, participants performed one block of trials under the full vision condition and one block under the no vision condition. Half of the participants performed the full vision condition first while the order was reversed for the other participants. The four movement time conditions were counterbalanced across participants. Each block of trials consisted of 30 trials (i.e., 10 to each target) giving a total of 240 trials per participant. Target order was randomized within each block of trials with the restriction that each target occurred before any target was repeated. Knowledge of results regarding directional accuracy (constant error (mm)) and movement time (msec) were presented in numerical form on the monitor for 3 seconds after each trial. At the beginning of each block of trials, participants were given approximately 10 practice trials to familiarise themselves with the movement time requirements. During testing, any trials in which movement times were not within ±10% of the criterion MT were repeated. This amounted to less than five trials in any one block of trials.

Dependent Measures and Analyses. The initiation of movement was defined as the point in time that the cursor moved 1 mm from the home position. The end of the movement was taken as the point at which the trajectory crossed the arc subtended by the three targets.

Our dependent measures were movement time, constant error and variable error at 25%, 50%, 75% and 100% of the longitudinal distance from the home position to the target (i.e., 6, 12, 18, 24 cm). Movement time (msec) at each longitudinal distance was defined as the interval from the start of the movement to when the pen crossed the arc at the respective longitudinal distances (see Figure 15). Constant error (mm) at each longitudinal distance was calculated as the distance from where the arc crossed the longitudinal axis to where the pen trajectory crossed the arc. Movements to the right of the longitudinal axis were recorded as positive while movements to the left were recorded as negative. Variable error (mm) was calculated as the within-participant standard deviation of constant errors and was used as our measure of spatial variability.

Movement times, constant errors and variable errors were submitted to separate 2 Visual Conditions (FV, NV) x 4 Criterion MT (150, 250, 350, 450 msec) x 3 Target (left, middle, right) x 4 Longitudinal Distance (6, 12, 18, 24 cm) repeated measures ANOVAs.

5.2. Results

Means of Movement Time, Constant Error and Variable Error

As would be expected, movement times increased as the Criterion MT increased, $F(3, 45) = 6482.5, p < .001$, and as Longitudinal Distance increased $F(3, 45) = 3960.2, p < .001$ (see Table 4). Also, movements to the left target had longer durations than movements to the right target $F(2, 30) = 26.9, p < .001$ (also see Elliott, Roy, Goodman, Carson, Chua, & Maraj, 1993). There was no effect of Visual Condition on movement times ($p > .05$). Hence, movement times at each longitudinal distance did not differ between visual conditions.

The analysis of constant error revealed a significant three way interaction between Visual Condition, Target, and Longitudinal Distance, $F(18, 270) = 4.9, p < .05$. Consistent with past research, there was a curvature in the trajectories which depended on the location of the target (Prablanc & Martin, 1992). Examination of the means in Table 5 revealed that movements to the left target were biased to the left of the longitudinal axis with this bias increasing as the movement progressed. Also, movements performed in the NV condition were more biased than those in the FV condition. For the middle target, movements tended to the left of the longitudinal axis early in the movement, but were then biased to the right at the end of the movement. This curvature in the trajectories was also apparent for movements to the right target. However, trajectories were more biased to the right of the longitudinal axis, especially in the NV condition.

		Target Location											
MT	Visual Condition	LEFT				MIDDLE				RIGHT			
150		25%	50%	75%	100%	25%	50%	75%	100%	25%	50%	75%	100%
	FV	81	110	135	161	76	104	128	154	74	101	124	149
		8	*9*	*9*	*10*	*6*	*7*	*7*	*7*	*6*	*7*	*7*	*6*
	NV	84	113	137	161	79	107	131	155	79	107	129	153
		8	*8*	*7*	*6*	*8*	*8*	*7*	*6*	*8*	*8*	*7*	*7*
250													
	FV	119	168	211	257	114	162	205	250	113	160	202	246
		12	*12*	*12*	*12*	*11*	*11*	*10*	*9*	*13*	*14*	*12*	*10*
	NV	124	173	216	259	118	167	208	251	116	163	203	244
		10	*10*	*9*	*10*	*10*	*10*	*8*	*8*	*13*	*14*	*13*	*11*
350													
	FV	155	224	287	355	150	220	282	351	148	216	278	346
		14	*14*	*12*	*11*	*12*	*13*	*14*	*15*	*12*	*13*	*12*	*10*
	NV	158	226	287	352	153	222	284	348	153	221	282	344
		13	*14*	*12*	*10*	*10*	*10*	*9*	*9*	*12*	*12*	*10*	*9*
450													
	FV	192	282	364	453	189	280	362	451	188	278	359	446
		14	*13*	*8*	*11*	*15*	*15*	*10*	*10*	*16*	*14*	*10*	*12*
	NV	194	285	367	454	191	281	364	451	189	278	357	444
		13	*13*	*10*	*10*	*16*	*16*	*12*	*13*	*16*	*15*	*11*	*10*

Table 4. Mean, *standard deviation*, movement times at 25%, 50%, 75%, and 100% of the longitudinal distance to the target (i.e., 6, 12, 18 and 24 cm) as a function of visual condition, criterion MT (msec) and target location.

		Target Location											
MT	Visual Condition	LEFT				MIDDLE				RIGHT			
		25%	50%	75%	100%	25%	50%	75%	100%	25%	50%	75%	100%
150	FV	-1.8	-2.7	-3.3	-1.9	-1.3	-1.1	-0.3	1.8	-2.9	-3.9	-3.5	-1.2
		4.2	*6.0*	*5.3*	*6.0*	*3.8*	*5.3*	*4.8*	*4.0*	*3.6*	*5.4*	*5.3*	*4.5*
	NV	-2.7	-4.7	-7.1	-8.3	-1.3	-1.2	-0.7	1.1	-1.1	-1	0.1	2.7
		5.5	*8.2*	*9.5*	*10.4*	*5.0*	*7.7*	*9.2*	*10.2*	*5.2*	*8.7*	*11.0*	*13.1*
250	FV	-0.8	-1.1	-1.2	-1.3	-0.4	-0.8	-0.9	0.1	-1.2	-1.4	-0.8	1.1
		2.5	*3.7*	*3.9*	*4.6*	*2.5*	*4.0*	*4.3*	*3.8*	*3.3*	*5.3*	*6.6*	*6.9*
	NV	-2.1	-3.9	-6.1	-8.1	-0.1	-0.1	0.2	1.6	0.9	2	4.1	7.5
		2.9	*4.9*	*6.6*	*8.3*	*3.2*	*5.1*	*6.4*	*7.6*	*3.5*	*6.8*	*8.8*	*9.9*
350	FV	-0.6	-0.2	-0.8	-1.6	-0.2	0.2	0.1	0.7	-0.8	-0.2	0.7	1.6
		2.1	*3.3*	*3.5*	*3.2*	*1.9*	*3.0*	*3.6*	*3.1*	*2.2*	*3.9*	*4.7*	*5.3*
	NV	-2.1	-3.3	-5.3	-7.2	-0.2	0.4	1.3	3.0	0.8	3.0	6.2	10.4
		2.9	*5.6*	*8.5*	*11.3*	*2.1*	*4.1*	*6.0*	*7.3*	*3.2*	*5.9*	*7.9*	*8.7*
450	FV	-1.1	-1.6	-2.4	-2.9	-0.3	0.2	0.6	1.1	-0.7	-0.3	0.3	1.6
		1.8	*3.9*	*5.5*	*6.0*	*1.8*	*3.1*	*3.9*	*3.5*	*2.6*	*4.9*	*6.8*	*7.8*
	NV	-2.0	-4.2	-7.1	-10.2	0.3	1.5	2.5	4.3	1.9	5.2	9.2	14.7
		2.0	*3.6*	*5.3*	*7.7*	*1.5*	*2.4*	*3.4*	*4.7*	*2.6*	*4.5*	*6.6*	*8.7*

Table 5. Mean, *standard deviation*, constant errors at 25%, 50%, 75%, and 100% of the longitudinal distance to the target (i.e., 6, 12, 18 and 24 cm) as a function of visual condition, criterion MT (msec) and target location.

Directional Variability

As illustrated in Figure 16, there was an overall increase in variability as Longitudinal Distance increased, *F* (3, 45) = 256.8, *p* < .001, with increases in variability being greater in the no vision compared to full vision conditions, *F* (3, 45) = 80.3, *p* < .001. Also, a significant three-way interaction between Visual Condition, Longitudinal Distance and Criterion MT, *F* (9, 135) = 6.9, *p* < .001, revealed that the difference in variability rise rates between visual conditions increased as movement time increased. More specifically, breakdown of this interaction using Tukey HSD (*p* < .05) indicated that movement time had no effect on variability in the no vision condition while there was a decrease in variability as movement time increased in the vision condition. In the 150 msec condition, there were significant differences in variability between visual conditions at longitudinal distances of 18 and 24 cm, while there were also significant differences between visual conditions when the longitudinal distance was 12 cm in the 250, 350 and 450 msec conditions. Trend analyses revealed that variability increased linearly in both visual conditions in the 150 and 250 msec conditions ($p < .05$). In the 350 and 450 msec conditions, there were linear increases in variability in the no vision conditions ($p < .05$). In the full vision conditions, both linear and quadratic components were significant as variability increased up to a longitudinal distance of 18 cm and then levelled off ($p < .05$).

A three-way interaction between Visual Condition, Longitudinal Distance and Target, $F(6, 90) = 5.1, p < .01$, revealed that the difference in variability rise rates between visual conditions was smaller for movements made to the middle target compared to the left and right targets. For movements to the middle target, spatial variability increased to 6.7 mm in the vision condition and 9.6 mm in the no vision condition. In the left and right target conditions, variability increased on average to 7.9 mm in the vision condition and 12.4 mm in the no vision condition.

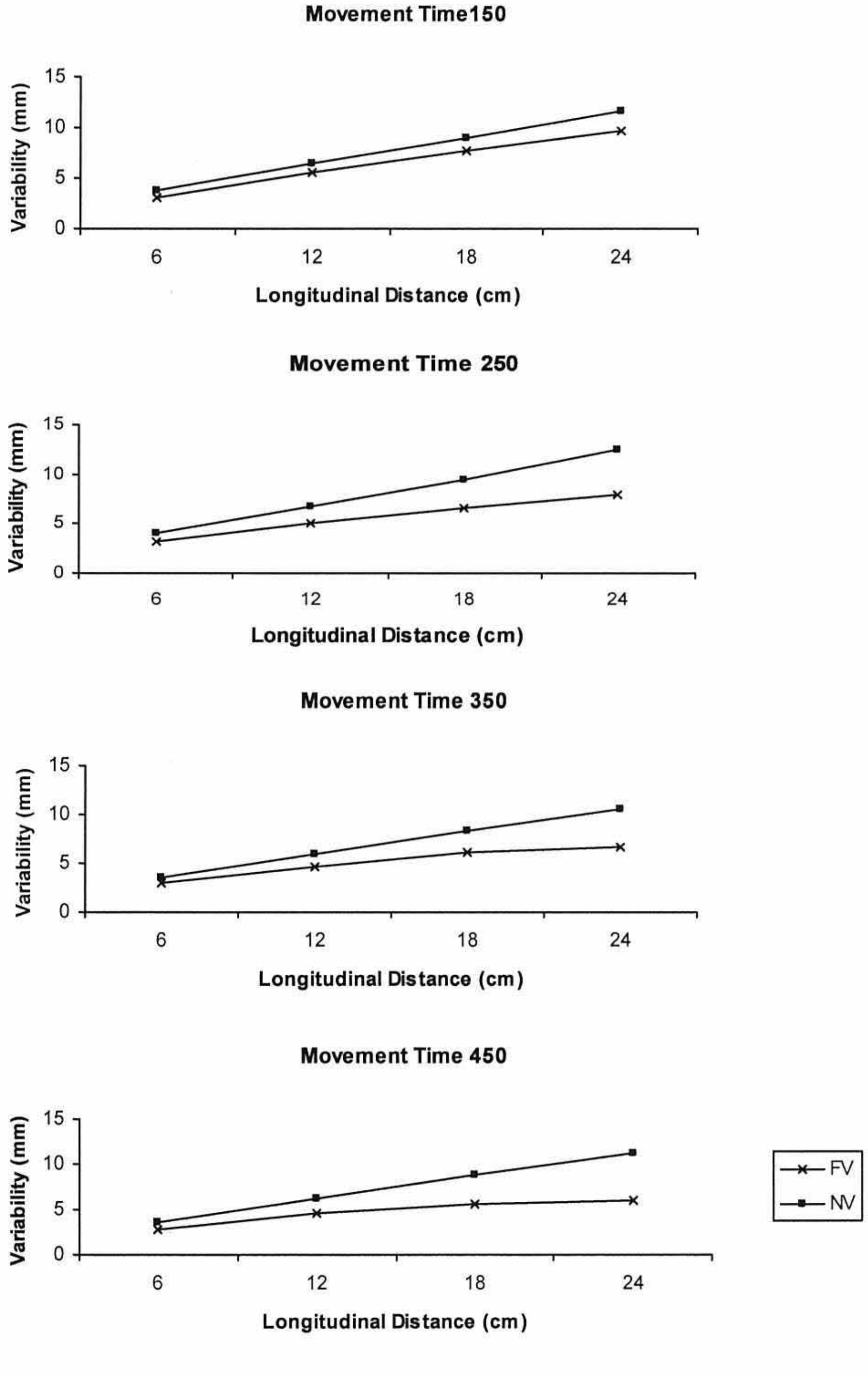

Figure 16. Variability in direction at longitudinal distances of 6, 12, 18, and 24 cm for the full (FV) and no vision (NV) conditions in the 150, 250, 350, and 450 msec movement time conditions.

In order to assess whether variability functions in the two visual conditions differed in form, the ratio in variability between the full and no vision conditions at longitudinal distances of 6, 12, 18 and 24 cm were calculated. These ratios were then submitted to a 4 Criterion MT (150, 250, 350, 450 msec) x 3 Target (left, middle, right) x 4 Longitudinal Distance (6, 12, 18, 24 cm) repeated measures ANOVA. This analysis revealed a significant interaction between Criterion MT and Longitudinal Distance, *F* (9, 135) = 6.8, $p < .001$ (see Figure 17). Breakdown of this interaction revealed that the ratio in variability between the vision and no vision conditions did not vary as the movement progressed in the 150 msec condition. However, there was a significant decrease in the variability ratio between the full and no vision conditions in the 250, 350 and 450 msec conditions. Tukey HSD ($p < .05$) post hoc tests revealed that in each of these movement time conditions, there was a significant decrease in the variability ratio between longitudinal distances of 6 and 18 cm and between 12 and 24 cm while there was also a significant decrease between 6 and 12 cm in the 350 msec condition.

Correlation of Directional Errors

The squared correlation coefficients as well as the square of the Fischer Z transforms of the correlation coefficients between directional errors at longitudinal distances of 12 and 24 cm are reported in Table 6. Since the number of subjects was equal to 16 and the alpha level was set at .05, any r^2 above .497 was classified as significant (Person and Hartley, 1966). A 2 Visual Condition (FV, NV) x 4 Criterion MT (150, 250, 350, 450 msec) x 3 Target (left, middle, right) repeated measures ANOVA performed on the squared Fischer Z transforms revealed significant main effects of

Visual Condition, $F(1, 15) = 86.1, p < .001$, and Criterion MT, $F(3, 45) = 4.8, p < .01$, as well as a significant interaction between Visual Condition and Criterion MT, $F(3, 45) = 11.1, p < .001$. Breakdown of this interaction using Tukey HSD ($p < .05$) revealed that the proportion of the variance in directional error at 24 cm explained by directional error at 12 cm did not differ between visual conditions in the 150 msec condition. However, the extent to which error at 24 cm was determined by error at 12 cm was less in the vision compared to no vision condition in the 250, 350 and 450 msec conditions.

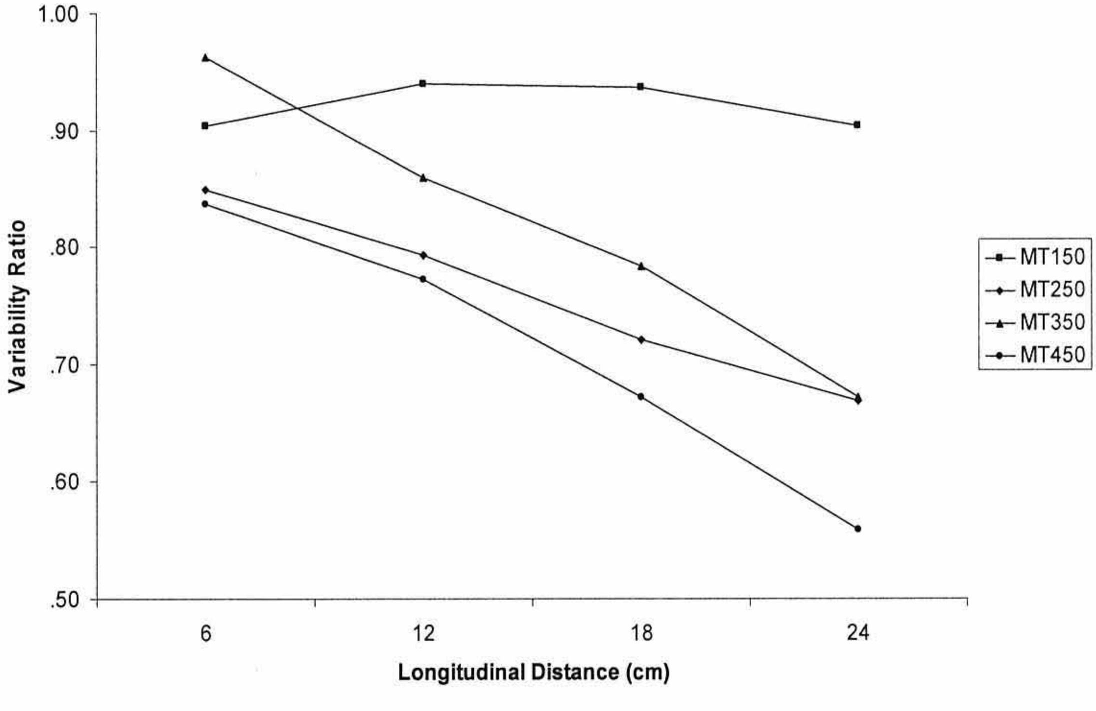

Figure 17. Ratios in variability between the full and no vision conditions at longitudinal distances of 6, 12, 18, and 24 cm in the 150, 250, 350, and 450 msec movement time conditions.

MT	Visual Condition	Target Location					
		LEFT		MIDDLE		RIGHT	
		r^2	Z^2	r^2	Z^2	r^2	Z^2
150	FV	0.83	3.22	0.77	2.32	0.85	3.12
		0.11	*2.13*	*0.17*	*1.18*	*0.10*	*1.57*
	NV	0.82	2.78	0.78	2.30	0.86	3.51
		0.12	*1.52*	*0.18*	*0.97*	*0.12*	*1.76*
250	FV	0.71	1.77	0.68	1.66	0.72	1.94
		0.16	*0.86*	*0.22*	*1.09*	*0.17*	*1.12*
	NV	0.89	3.65	0.83	2.85	0.91	3.86
		0.06	*1.61*	*0.11*	*1.33*	*0.06*	*1.29*
350	FV	0.66	2.25	0.60	1.43	0.59	1.4
		0.27	*2.16*	*0.23*	*1.08*	*0.27*	*0.97*
	NV	0.78	2.53	0.76	2.49	0.83	3.17
		0.18	*1.27*	*0.17*	*1.66*	*0.16*	*1.73*
450	FV	0.47	0.93	0.57	1.47	0.60	1.28
		0.25	*0.75*	*0.30*	*1.24*	*0.22*	*0.87*
	NV	0.84	3.06	0.75	2.58	0.84	3.07
		0.11	*1.64*	*0.20*	*1.35*	*0.09*	*1.61*

Table 6. Mean, *standard deviation*, squared correlation coefficients (r^2) and the squares of the Fischer Z transforms (Z^2) of the correlation coefficients between constant error at 50 % (i.e., 12 cm) and 100 % (i.e., 24 cm) of the longitudinal distance to the target as a function of visual condition, criterion MT (msec) and target location.

5.3. Discussion

An important issue regarding the control of goal directed movements is the extent to which accuracy is determined by planning processes prior to movement initiation versus online adaptations to the limb trajectory. In past work, researchers have examined the curvature of trajectories to determine the extent to which trajectories are modified during movement execution (e.g., Bedard & Proteau, 2001). However, it is often difficult to distinguish whether curved trajectories are the result of online adjustments or directional differences in limb inertia (Ghez, Gordon, Ghilardi, & Sainburg, 1995). The present study analysed the variability in limb trajectories at various stages throughout the movement in order to determine the contributions of online and offline processing of visual feedback. The rationale was that evidence for offline processing of visual feedback would be gained if directional variability is lower in the vision compared to no vision condition but the form of the variability profiles does not differ between visual conditions. Differences in the form of the variability profiles would imply that directional accuracy at the end of the movement was a consequence of compensatory adjustments that occurred during movement execution.

Examination of the variability profiles revealed that directional variability increased linearly throughout the movement in the no vision conditions. Also, correlations between directional error at 50 % of the longitudinal distance to the target and directional error at the target revealed that a high proportion of the variance (i.e., 82%) in directional error at the target was explained by error at 50% of the movement. Therefore, it seems that directional error in the no vision conditions was determined primarily by planning processes. In contrast to the no vision conditions, variability increased linearly throughout the movement in the full vision condition when movement times were relatively short whereas variability levelled off by 75% of the distance to the target in the longer movement time conditions. Also, the extent to which the variance in directional error at the target was explained by directional error at 50% of the distance to the target decreased as movement time increased (i.e., from 82% in the 150 msec condition to 55% in the 450 msec condition). This suggests that when movement times were relatively long, directional accuracy was determined by processes other than movement planning.

Comparison of the variability profiles between visual conditions in the 150 msec condition revealed that variability was lower in the full vision compared to no vision condition. However, analysis of the ratios in variability between the full and no vision conditions revealed that the form of the variability profiles was similar under both visual conditions. Also, although there were differences in directional variability between visual conditions, the proportion of the variance in directional error at the target that was explained by directional error at 50% of the longitudinal distance did not differ between visual conditions. Hence, the greater consistency in directional accuracy in the full compared to no vision condition was not due to processes that occurred during movement execution. It is believed that in the 150 msec condition, participants used visual information from a completed movement to enhance the planning of subsequent movements. The use of visual information as a form of knowledge of results implies that visual feedback can have an effect on movement accuracy at movement times which may be too short to incorporate visuomotor delays.

Although there was no evidence for online processing of visual feedback in the 150 msec condition, other researchers have shown that visual feedback can be processed with lag times as short as 100 msec (Carlton, 1992). The task used in the present study involved a translation between movement of the limb in the horizontal plane to movement of a cursor in the vertical plane. The complexity of the sensorimotor transformations imposed by this dissociation would likely have involved visuomotor loops with longer lag times compared to conventional aiming tasks where visual information is gained directly from the limb (also see Messier & Kalaska, 1997).

In contrast to the variability profiles in the 150 msec condition, there was a significant reduction in the variability ratio between full and no vision conditions in the 250, 350, and 450 msec conditions. Hence, the form of the variability profiles in the full vision conditions deviated from that in the no vision conditions. Also, the proportion of the variance in directional error at the target that was explained by directional error at 50% of the longitudinal distance to the target was lower in the full compared to no vision condition. This implies that the extent to which directional accuracy was determined by planning processes was less when participants received visual feedback compared to when they did not. It appears that at these longer movement times, visually based adjustments occurred during movement execution to compensate for variations in the early part of trajectory.

In the previous Chapter, in which the control of an amplitude aiming task was examined, variability increased up to peak negative acceleration (i.e., at approximately 75% of the movement amplitude) and then decreased towards the end of the movement when movement times were relatively long. Also, while there was no change in the variability ratio between the full and no vision conditions up to peak negative acceleration, there was a significant reduction from peak negative acceleration to the end of the movement. In the present study, there were significant reductions in the variability ratio between full and no vision conditions by 50% and 75% of the distance to the target. Hence, corrections to the trajectory occurred earlier in the control of direction compared to movement amplitude. This is consistent with proposals made by Paillard and Amblard

(1985) that information relevant to the control of direction is processed primarily from peripheral vision while central vision is more critical for the control of movement amplitude.

In summary, the comparison of variability profiles between the full and no vision conditions revealed that visual feedback was used in the planning of upcoming movements and to compensate for directional errors during the course of movement execution. At shorter movement times, variability was lower in the full compared to no vision conditions, but the form of the variability profiles did not differ between visual conditions. Also, the extent to which the variance in directional error at the target was determined by directional error earlier in the movement was relatively high and did not differ between visual conditions. Hence, the utilisation of visual feedback in fast movements was primarily associated with offline processes whereby information from completed movements was used to adjust the programming of upcoming movements. When movement times were relatively long, the form of the variability profiles differed between visual conditions. This suggests that when visual feedback was available, directional accuracy was determined by visually based adjustments that occurred online to compensate for variations in direction from the early parts of the limb trajectory.

CHAPTER 6

THE UTILISATION OF VISUAL FEEDBACK FROM PERIPHERAL AND CENTRAL VISION IN THE CONTROL OF DIRECTION

When performing manual aiming movements, participants typically fixate on the target prior to limb movement or relatively early in the limb trajectory (Abrams et al., 1990). Hence, the limb is seen in the peripheral visual field during the early stages of the trajectory and enters the central visual field upon approaching the target. Paillard and Amblard (1985) have proposed that peripheral vision is the primary source of visual afferent information for the control of movement direction while central vision is utilised for the control of movement amplitude. In support of Paillard and Amblard's model, researchers have demonstrated that directional accuracy is improved when peripheral vision is available (Abahnini et al., 1997; Abahnini & Proteau, 1999; Bard et al., 1990). However, the availability of central vision has also been shown to influence the control of movement direction. It has been proposed that since central vision is available late in the trajectory, it is not utilised to correct for errors during movement execution. Rather, information about where the limb passes the target is used to improve the programming of subsequent movements.

The present study focussed on the role of peripheral and central vision in the control of movement direction by analysing directional variability in limb trajectories. The direction aiming task employed consisted of movement of a pen on a digitizing tablet that was represented by a cursor on a monitor. The contribution of peripheral and central vision was investigated by manipulating where in the visual field the cursor was visible. The cursor could be seen throughout the movement, only in the peripheral or central visual field, or was invisible throughout the movement. It was expected that if central vision was used in the control of direction, variability would be lower in the central vision condition compared to the no vision condition. However, if the benefit of central vision was only due to offline processing of visual information, the form of the variability profiles would not be different. That is, the variability profiles in the central and no vision conditions could be expressed as scalar multiples of each other. On the other hand, if peripheral vision was used to adjust limb trajectories during movement execution, variability profiles in the peripheral vision condition would differ in form from that in the no vision condition.

Also of interest in the present study was whether differences in the utilisation of visual feedback from peripheral and central vision are actually due to "where" in the visual field information is available or "when" visual feedback is available. It is possible that peripheral vision is processed online because it is available early in the limb trajectory and therefore participants have sufficient time to use this information. Central vision may be presented too late in the limb trajectory to be processed during movement execution. In order to address this issue movement trajectories were analysed beyond the target to examine whether adjustments took place after the limb passed the target. In addition, the point at which participants fixated was also manipulated. In Experiment 1, participants fixated on the target and therefore early visual information was in the peripheral field while late visual information was in central vision. In Experiment 2, participants fixated on the start position throughout the movement. Therefore, early visual information was in central vision while late visual information was in peripheral vision. Support for the existence of a kinetic visual channel (Paillard and Amblard 1985) would be gained if participants were better able to process early visual information online when it occurred in peripheral vision.

6.1. EXPERIMENT 1

6.1.1. Method

Participants. Sixteen self declared, right hand dominant, university students served as participants in the study (12 males, 4 females, ages 18-35 yrs). All participants in this experiment and in the second experiment were naive to the hypothesis being tested and inexperienced at the experimental task. They gave their informed consent prior to participation in the study. The experimental protocols were approved by the Ethics Committee of the School of Sport, Health and Exercise Sciences, University of Wales, Bangor for research involving human participants.

Apparatus. The aiming movements were performed with a pen on a Calcomp III digitising tablet (size =122 x 91.5 cm, sample rate = 200 Hz, accuracy = ± 0.125mm) positioned horizontally in front of the participants. The position of the pen was illustrated by a round cursor 1 cm in diameter on a 37" Mitsubishi Diamond Pro monitor located 33 cm in front of the participants and 20 cm above the tablet. There was a one to one mapping between the movement of the pen and the movement of the cursor. Movements of the pen away from the body on the tablet corresponded to vertical movements of the cursor on the monitor. The home position (i.e., the start location of the cursor) consisted of a round dot (1 cm in diameter) and was located at the bottom of the monitor. Three circular targets (1 cm in diameter) were located above the home position along an arc of radius of 24 cm. The centre target was located directly above the home position while the other two targets were located 10 degrees to either side of the centre target. The distance of 24 cm between the home and target markers yielded a visual angle of 40 degrees. An arc which was centred at the home position and of radius 30 cm (i.e., 125% the distance from the home position to the targets) was located above the target positions. The participants chair and chin rest were adjustable in height so that the participants' eyes were at a level midway between the home and target markers. The arm and hand were hidden from the participants' view by an opaque shield thus preventing vision of the arm at all times.

To ensure that participants did not move their eyes during the trials, a Sony CVX-VIP colour video camera (lens diameter = 8mm) was positioned at the base of the monitor. The experimenter monitored the output from the camera using a digital Sony Video Walkman GV/D 900E placed on the experimenter's desk.

Task and Procedure. At the beginning of each trial, the home and target positions and the cursor representing the position of the pen appeared on the monitor. Participants were required to place the cursor on the home position. Once the cursor was steadily aligned, one of the targets changed colour from red to green informing the participants which target to aim for. Participants were instructed to fixate on the green target. A tone was then presented after a 1500 msec interval. Participants were required to make a sweeping movement from the starting position towards and past the target and beyond the arc of radius 30 cm while maintaining fixation on the target. Since they were not required to stop on the target, the task had a direction but no amplitude requirement. Participants were told to make their movements as smooth as possible. It was explained to participants that RT was not important. However, they were required to produce their movements with a criterion movement time of 450 (± 10%) msec (i.e., the interval from initiation of movement to when the pen crossed the arc subtended by the three targets).

Each participant performed the task under four visual conditions (full vision [FV], early vision [EV], late vision [LV], and no vision [NV]). In the full vision condition, the cursor was visible throughout the movement. In the early vision condition, the cursor was visible for the first 18 cm of the movement and then disappeared. Since participants fixated on the target, the cursor was visible in peripheral vision from 40-10 degrees eccentricity. In the late vision condition, the cursor was invisible for the first 18 cm of the movement and then reappeared 6 cm before the target. Hence, the cursor was visible in central vision from 10-0 degrees eccentricity. In the no vision condition, the cursor disappeared as soon as it left the home position and did not reappear until it was time to get ready for the next trial. The home and target markers were visible throughout the trial in all visual conditions. Participants performed one block of 30 trials under each visual condition giving a total of 120 trials per participant. The order of the four visual conditions was counterbalanced across participants. Target location was randomized within a block of trials with the restriction that no target was repeated before each target was presented. Knowledge of results regarding accuracy (constant error) (mm) and movement time (msec) was presented in numerical form on the monitor after each trial. At the beginning of each block of trials, participants were given approximately 10-15 practice trials to familiarise themselves with the experimental condition. During testing, those trials which were not within ±10% of the criterion MT or in which participants moved their eyes during the trial were repeated. This amounted to less than five trials in any one block of trials.

Dependent Measures and Analyses. The initiation of movement was defined as the point in time that the cursor moved 1 mm from the home position. Our dependent measures were movement time, directional error and directional variability at 25%, 50%, 75%, 100% and 125% of the longitudinal distance from the home position to the target (i.e., 6, 12, 18, 24, 30 cm). Movement time at each longitudinal distance was defined as the interval from the start of the movement to when the pen crossed the arc at the respective longitudinal distances. Directional error at each longitudinal distance was calculated as the distance from where the arc crossed the longitudinal axis to where the pen trajectory crossed the arc. Movements to the right of the longitudinal axis were recorded as positive while movements to the left were recorded as negative. Spatial variability was calculated as the within-participant standard deviation of directional errors.

Movement times, directional errors and spatial variability were submitted to separate 4 Visual Conditions (FV, EV, LV, NV) x 3 Target (left, middle, right) x 5 Longitudinal Distance (6, 12, 18, 24, 30 cm) repeated measures ANOVAs. Greenhouse-Geisser adjustments to the degrees of freedom were applied when sphericity was violated (i.e., epsilon less than 1) (Greenhouse & Geisser, 1959). Post hoc tests were performed using Tukey HSD methods. However due to the extreme conservativeness of these tests, Bonferroni tests were used when sphericity was highly violated (i.e., epsilon less than .70) (Stevens 2002, p. 509).

6.1.2. Results

Means of Movement Time and Directional Error

The analysis of movement times revealed significant main effects for both Target, $F\,(2, 30) = 21.2, p < .001$, and Longitudinal Distance, $F\,(1, 16) = 1570.1, p < .001$. There was also a significant interaction between Target and Longitudinal Distance $F\,(2, 31) = 3.7, p < .05$. As would be expected movement time increased as longitudinal distance increased. Movements to the left target were longer than movements to the right with this difference increasing as the movement progressed (see Table 7). There was no main effect or interactions involving Visual Conditions ($p > .05$). Hence, movement times at each longitudinal distance did not differ between visual conditions.

	Target Location														
	LEFT					MIDDLE					RIGHT				
Visual Condition	6	12	18	24	30	6	12	18	24	30	6	12	18	24	30
FV	119	290	369	453	566	195	285	364	445	551	193	283	362	444	547
	13.2	*14.4*	*14.1*	*13.2*	*35.1*	*15.2*	*15.6*	*12.4*	*8.3*	*26.4*	*13.6*	*14.4*	*12.4*	*9.6*	*29.2*
EV	200	292	372	453	560	197	284	367	448	551	192	283	362	442	540
	16.8	*16.8*	*12.8*	*8.1*	*28.2*	*16.1*	*15.2*	*10.4*	*6.4*	*28.2*	*14.8*	*12.8*	*8.1*	*7.6*	*28.4*
LV	201	293	372	456	572	196	287	365	447	564	192	283	362	444	556
	11.6	*11.6*	*9.2*	*11.2*	*30.4*	*15.2*	*15.6*	*12.8*	*9.6*	*40.8*	*13.2*	*13.2*	*10.8*	*8.4*	*29.6*
NV	202	296	376	455	561	199	292	371	448	544	197	289	365	441	543
	11.2	*11.6*	*12.4*	*10.4*	*20.4*	*8.4*	*9.2*	*9.2*	*8.8*	*23.2*	*6.1*	*4.2*	*.8*	*12.1*	*46.2*

Table 7. Mean, *standard deviation*, movement times at 25%, 50%, 75%, 100% and 125% of the longitudinal distance to the target (i.e., 6, 12, 18, 24 and 30cm) as a function of visual condition, criterion MT and target location.

The analysis of directional error revealed a significant three-way interaction between Visual Condition, Target and Longitudinal Distance, $F\,(24, 360) = 22.6, p < .001$. Movements to the left target were biased to the left of the longitudinal axis (FV: 8.2 mm, EV: 8.0 mm, LV: 10.6 mm, NV: 20.3 mm) whereas movements to the right target were biased to the right (FV: 0.6 mm, EV: 1.0 mm, LV: 0.8, NV: 12.6 mm). Movements performed without visual feedback showed greater biases than movements performed with visual feedback.

Directional Variability

The analysis of spatial variability revealed significant main effects of Visual Condition, $F\,(3, 45) = 8.4, p < .001$, Target, $F\,(2, 30) = 15.2, p < .001$, and Longitudinal Distance, $F\,(1, 20) = 212.5, p < .001$. There was a significant two-way interaction between Visual Condition and Longitudinal Distance, $F\,(4, 62) = 28.9, p < .001$. A breakdown of this interaction revealed that the no vision condition showed greater variability than all other visual conditions at longitudinal distances of 12, 18, 24, & 30 cm (see Figure 18). Also, the variability in directional error was greater at 24 and 30 cm in the late vision compared to the early and full vision conditions. Both the no vision and late vision conditions showed a continual rise in variability throughout the movement, whereas in the early and full vision conditions variability increased up to a longitudinal distance of 18 cm and then levelled off. Separate one-way ANOVAs performed on each visual condition revealed that variability increased linearly for all visual conditions while there was also a significant quadratic component for the early and full vision conditions ($p < .05$).

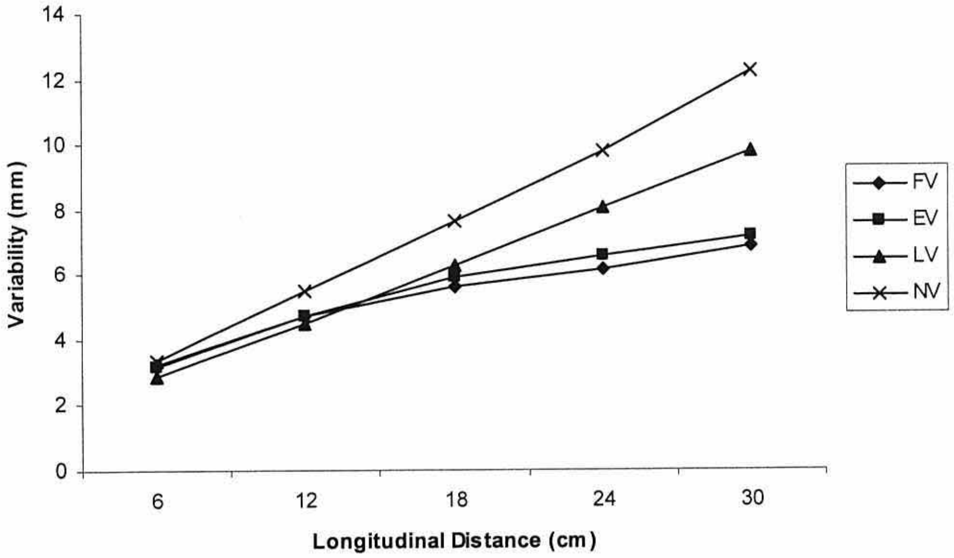

Figure 18. Variability in direction at longitudinal distances of 6, 12, 18, 24 and 30 cm for the full (FV), early (EV), late (LV) and no vision (NV) conditions in Experiment 1.

The analysis of spatial variability also revealed a three-way interaction between Visual Condition, Target and Longitudinal Distance, *F* (24, 360) = 1.8, $p < .05$. The difference in variability rise rates between visual conditions was smaller for movements made to the middle target compared to the left and right targets.

To assess whether the form of the variability profiles differed between visual conditions, the ratio in variability between each visual condition (FV, EV, LV) and the no vision condition at longitudinal distances of 6, 12, 18, 24 and 30cm was calculated for each participant. The variability ratios were submitted to a 3 Visual Condition (FV:NV, EV:NV, LV:NV) x 3 Target (left, middle, right) x 5 Longitudinal Distance (6, 12, 18, 24, 30 cm) repeated measures ANOVA. This analysis revealed a significant interaction between Visual Condition and Longitudinal Distance, *F* (2, 41) = 9.3, $p < .001$ (see

Figure 19). A breakdown of this interaction revealed that the ratio in variability between the late and no vision conditions did not vary as the movement progressed. Hence, the form of the variability profiles in the early and no vision conditions were similar. However, there was a significant decrease in the variability ratios between each longitudinal distance for both the full and the early vision conditions.

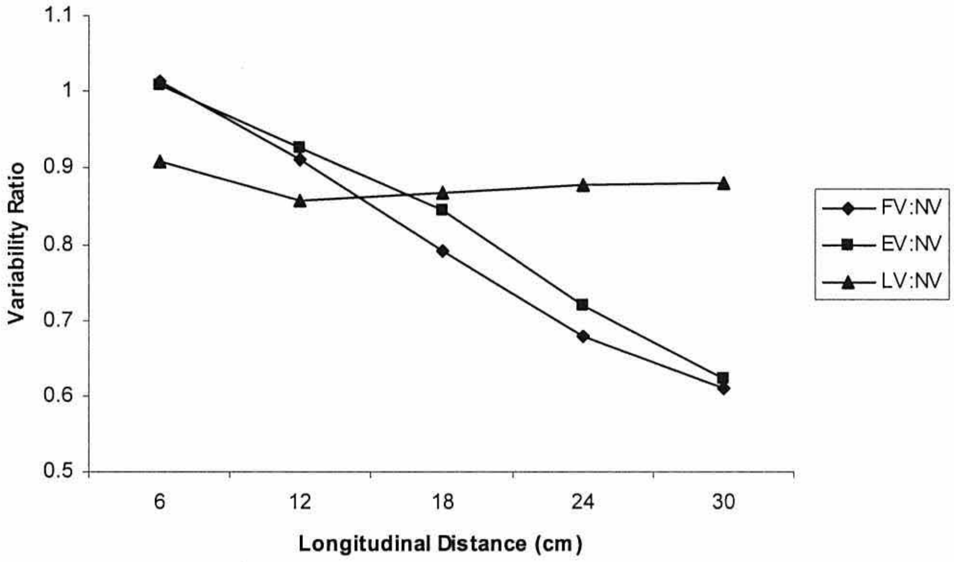

Figure 19. Ratios in variability between the full and no vision conditions (FV:NV), early and no vision conditions (EV:NV) and late and no vision conditions (LV:NV) at longitudinal distances of 6, 12, 18, 24 and 30 cm in Experiment 1.

Correlation of Directional Errors

In order to complement the analysis of spatial variability, directional error at 50% of the distance to the target was correlated with the directional error at the target. The squared correlation coefficients and the square of the Fischer Z transformations of the correlation coefficients between directional errors at longitudinal distances of 12 and 24 cm are reported in Table 8. Since the number of subjects was equal to 16 and the alpha level was set at .05, any r^2 above .497 was classified as significant (Person and Hartley, 1966). A 4 Visual Condition (FV, EV, LV, NV) X 3 Target (left, middle, right) repeated measures ANOVA performed on the squared Fischer Z transformations revealed a significant main effect for both Visual Condition, F (3,45) = 8.7, $p < .001$, and Target, F (2,30) = 7.7, $p < .05$. Breakdown of these main effects revealed that the proportion of the variance in directional error at 24 cm explained by the variance in directional error at 12 cm was less in both the full and early vision conditions compared to the no vision condition. Additionally, squared Fischer Z scores were less for movements to the middle target compared to movements to the left and right targets.

Visual Condition	Target Location					
	LEFT		MIDDLE		RIGHT	
	r^2	Z^2	r^2	Z^2	r^2	Z^2
FV	0.64	1.55	0.57	1.21	0.61	1.85
	0.22	*0.94*	*0.21*	*0.86*	*0.27*	*2.06*
EV	0.60	1.24	0.55	1.24	0.69	1.81
	0.18	*0.61*	*0.27*	*0.94*	*0.22*	*1.05*
LV	0.78	2.76	0.69	1.77	0.75	2.34
	0.24	*1.45*	*0.21*	*1.01*	*0.19*	*1.30*
NV	0.79	2.61	0.69	1.63	0.82	2.65
	0.17	*1.28*	*0.16*	*0.81*	*0.11*	*1.24*

Table 8. Mean, *standard deviation*, squared correlation coefficients (r^2) and the squares of the Fischer Z transformations (Z^2) of the correlation coefficients between constant error at 50% (i.e. 12 cm) and 100% (i.e. 24 cm) of the longitudinal distance to the target as a function of visual condition and target location.

6.1.3. Discussion

Consistent with the results from previous research, there was less variability in directional error when participants received visual feedback from the peripheral field compared to when no visual feedback was available. This finding is consistent with the two-channel model proposed by Paillard and Amblard (1985) in which directional information is processed from peripheral vision via the kinetic visual channel. However, in contrast to the proposals made by Paillard and Amblard, the results of the present experiment also revealed that the availability of central vision had a significant impact on performance. Although the availability of central vision had a smaller effect on directional variability compared to peripheral vision, limb trajectories were less variable when participants received central visual feedback compared to when no visual feedback was available. Similar benefits of central vision in the control of direction have been reported in previous research (Abahnini et al. 1997; Abahnini and Proteau 1999; Bard et al. 1985; Bard et al. 1990). It has been suggested that the contribution of central vision was not due to online control but that participants used the information gained in central vision to improve the programming of subsequent trials. One rationale for this argument was that since visual information from the central visual field was presented relatively late in the movement, participants may not have had sufficient time to process this information. The goal of the present research was to first examine the contributions of online and offline processing of visual feedback. Also of interest, was determining whether the difference in performance between the peripheral and central vision conditions was due to where in the visual field information was available or differences in the time to use visual feedback.

The analysis of directional variability at different stages of the movement revealed that variability increased linearly throughout the movement in the no vision and central vision conditions. Consistent with this, the ratios in variability between the central and no vision conditions remained constant throughout the movement implying that the form of the variability profile was similar in these two conditions. This finding provides strong evidence that the contribution of central vision was indeed due to offline processing. That is, modifications to the trajectory were not made during movement execution but in the programming of subsequent trials.

In the peripheral and full vision conditions, variability increased up to 50% of the longitudinal distance to the target and then levelled off. Also, the ratios in variability between the peripheral and no vision conditions and between the full and no vision conditions decreased as the movement progressed. Hence, the form of the variability profile was fundamentally different in the peripheral and full vision conditions compared to the no vision condition. This provides evidence that participants compensated for variations in the trajectory based on information gained from the peripheral visual field.

The time for which visual feedback was available in the central vision condition prior to the limb passing the target was on average 83 msec. Since the minimum time needed to process visual feedback has been estimated to be about 100 msec (Carlton 1992), it is likely that the lack of online control in the central vision condition was due to limitations in the time available to process visual feedback. To address this possibility, analyses were performed on movements up to 25% of the longitudinal distance past the target during which time the cursor was visible for a further 115 msec. This was to examine whether participants attempted to use central vision online but adjustments to the trajectory did not take effect until after the limb passed the target. Examination of the variability profiles revealed that there was still a linear increase in variability in the central vision condition between 100% and 125% of the target amplitude. Also, the variability ratio between the central and no vision conditions did not vary at this point in the limb trajectory. Hence, there was no evidence for online control in the central vision condition in the 115 msec interval after the limb passed the target. This would suggest that the lack of online control in the central vision condition was due to the location of information in the visual field rather than the lack of time needed to process visual information. However, this conclusion should be taken with some degree of caution at this point. The video aiming task employed in the present study involved a translation of information between the monitor display and movement of the limb and therefore, visuomotor delays may have been longer compared to more traditional aiming tasks (Chapter 4; Chapter 5; Messier and Kalaska 1997). Hence, the viewing time of 83 msec before the target plus the additional time of 115 msec after the limb passed the target may still not have been sufficient for visually based corrections to take effect in the central vision condition.

6.2. EXPERIMENT 2

The aim of the present experiment was to seek further evidence that the differences in performance between the peripheral and central vision conditions were due to the location of visual information in the visual field rather than the time required to process visual feedback. In Experiment 1, participants were instructed to fixate on the target prior to limb movement. Hence, visual feedback from the early part of the trajectory was in peripheral vision. In the present experiment, participants were required to fixate on the home position throughout the movement. Therefore, early visual information was now in central vision rather than the peripheral visual field. If the location of information in the visual field is the critical factor governing whether or not visual feedback is processed online, it was expected that the processing of early visual feedback would be superior when it was available in peripheral compared to central vision.

6.2.1. Method

Participants. Sixteen self declared, right hand dominant, university students served as participants in this experiment (12 males, 4 females, ages 18-35 yrs). All participants gave their informed consent prior to taking part and none had participated in Experiment 1.

Task and Procedure. The task and procedures were similar to Experiment 1 with the exception that participants were required to fixate on the home position throughout the trial. This meant that early visual information was now in central vision while late visual information was in peripheral vision. Trials in which participants moved their eyes or in which movement times were not within ±10% of the criterion MT were repeated. This amounted to less than five trials in any one block of trials.

6.2.2. Results

Means of Movement Time and Directional Error

Similar to Experiment 1, movements to the left target had longer durations than movements to the right target, $F(2, 30) = 10.1, p < .001$ (left = 455 msec; middle = 448 msec; right = 443 msec) There were no differences in movement times between visual conditions ($p > .05$) (FV = 447 msec; EV = 448 msec; LV = 449 msec; 448 msec).

The analysis of directional error revealed a significant three-way interaction between Visual Condition, Target and Longitudinal Distance, *F* (24,360) = 11, $p < .001$. Limb trajectories tended to be biased to the left of the longitudinal axis for movements to the left target (FV: 16.2 mm, EV: 16.2 mm, LV: 18.7 mm, NV: 28.7 mm) whereas biases to the right of the longitudinal axis were observed for movements to the right target (FV: 12.1 mm, EV: 13.5 mm, LV: 12.1 mm, NV: 20.9 mm). Movements performed with visual feedback were less biased than movements performed without visual feedback.

Directional Variability

As illustrated in Figure 20, there was an overall increase in variability as Longitudinal Distance increased, *F* (1, 16) = 320.2, $p < .001$. There was also a significant interaction between Visual Condition and Longitudinal Distance, *F* (3, 48) = 7.3, $p < .001$. A breakdown of this interaction revealed that variability was greater in the no vision compared to the early and full vision conditions at a longitudinal distance 12cm and greater in the no vision condition than all visual conditions at longitudinal distances 18, 24 and 30 cm. Additionally, variability was greater in the late visual condition than the early and full visual conditions at longitudinal distances of 24 and 30 cm. Separate One-way ANOVAs performed on each visual condition revealed that variability increased linearly for all visual conditions ($p <.05$) while there were no significant quadratic components ($p >.05$).

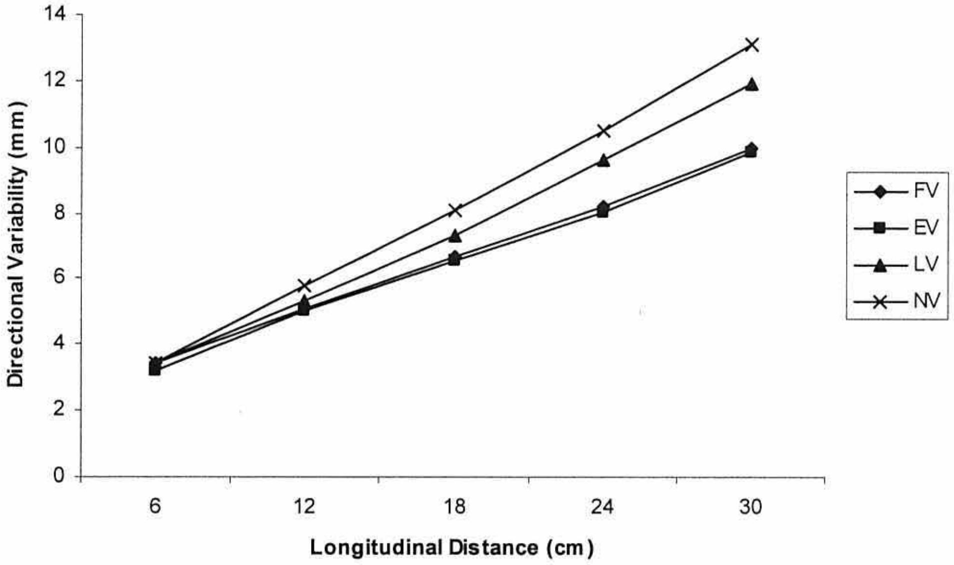

Figure 20. Variability in direction at longitudinal distances of 6, 12, 18, 24 and 30 cm for the full (FV), early (EV), late (LV) and no vision (NV) conditions in Experiment 2.

The analysis of the ratios in variability between each visual condition (FV, EV, LV) and the no vision (NV) condition revealed a significant interaction between Visual Condition and Longitudinal Distance, $F(3, 47) = 3.9, p < .05$ (see Figure 21). A breakdown of this interaction revealed that the ratio in variability between the late and no vision conditions did not vary as the movement progressed. However, there was a significant decrease in the variability ratios for both the full and the early vision conditions. Post hoc tests revealed that the variability ratios were significantly higher at longitudinal distances of 6 and 12 cm compared to 18, 24 and 30 cm.

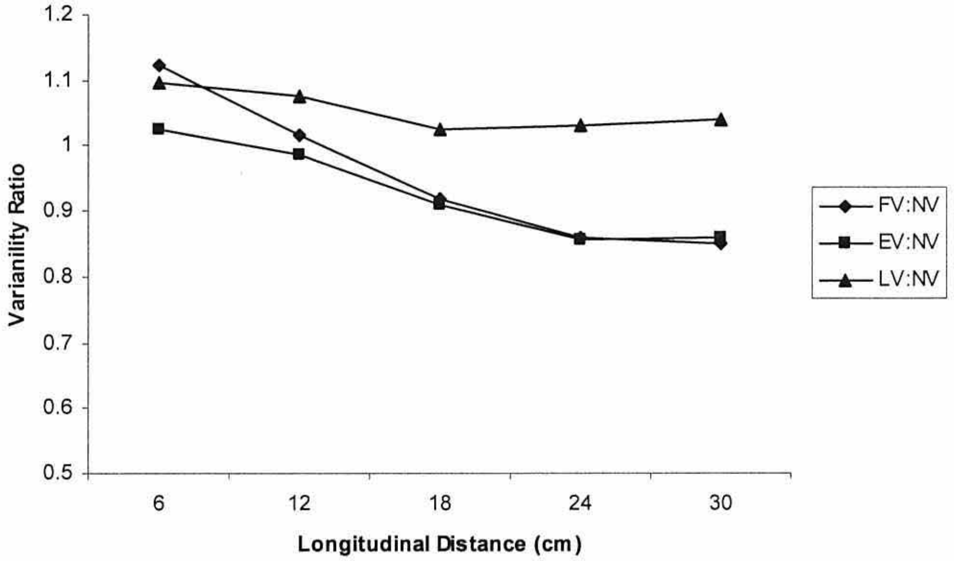

Figure 21. Ratios in variability between the full and no vision conditions (FV:NV), early and no vision conditions (EV:NV) and late and no vision conditions (LV:NV) at longitudinal distances of 6, 12, 18, 24 and 30 cm in Experiment 2.

Correlation of Directional Errors

The squared correlation coefficients and the square of the Fischer Z transformations of the correlation coefficients between directional errors at longitudinal distances of 12 and 24 cm are reported in Table 9. Analysis of the squared Fischer Z transformations revealed a significant main effect for Visual Condition, *F* (3, 45) = 4.3, *p* < .05. Breakdown of this main effect revealed that the proportion of the variance in directional error at 24 cm explained by the variance in directional error at 12 cm was less in the early vision condition compared to both the late and no vision conditions.

Visual Condition	Target Location					
	LEFT		MIDDLE		RIGHT	
	r^2	Z^2	r^2	Z^2	r^2	Z^2
FV	0.67	1.79	0.69	1.78	0.76	2.39
	0.23	*1.13*	*0.20*	*1.05*	*0.17*	*1.60*
EV	0.68	1.78	0.55	1.10	0.69	1.93
	0.24	*0.99*	*0.23*	*0.65*	*0.22*	*1.35*
LV	0.73	2.33	0.72	1.85	0.77	2.49
	0.23	*1.69*	*0.17*	*0.82*	*0.22*	*1.28*
NV	0.73	2.13	0.76	2.71	0.82	2.62
	0.18	*1.36*	*0.22*	*2.25*	*0.10*	*1.00*

Table 9. Mean, *standard deviation*, squared correlation coefficients (r^2) and the squares of the Fischer Z transformations (Z^2) of the correlation coefficients between constant error at 50% (i.e. 12 cm) and 100% (i.e. 24 cm) of the longitudinal distance to the target as a function of visual condition and target location.

6.2.3. Discussion

Similar to Experiment 1, variability increased linearly in the no vision and late vision conditions. However, the form of the variability profiles in both the early vision conditions differed in the two experiments. While variability levelled off at 50% of the distance to the target in Experiment 1, variability increased throughout the movement in a linear fashion in the present experiment. Hence, the form of the variability profiles in the early vision conditions was influenced by the location of information in the visual field. It appears that when early visual information was in peripheral vision, participants were better able to utilise this information compared to when it was available in central vision. This finding implies that the utilisation of visual feedback from different parts of the trajectory was not determined strictly by the time available to process this information. The present results clearly indicated that the ability to effectively process visual feedback online depended on the location of this information in the visual field.[12]

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[12] Although eye movements were not formally analysed, it is reasonable to assume that participants obeyed the eye fixation instructions since failure to maintain fixation would have reduced any differences in results between the two Experiments.

Although variability increased linearly in the early and full vision conditions, it is believed that online control was still present in these conditions albeit to a lesser extent than in Experiment 1. Ratios in variability between the early and no vision conditions and between the full and no vision conditions decreased as the movement progressed. This suggests that the form of the variability profiles in the early and full vision conditions were different from the no vision condition since they differed by more than multiplication of a scalar factor. In addition, correlations of directional error at 50% and 100% of the distance to the target revealed that the extent to which error at the end of the movement was explained by error at 50% of the movement was less when early visual feedback was available compared to when no vision was available.[13] Therefore, trajectories were modified online during the latter parts of the movement when early visual feedback was available. It is possible that a linear increase in variability resulted because adjustments also took place during the early phases of the movement (i.e., prior to 50% of the movement). Early adjustments would cause the variability profile to be lowered between 25% and 50% of the movement thereby preserving the linearity of the profile but with a lower slope. To address this possibility, the distance travelled at 25% of the movement was correlated with the distance travelled at 50% of the movement. A one way ANOVA performed on the squared Fischer Z transforms of the correlation coefficients revealed that correlations were lower when visual feedback was available early in the trajectory ($r^2 = .79$, $Z^2 = 2.04$) compared to when it was not ($r^2 = .86$, $Z^2 = 2.75$), $F(3, 45) = 3.0$, $p < .05$. This implies that adjustments to the limb trajectory were

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[13] Bédard and Proteau (2003) have inferred offline control from linear variability profiles. However, they did not analyse the ratios in variability or correlations in error.

made early in the movement which lowered the slope of the variability profiles. Therefore, it appears that when early visual information was in the central visual field, participants did have sufficient time to utilise this feedback online. However, it should be kept in mind that the extent to which adjustments were made was greater when early visual information was in the peripheral compared to central visual field.

6.4. General discussion

Past research has revealed that peripheral vision plays an important role in the control of direction. This finding is consistent with the two channel model proposed by Paillard and Amblard (1985) in which movement direction is processed via the kinetic visuomotor channel which operates in the visual periphery. However, in contrast to Paillard and Amblard's model, the availability of central vision has also been shown to have an influence on directional accuracy. It has been suggested that central vision was not used to regulate movement online but that visual feedback was processed offline to improve movement programming (Abahnini and Proteau 1997; Bard et al. 1985). In the present study, this hypothesis was tested by analysing the variability in limb trajectories at different stages throughout the movement.

The results of Experiment 1 indicated that limb trajectories were less variable when either central or peripheral vision was available. However, the form of the variability profile was not affected by the availability of central vision. This suggests that central vision was not used to adjust movements online but participants used information about where the cursor passed the target to improve the planning of subsequent trials. In contrast, the form of the variability profile was influenced when peripheral vision was available. This deviation in the form of the variability profile implies that participants were able to compensate for variations in the limb trajectory during movement execution.

Of interest in the present work was whether the differences in the processing of central and peripheral vision was actually due to the location of vision in the visual field or the time available to use this information. It was possible that peripheral vision was processed online while central vision was only used for offline control because participants had more time to use peripheral vision information since it was available early in the limb trajectory. Comparison of the variability profiles for the early vision conditions between the two experiments revealed that the location of information in the visual field was an important determinant of whether vision was processed effectively during movement execution. When early visual information was available in peripheral vision, increases in variability levelled off towards the end of the movement resulting in a quadratic variability profile. When early visual information was available in central vision, variability increased linearly throughout the movement. Hence, participants were better at using early visual information to adjust limb trajectories when it was available in peripheral versus central vision.

The present findings also revealed that the utilisation of central vision depended on when it was available in the limb trajectory. In Experiment 1, central vision was available late in the movement and therefore was only used to improve the programming of subsequent movements. In Experiment 2, the availability of central vision early in the movement enabled participants to use this information during movement execution. It should be noted however, our results do not rule out the possibility that central vision presented late in the movement may be utilised online in the control of direction when movement times are longer than that employed in the present studies. As mentioned earlier, when the target was fixated, the cursor was visible for approximately 200 msec in the central vision condition at the point in which the limb had travelled 125% of the longitudinal distance. It may be that longer vision times in the central visual field would enable corrections to be performed online in the video aiming tasks employed in the present experiments.

It has been suggested that participants were better at using early visual feedback online when it was available in peripheral vision compared to central vision. However, it is also important to consider that when participants fixated on the target, the movement was performed in the lower visual field whereas the movement was performed in the upper visual field when participants fixated on the home position. Danckert and Goodale (2001) have shown that target size had a greater influence on movement duration when movements were performed in the lower compared to upper visual field. On this basis, they suggested that visual feedback processing was more effective in the lower visual field. The results of the present experiments are consistent with this viewpoint in that there were linear increases in variability throughout the movement when movements were in the upper visual field. When movements were in the lower visual field, the availability of early visual feedback resulted in variability levelling off at the later stages of the limb trajectory. Therefore, compensations for variability in the limb trajectories were more effective when movements were performed in the lower visual field.

One other point to consider is that previous research has shown that target eccentricity is overestimated and movement endpoints are more scattered when aiming to peripheral targets (Bock 1986; Enright 1995). Comparison of the directional errors in both experiments reveals that trajectories were more biased when the home position was fixated than when the target was fixated. Movements to the left target were more biased to the left of the longitudinal axis and similarly movements to the right target were more biased to the right. It appears that when the home position was fixated, participants overestimated the horizontal eccentricities of the targets. Furthermore, directional variability at the target was greater in all visual conditions when participants fixated on the home position than when they fixated on the target.[14]

It is also possible that when participants fixated on the start position throughout the movement, corrections to the limb trajectories were more effective early in the movement than when participants fixated on the target. This is because processing cursor movement would have been more effective when it was closer to the direction of gaze. The ability to perform early corrections when the home position was fixated would have lowered the variability profile early in the movement resulting in a linear increase in variability as the movement progressed. A quadratic profile would have emerged when participants fixated on the target because corrections occurred relatively later in the trajectory as movement of the cursor got closer to the direction of gaze.[15] However, two lines of evidence suggest that early corrections were not more effective when the home position was fixated. First, variability was actually greater early in the movement when the home position was fixated compared to when the target was fixated. Second, there were no differences in correlations between error at 25% and 50% of the movement when the home position versus the target was fixated ($p = .93$). As mentioned above, it may be that when the home position was fixated, the eccentricity of the target (i.e., 40 degrees)

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[14] A 2 Experiment x 4 Visual Conditions ANOVA revealed that directional variability at the target was greater in Experiment 2 compared to Experiment 1 in all visual conditions, $F(1, 30) = 7.8$, $p < .01$.

[15] Thanks are given to an anonymous reviewer for this suggestion.

reduced the effectiveness of error corrections early in the movement that would have been due to the proximity of the cursor to the direction of gaze.

In summary, the present results indicated that visual information from early in the limb trajectory was used more effectively to correct errors online when it was available in the peripheral compared to central visual field. This finding is consistent with the two channel model proposed by Paillard and Amblard (1985) and supports the existence of a kinetic channel for the processing of movement direction. Processing of central visual information depended on when it was available during movement execution. When participants fixated on the target, feedback from central vision was available late in the trajectory and hence this information was only used to improve the programming of subsequent movements. When participants fixated on the start position, the availability of central vision early in the trajectory allowed participants to utilise this information to correct errors online. Therefore, the utilisation of central vision depended on the time available to use this information.

CHAPTER 7

THE UTILISATION OF VISUAL FEEDBACK FROM PERIPHERAL AND CENTRAL VISION IN THE CONTROL OF AMPLITUDE

Paillard and Amblard (1985) postulated that information from the central visual field is processed via the static channel which is thought to be primarily responsible for the control of movement amplitude. This is supported by numerous studies that have shown that early visual information does not influence amplitude accuracy while the availability of visual feedback late in the trajectory improves endpoint accuracy (Bard et al., 1990, Carlton, 1981, Tempardo et al., 1996).

The goal of the present experiment was to determine whether information from the central visual field could be used to detect amplitude errors in limb trajectory and correct for them during movement execution. It is possible that since central vision is available late in the trajectory, its primary function may be to improve the programming of subsequent movements. Also of interest was to re-examine whether peripheral vision has no influence in the control of movement amplitude throughout the limb trajectory. Research on amplitude control has typically involved pointing movements in which participants are required to move towards and stop on a specific target (Bard et al. 1990; Carlton 1981; Temprado et al. 1996). Since these tasks require participants to move a specified distance kinematic markers are readily available. Therefore, to assess the variability in limb trajectories the within-participant standard deviation in the distance travelled at peak acceleration, peak velocity, peak negative acceleration and movement end were calculated.

The task used in the present experiment consisted of a manual amplitude aiming task in which participants performed movements of a pen on a digitizing tablet to a specified target. Movements were performed at a criterion movement time sufficient for online processing of visual feedback to occur. The contribution of peripheral and central vision was investigated by manipulating where in the visual field the pen was visible. The pen could be seen throughout the movement, only in the peripheral or central visual field, or was occluded throughout the movement. It was expected that variability in the peripheral vision condition would not differ to that of the no vision condition suggesting that the availability of peripheral vision is of no benefit to extent accuracy. On the other hand, if central vision was used in the control of amplitude, then variability would be lower in the central vision condition compared to the no vision condition. Furthermore, it was expected that variability profiles in the central vision condition would differ in form from that of the no vision condition if central vision was utilised online.

7.1. Method

Participants. Sixteen, self declared right hand dominant, university students volunteered to participate in the study (8 males, 8 females, ages 18-32). All were naïve to the hypothesis being tested and had no previous experience in the experimental task. The experiment was carried out according to the ethical guidelines laid down by the Ethics Committee of the School of Sport, Health and Exercise Sciences, University of Wales, Bangor for research involving human participants.

Apparatus. The aiming movements were performed with a pen on a SummaSketch III Professional digitizing tablet (size = 45 x 31 cm, sample rate = 120 Hz, accuracy = ± .02 mm) positioned horizontally in front of the participant. Movements were performed with the right hand in the right to left direction along a track way. The home position and target were presented on the digitizing tablet. The target was positioned inline with the participants' midline while the home position was located 24 cm to the right of the target. Both consisted of lines 2 cm long and 0.2 cm in width orientated perpendicular to the direction of the trackway. The distance of 24cm between the home position and target yielded a visual angle of 40 degrees. The participants' chair and chin rest were positioned so that the home and target markers were at the same level as the participants' eyes. In order to manipulate the availability of visual feedback, participants wore a pair of Plato liquid crystal occlusion goggles at all times.

Task and Procedure. At the beginning of each trial, participants were required to position the pen on the home position and then fixate on the target. Once the pen was steadily aligned, a tone was presented signalling the start of the trial. Participants were required to move from the home position to the target as smoothly and as accurately as possible and come to a complete stop. Since movements were constrained in a track way and participants were required to stop on the target, the task had an amplitude but no direction requirement. It was explained to the participants that RT was not important. However, they were required to produce their movements with a criterion movement time of 450 (± 10%) msec

Each participant performed the task under four visual conditions (full vision [FV], peripheral vision [PV], central vision [CV], and no vision [NV]). In the FV condition, the participants' limb was visible throughout the movement. In the PV condition, the occlusion goggles were open for the first 18 cm of the movement and then closed for the remainder of the movement. Vision was occluded until the pen was returned to the home position, thus no visual information about the terminal accuracy of the movement was available. Since participants fixated on the target, the limb was visible in peripheral vision from 40-10 degrees eccentricity. In the CV condition, vision was occluded for the first 18 cm of the trajectory. Vision was then available 6 cm before the target. Hence, the limb was visible in central vision from 10-0 degrees eccentricity. In the NV condition, the occlusion goggles were closed as soon as movement onset occurred and occluded the participants' vision until it was time to get ready for the next trial. Participants performed one block of 25 trials under each visual condition giving a total of 100 trials per participant. The order of the four visual conditions was counterbalanced across participants. Knowledge of results regarding accuracy (constant error in mm) and movement time (msec) was presented in numerical form after each trial on a Dell Trinitron 19" monitor positioned 40 cm in front of the participant. At the beginning of each block of trials, participants were given approximately 10-15 practice trials to familiarise themselves with the experimental condition. During testing, those trials which were not within ±10% of the criterion MT were discarded and repeated. This amounted to less than three trials in any one block of trials.

Data Reduction, Dependent Measures and Analyses. The displacement data for each trial were filtered using a second-order dual-pass Butterworth filter with a low-pass cut-off frequency of 10 Hz. Instantaneous velocity data were obtained by differentiating the displacement data using a two-point central finite difference algorithm. This process was repeated to obtain acceleration data. In order to locate the beginning of the movement, peak velocity was first obtained. The velocity profile was then traversed backwards in time until the velocity fell below 1 cm/sec. The end of the movement was described as the point in time following peak velocity in which the absolute velocity of the pen fell below 1 cm/sec. This criteria at the end of the movement meant that trajectories could not contain a reversal in direction.

Dependent measures included the time and distance travelled at each of the kinematic markers. In order to investigate spatial variability throughout the movement the within-participant standard deviation in distance travelled at peak acceleration, peak velocity, peak negative acceleration and the end of the movement was calculated.

7.2. Results

Means of Movement Time and Distance Travelled

The mean movement time and distance travelled at the kinematic markers were analysed using separate 4 visual conditions (FV, PV, CV and NV) x 4 kinematic markers (peak acceleration, peak velocity, peak negative acceleration and movement end) repeated measures ANOVAs. As expected, the analysis of movement time revealed a significant main effect of kinematic marker, $F\ (3, 45) = 2798.7, p < .001$, with movement times increasing as the movement progressed. There were no effects of visual condition ($p > .05$). Hence, there were no differences in movement time between visual conditions at any of the kinematic markers.

The analysis of the distance travelled at each kinematic marker revealed significant main effects for both kinematic marker, $F\ (3, 45) = 7066.4, p < .001$, and visual condition, $F\ (3, 45) = 9.3, p < .001$. There was also a significant visual condition x kinematic marker interaction, $F\ (9, 135) = 5.3, p < .001$. Breakdown of this interaction using Tukey's HSD revealed that the distance travelled at peak velocity, peak negative acceleration and the end of the movement was greater in the PV condition compared to all other conditions. In addition, the distance travelled at the latter stages of the movement (i.e. peak negative acceleration and movement end), was greater in the FV condition compared to the CV and NV conditions (see table 10).

Visual Condition	Dependent Variable			
	PKA	PKV	PKNA	END
FV	18.86 *7.91*	119.24 *5.63*	220.43 *3.91*	241.07 *1.51*
PV	19.77 *8.77*	122.14 *4.17*	223.55 *6.98*	245.06 *3.75*
CV	18.08 *8.38*	119.25 *4.61*	215.66 *3.98*	238.07 *2.09*
NV	18.12 *8.34*	119.34 *7.88*	214.43 *6.86*	237.94 *6.75*

Table 10. Mean, *standard deviation*, of the distance travelled (mm) at peak acceleration (PKA), peak velocity (PKV), peak negative acceleration (PKNA), and movement end (END) as a function of visual condition.

Spatial Variability

The variability in the distance travelled at the various kinematic markers were analysed by performing a 4 visual conditions x 4 kinematic markers repeated measures ANOVA. This analysis revealed significant main effects for visual condition, $F\ (3, 45) = 4.2, p < .01$, and kinematic marker, $F\ (3, 45) = 37.4, p < .001$. The analysis also revealed a significant visual condition x kinematic marker interaction, $F\ (9, 135) = 9.7, p < .01$. A breakdown of this interaction revealed that variability increased up to peak negative acceleration and then decreased toward the end of the movement in all visual conditions. However, variability was lower in the FV and CV conditions compared to the NV and PV conditions at peak negative acceleration. Additionally, variability at the end of the movement was lower in both the FV and CV conditions compared to the NV condition while the FV condition was significantly lower than the PV condition (see Figure 22).

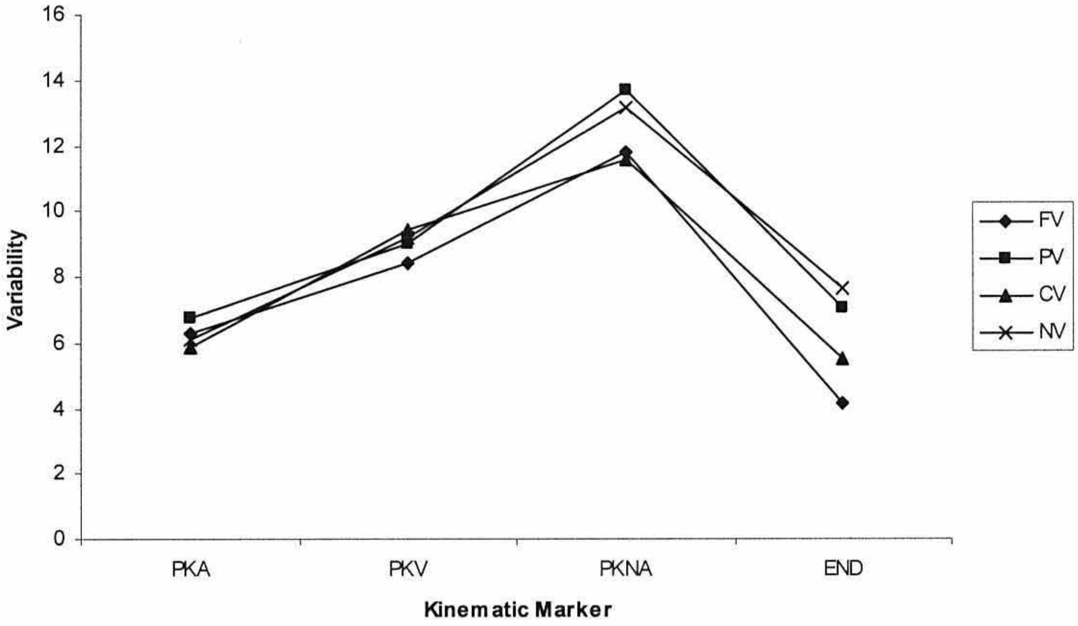

Figure 22. Variability in distance travelled at peak acceleration (PKA), peak velocity (PKV), peak negative acceleration (PKNA), and movement end (END) for the full (FV), peripheral (PV), central (CV) and no vision (NV) conditions.

The ratios in spatial variability between each visual condition and the NV condition at each kinematic marker were submitted to a 3 visual condition (FV:NV, PV:NV and CV:NV) x 4 kinematic marker repeated measures ANOVA. This analysis revealed significant main effects for both visual condition, $F(2, 30) = 5.9, p < .01$, and kinematic marker, $F(2, 30) = 5.7, p < .01$, as well as a significant interaction between visual condition and kinematic marker, $F(6, 90) = 2.5, p < .05$. A breakdown of this interaction revealed that the ratio in variability between the FV and NV conditions and the PV and NV conditions decreased from peak acceleration to peak velocity. After peak velocity, the ratio in variability between the PV and NV conditions remained constant. However, the ratio in variability between the FV and NV conditions and the CV and NV conditions significantly decreased from peak velocity to the end of the movement with this decrease being greater for the FV: NV ratio compared to the CV: NV ratio (see Figure 23).

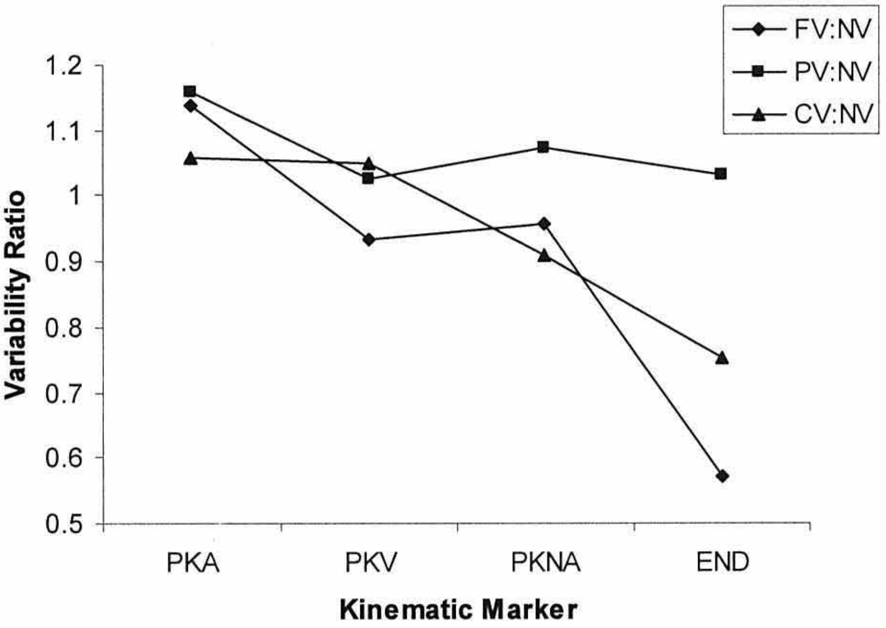

Figure 23. Ratios in variability between the full and no vision conditions (FV:NV), peripheral and no vision conditions (PV:NV) and central and no vision conditions (CV:NV) at peak acceleration (PKA), peak velocity (PKV), peak negative acceleration (PKNA), movement end (END).

Correlations Between Kinematic Markers and Movement Outcome

The squared within-participant correlation coefficients (r^2) and the squared Fischer Z transformations of the correlation coefficients (Z^2) between the distance travelled at peak velocity and the end of the movement are presented in Table 11. Since the number of subjects was equal to 16 and the alpha level was set at .05, any r^2 above .497 was classified as significant (Person and Hartley, 1966). A 4 visual condition repeated measures ANOVA performed on the squared Fischers Z transformations revealed a significant main effect of visual condition, $F(3, 45) = 3.83, p < .05$. Post hoc tests revealed that the proportion of the variance in the distance travelled at the end of the movement explained by the distance travelled at peak velocity was greater in the NV condition compared to all other conditions.

Since examination of the ratios in variability revealed that both the FV: NV ratio and the PV: NV ratio decreased from peak acceleration to peak velocity, the correlation between the distance travelled at these two kinematic markers was also analysed. The results of this analysis revealed no significant differences between the visual conditions ($p > .05$).

Visual Condition	Dependent Variable	
	r^2	Z^2
FV	.05	.09
PV	.08	.15
CV	.08	.16
NV	.14	.32

Table 11. Mean, *standard deviation*, squared correlation coefficients (r^2) and the squares of the Fischer Z transformations (Z^2) of the correlation coefficients between distance travelled at peak velocity and distance travelled at the end of the movement as a function of visual condition.

7.3. Discussion

Past research has revealed that central vision plays an important role in the control of movement amplitude. However, an important issue regarding the benefits of central vision is the extent to which accuracy is determined by movement planning versus online control. Therefore, the primary goal of the present research was to determine whether seeing ones hand while it is moving in central vision can be used to detect and correct errors in limb trajectory during movement execution. Consistent with the findings from previous research (Bard et al., 1990; Carlton 1981; Temprado et al., 1996), the results of the present experiment revealed that there was less variability in spatial error at the end of the movement in the central vision and full vision conditions compared to the no vision condition. This is consistent with Paillard and Amblard's (1985) two-channel model which proposes that movement amplitude is processed via the static visuomotor channel which operates in the central visual field.

The analysis of spatial variability at different kinematic markers revealed that variability increased up to peak negative acceleration and then decreased toward the end of the movement in all visual conditions. However, the central vision and full vision conditions revealed significantly lower variability than the no vision condition at both peak negative acceleration and the end of the movement. Consistent with this, the ratios in variability between the central and no vision conditions and between the full and no vision conditions were constant up to peak velocity and then decreased as the movement progressed. Hence, the form of the variability profile was fundamentally different in the central and full vision conditions compared to the no vision condition at the latter stages of the movement. This provides evidence that participants compensated for variations in the trajectory based on information gained from the central visual field.

The results of the correlation analysis provide additional support for this interpretation. The analysis revealed that the proportion of variance in movement distance explained by the distance travelled at peak velocity was significantly lower in the central and full vision conditions compared to the no vision condition. Hence, early kinematics were a poorer predictor of movement outcome when both full and central visual information was available. This finding along with the results from the ratio in variability analysis provides strong evidence that the differences observed in the variability profiles between the central and full vision conditions and the no vision condition was likely due to processes occurring during movement execution.

Although spatial variability at the end of the movement did not differ between the peripheral and no vision condition, the analysis of spatial variability throughout the movement revealed evidence for early online control in both the peripheral and full vision conditions. The ratio in variability between the peripheral and no vision conditions and the full and no vision conditions significantly decreased from peak acceleration to peak velocity. Hence, the peripheral and full vision variability profiles differed to that of the no vision condition at these early kinematic markers. This suggests that visually based corrections were made early during movement execution. It should be noted, that for amplitude tasks there has generally been no evidence for early online control through the utilisation of peripheral vision (Bard et al., 1985; Bard et al., 1990; Carlton, 1981; Temprado et al., 1996). These studies typically found that amplitude accuracy was not improved through the availability of vision in the first portion of the movement. However, since only the terminal accuracy of movements were analysed, these researchers were unable to investigate the utilisation of vision throughout the movement trajectory.

It was expected that if early online control was present in the peripheral and full vision condition, the proportion of variance in the distance travelled at peak velocity explained by the distance travelled at peak acceleration would be lower in these two visual conditions compared to the central and no vision conditions. However, the analysis of the correlation coefficients between the distance travelled at peak acceleration and the distance travelled at peak velocity revealed no significant difference between visual conditions. At present it is not clear as to why the results of the correlation analysis do not support the results of the variability ratio analysis. Nonetheless, findings from recent research (Bédard & Proteau ,2004) using a video aiming task support the interpretation that peripheral vision can be used to correct errors during the movement trajectory in an amplitude task. Bédard and Proteau (2004) instructed participants to reach towards visible targets at different movement times ranging from 300 to 900 msec. They reported that at the longer movement times (> 500 msec) extent variability decreased significantly between peak velocity and movement outcome for the full, peripheral and central vision conditions. It was suggested that this decrease was a result of modulations to the movement trajectory based on online visual afferent information. Thus, they concluded that because extent variability decreased and did not differ between the central and peripheral visual conditions both are utilised to correct amplitude planning errors online. The present results add to these findings by reporting the early use of peripheral visual feedback in controlling movement amplitude.

In summary, the comparison of the variability profiles revealed that visual feedback was utilised to compensate for amplitude errors during the course of movement execution in all visual conditions. However, visual information from the central visual field was utilised more effectively to correct errors online compared to visual information from the peripheral visual field. This finding supports Paillard and Amblard's (1985) two channel model and the existence of a static channel for the processing of movement amplitude.

CHAPTER 8
GENERAL DISCUSSION

The investigation of target directed movements dates back over a century to the work of Woodworth (1899). He proposed that aiming movements consist two phases; an initial impulse and a current control phase. The initial impulse is assumed to be a centrally programmed 'ballistic' movement designed to take the limb into the vicinity of the target. The current control phase is assumed to utilise afferent information to evaluate the discrepancy between the position of the limb at the end of the initial impulse and the target to be reached in order to provide the parameters for the programming of the subsequent correction. Although this proposition was formulated over 100 years ago and provides the basis for many theories describing limb control (Crossman & Goodeeve, 1983; Meyer et al., 1988), the relative contributions of central planning and sensory feedback in the control of movement are still debated. In this thesis, the effect of response complexity on programming processes during both reaction time and movement execution was investigated. It is proposed that prior knowledge of the number of elements in a response and the availability of visual feedback determines the extent to which movements are programmed in advance and the nature of the online programming. Also, the role of visual feedback in the programming and online control of movements was investigated by employing a novel method whereby the variability in limb trajectories throughout the movement was analysed.

8.1. Motor Programming

In their classic study, Henry and Rogers (1960) demonstrated a positive relationship between response complexity and reaction time (RT). However, further research in this area suggests that response complexity does not always have the same influence on simple and choice RT (Canic & Franks, 1989; Franks & Van Donkelaar, 1990; Henry & Rogers, 1960; Klapp, 1975, 1995, 2003; Klapp et al., 1974; Klapp & Rodriguez, 1982; Sternberg et al., 1978, 1990). Klapps' (1995, 2003) two process model postulates that it is the duration of an individual response element (INT) that influences choice RT, whereas it is the scanning of an abstract time frame, specifying the timing of initiation of response elements (SEQ), that influences simple RT. An alternative interpretation is the hypothesis that participants distribute the programming of responses differently under simple and choice RT conditions. It has been suggested that responses may not be programmed in their entirety during the RT interval and that programming can persist during movement execution (i.e. online) (Glencross, 1980; Smiley-Oyen & Warringham, 1996). It is possible that participants in the choice RT condition adopted a programming strategy where online programming was more prevalent than in simple RT. If this were the case, it was expected that movement times for the first element would be longer in the choice compared to simple RT condition.

This thesis tested Klapps' (1995, 2003) two process model through a series of three experiments using rapid aiming movements. Experiment 1 required participants to make horizontal sliding movements, consisting of one or two movements to either small or larger targets, under both simple and choice RT conditions. If the assumptions of the two process model (Klapp, 1995, 2003) are correct then it was expected that only simple RT should be greater for the two compared to one element responses. Furthermore, given that movement time increases as the accuracy demands of a task increases (Fitts, 1954), it was expected that choice RT should be greater for the small compared to large target conditions. In order to investigate the issue of online programming, two additional experiments adopting a dual task procedure were conducted. By examining the type of interference created by the dual task, inferences could be drawn about the nature of the online programming occurring.

The RT results of all three experiments revealed that simple RT increased from the single to the two element responses, whereas there was no effect of the number of elements on choice RT. Although these results are consistent with the two process model of response programming (Klapp, 1995, 2003), the findings from the dual task procedure revealed that an online programming explanation could account for the effects of complexity on simple and choice RT. The secondary task RTs indicated that the attention demands during the first element were greater in the two compared to single element responses in both the simple and choice RT conditions. This heightened degree of interference during movement execution of the first element indicates that online programming occurred in both RT tasks. It is believed that participants in the choice RT condition programmed the second element online in order to reduce the effects of response complexity on RT. Support for this is provided by the null effect of the number of elements on choice RT. However, it appeared that the nature of the online programming in the simple RT condition was different to that in the choice RT condition. The terminal accuracy of the first element significantly decreased in simple but not choice RT when the secondary task occurred during movement execution. In addition, movement times to the first target in the two element responses were longer in simple compared to the choice RT. Therefore, it seems that online programming in the simple RT condition involved the utilisation of visual feedback to time the implementation of the second element. This is consistent with the movement integration hypothesis (Adams et al., 2000) which suggests that increased executive control is involved during the execution of the first element to enhance the integration with the second element. It has been suggested that visual feedback obtained during the execution of the first element may be used to time the implementation in order to enhance the integration further (Helsen et al., 2001). Thus, it appears that participants in the simple RT condition programmed movements to the first target with longer durations in order to use visual feedback to time the implementation of the second element online. Diverting attention away from these processes by employing a dual task procedure resulted in a reduction in the terminal accuracy of the first element.

The characteristics of the experimental tasks may account for the difference in the distribution of programming between the simple and choice RT conditions. The certainty of early responses might have promoted an online programming strategy in the choice RT condition. In all three experiments, the first element of any response was always to the same target and therefore there was no uncertainty with regards to the first element. It has been reported that choice RT decreases when the unknown element of a response occurs later in a movement sequence (Garcia-Colera & Semjen, 1988; Rosenbaum et al., 1984). It was concluded from this that participants program the latter elements of a response online when the early elements are known in advance. With this in mind, participants in the choice RT condition may have always programmed the first element in the same way and then relied on online programming in the experimental conditions where two element responses were required.

It is also possible that the relative complexity of responses promoted online programming in the choice RT. Previous research has shown that choice RT increases as a function of response complexity when responses are relatively simple (Klapp et al., 1973, 1974; Klapp, 1995) but is unaffected when responses are more complex (Chamberlin & Magill, 1989; Klapp, 1995). Therefore, it seems that when responses are relatively simple in complexity, participants in choice RT conditions program the entire movement response during the RT interval. However, when responses are situated on the higher end of the complexity scale, as in the present experiments, participants in a choice RT condition are more likely to use online programming as a strategy to minimise RT.

Finally, the availability of vision may have influenced the type of programming strategy that emerged in the simple RT condition. It was concluded from the results of Experiment 1 and 2 that participants programmed both response elements prior to movement initiation in the simple RT condition and then utilised visual feedback in order to time the initiation of the second element online. It has been suggested that visual guidance of the first element facilitates the timing of initiation of the second element so that response elements can be optimally integrated (Helsen et al., 2001). Therefore, the knowledge that visual feedback was available during movement execution may have promoted a programming strategy in which participants were concerned with the integration of response elements. Consequently, it is difficult to conclude whether a similar programming strategy would emerge for the simple RT conditions in situations where vision is occluded.

In summary, when performing aiming movements, were vision is available and movement times are free to vary, the distribution of response programming between RT and movement execution differs between simple and choice RT as response complexity increases. In simple RT, components of multiple element movements are loaded into a buffer prior to movement execution. The execution of the first element is then visually guided so that the movement commands associated with the second element can be implemented at a time that results in the optimal integration between response elements. In choice RT, the programming of the second element is delayed until after the RT interval and carried out during movement execution of the first element. This strategy reduces the effects of response complexity on RT since only one element is programmed in advance of movement initiation.

8.2. Visual Feedback

Aiming movements that are performed with vision result in greater accuracy than movements performed without vision. In has been reported that these accuracy benefits are due to the utilisation of vision during movement execution (i.e. online) (Blouin et al, 1993, Zelaznik et al., 1983). However, researchers have also suggested that the utilisation of vision may occur after movement execution (i.e. offline), whereby visual feedback from a completed movement is used as an enriched form of knowledge of results to enhance the programming of subsequent actions (Abahnini et al., 1997; Blouin et al, 1993; Zelaznik et al., 1983). The role of vision greatly depends on the movement duration of the required action, since a prerequisite for online processing of visual feedback is that movement durations are sufficiently long enough to encompass visuomotor delays.

In general, the utilisation of vision online has been inferred from the presence of discrete corrections in the movement trajectory. This is based on the assumption that visual control is intermittent, in that corrections cannot take effect until the initial impulse has ended (Vince, 1948; for a review see Elliott et al., 2001). However, it has been suggested that visual control may be continuous in nature (Elliott et al., 1991, 1995, 1999). Thus, the online regulation of movements will not be reflected in discrete corrections to the kinematic profiles. With this in mind, the current thesis adopted a novel methodology in which the variability in limb trajectories at different stages of movement was analysed. Offline processing of visual feedback was inferred if the availability of vision resulted in a lowering of the variability profiles but the form of the profile was not altered. The online utilisation of visual feedback was inferred only if there was a significant difference in the form of the variability profiles between visual conditions.

In order to compliment the analysis of variability, the distance travelled at early kinematic markers was correlated with the distance at the end of the movement. The rationale being that if movements are programmed in advance and not modulated online then the proportion of variance at the end of the movement that can be explained by variability at the early kinematic markers will be high (Gordon & Ghez, 1987; Messier & Kalaska, 1999)[16]. Conversely, if adjustments are made online then the extent to which variability at the end of the movement is determined by variability earlier in the movement will be low.

It was observed that when vision was available under relatively fast movement times or when vision was presented late in the movement, variability profiles were lowered but the form of the profile was not affected when compared to situations in

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[16] When movement end points are determined before movement initiation and not subject to changes during the limb trajectory then one would expect r^2 to be equal to 1. However, this is not demonstrated by the results of the current thesis as the NV r^2 values were approximately 0.6-0.7. This may be due to inherent noise in the motor system.

which vision was not available. In addition, the proportion of variance in the distance travelled at the end of the movement that was explained by the distance travelled at the early kinematic markers did not differ between visual conditions. Hence, vision was used offline as a form of knowledge of results to improve the programming of subsequent trials. In contrast, there were significant differences in both the form of the variability profiles and the coefficient of determination (r^2) between the vision and no vision conditions at longer movement times or when vision was presented early in the movement. This implies that visual feedback was utilised online so that adjustments to the limb trajectory could be made to compensate for variations in the early part of the movement.

A primary assumption underlying the utilisation of variability profiles as an indicator of offline and online processing is that variability would increase throughout the movement if trajectories are not modified during movement execution. In the analyses of variability ratios, the no vision condition was used as a control condition. However, the variability profiles decreased from peak negative acceleration to the end of the movement in the no vision conditions. This decrease may be due to a number of factors. Firstly, the utilisation of proprioceptive feedback, the processing of which could have been enhanced due to the tasks' relatively simple nature. In the amplitude aiming task, all movements were in a single dimension and to one target. Secondly, the acceleration data were obtained by a double differentiating procedure, whereby the displacement data were differentiated to obtain the velocity data which was then differentiated to obtain the acceleration data. This double differentiating procedure may have elevated noise in the data and hence variability at peak negative acceleration relative to the end of the movement which was determined by a velocity criterion. Finally, consistent with equilibrium point theories, the movement endpoint may have been programmed and the limb trajectory determined by the elastic muscle properties. When movements are controlled through the specification of an equilibrium point between the agonist and antagonist muscles, endpoints are reached despite variations throughout the limb trajectories. These factors help to stress the importance that the online utilisation of visual feedback should not be inferred only from a decrease in the variability profile. The utilisation of visual feedback online should only be inferred if the variability profiles differ in form between the visual conditions and, if the coefficients of determination are lower in the full compared to no vision conditions when early kinematic markers are correlated with the end of the movement.

In summary, the combination of the variability and correlation analysis is a viable method to establish the roles of offline and online visual feedback processing. The results revealed that at fast movement durations the benefit of vision was only due to the offline processing of visual feedback. However, when movement durations were longer, the predominant role of vision was in the online regulation of movements, whereby visually based corrections compensated for variations in the movement trajectory during the latter part of the movement. These results challenge previous research that shows visual feedback is processed online when movement durations are relatively fast (Carlton, 1992; Zelaznik et al., 1983). It may be that the benefit of vision reported by these researchers was due to offline visual feedback processing rather than online visual feedback processing. Finally, the online regulation of movement trajectories occurred in the absence of discrete corrections to the kinematic profiles, this supports suggestions by

Elliott and colleagues (Elliott et al., 1991, 1995, 1999) that visual control is continuous rather than intermittent in nature.

8.3. The Interplay Between Programming and Feedback Processing in the Control of Target Directed Movements

In a study designed to investigate the effect of practice on the control of target directed aiming movements, Khan, Franks and Goodman (1998) have demonstrated that an interdependency between movement programming and the utilisation of sensory information develops with practice. In their study, participants performed an aiming movement as fast and as accurately as possible in either a full or no vision condition. The influence of visual feedback on the initial impulse and error correction phases during acquisition was examined. The results showed that initial impulses consistently undershot the target when movements were performed in the full vision condition. In contrast, there was no bias in the endpoint of the initial impulse for movements in the no vision condition. It was concluded that these findings were a result of participants programming movements with different strategies, the emergence of which depended on the type of feedback available during movement execution. It was suggested that when participants new that visual feedback was available they programmed the ballistic phase of the movement to finish short of the target. This strategy meant that visual feedback could be utilised online to ‘home in’ on the target and that the error corrections involved in this process were more efficient since adjustments to the limb trajectory were always made in the same direction as the initial impulse. However, when vision was unavailable participants adopted a different strategy whereby initial impulses were programmed to finish on the target, presumably to avoid the use of less effective proprioceptive feedback. These findings imply that movement programming depends on the type of feedback available during movement execution and that the programming strategy adopted influences the use of visual feedback.

Similarly, Khan et al. (2002) have recently shown that prior knowledge of whether or not vision would be available had a significant impact on the strategies that participants adopted. When the visual condition was not known in advance of movement initiation, participants adopted similar control strategies in the vision and no vision conditions. However, when participants knew that they were going to receive visual feedback, they spent less time initiating their movements, less time reaching peak deceleration, but more time after peak deceleration compared to when they did not receive visual feedback. It appeared that when visual feedback was available, participants spent less time preparing the movement but made effective use of the visual feedback by getting the limb to the vicinity of the target quickly and allowing time to adjust trajectories at the end of the movement. When visual feedback was not available, more time was spent preparing the movement prior to initiation in order to reduce the need for feedback-based corrections during movement execution.

The work reported in this thesis provides further evidence that the programming of movements is influenced by the availability of feedback. If the number of elements in a response is known prior to stimulus presentation, it appears that participants load the elements in a buffer so they can be implemented when necessary in order that the integration between movements is optimal. When vision is available in these situations, it is utilised to monitor the execution of the first movement in order to enhance this integration further by specifying when the second movement should be implemented. However, when the number of movements is not known before stimulus presentation then the role of vision in monitoring the first movement is reduced. This may be due to limitations in attention, since participants adopt strategies of online programming in these situations. Results from a recent experiment investigating the effects of the number of response elements on both simple and choice RT under conditions of no vision provide additional support for this interpretation (Moreton, 2004). In contrast to the results reported in the present thesis which revealed longer movement times in simple compared to choice RT conditions, Moreton showed that for the multiple element conditions movement durations to the first target were longer in the choice compared to simple RT conditions. These results support the initial online programming hypothesis which suggests that online programming was only occurring in the choice RT condition. Therefore, it seems that the integration hypothesis may only hold in situations where vision is available. That is, in situations where the number of elements is known in advance, participants may program movements to enhance the integration between elements only when visual feedback is available.

Both the contribution of central programming and visual feedback in the control of movements where responses are known in advance compared to movements where responses are not known in advance needs further investigation. Future research in this area should include methodologies which compare the effect of the number of elements on simple and choice RT under both vision and no vision conditions. Variability profiles should then be compared between conditions to see if participants in the simple RT condition utilise vision to reduce the variability at the end of the first movement to enhance the integration between response elements. In addition, similar experiments to those proposed above should be conducted that manipulate the amplitude of the responses (i.e. long versus short). This would enable researchers to investigate how programming strategies and the utilisation of vision change when movement amplitudes change. Finally, the movement integration interpretation of the present results may not be limited to movements with a reversal in direction. In sequential aiming movements in which the second element is in the same direction of the first, movement times to the first target are typically longer compared to single element responses. This one-target movement time advantage has been said to be due to increased executive control which mediates the transition between response elements (Adam et al., 2000). Therefore, it would be interesting to determine if the integration between elements in unidirectional sequential aiming movements is enhanced when participants have prior knowledge that a two element response is required (i.e. simple RT) compared to when the number of elements is unknown (i.e. choice RT).

In summary, for single element movements that are known in advance, vision is utilised to modify limb trajectories during movement execution providing that sufficient time is available to encompass visuomotor delays. Vision can also be used as a form of knowledge of results to improve the programming of subsequent trials and hence have an impact on movement accuracy when there is not sufficient time to correct error during movement. In multiple element movements, vision serves a dual process during movement execution. First, visual information can be utilised to correct error in the limb trajectory during execution of the first element. Second, the execution of the first element can be monitored through the use of vision so that the integration with the second element is enhanced. Here visual feedback from the first element provides information for specifying when the second element is implemented and the distance required on the second element to reach the final target. These two functions of vision are not mutually exclusive since the reduction in variability at the first target can enhance the specification of the timing and amplitude of the second element by reducing the uncertainty in these variables.

List of References

Abahnini, K, Proteau, L., & Temprado, J.J. (1997). Evidence supporting the importance of peripheral visual information for the directional control of aiming movement. *Journal of Motor Behavior, 29*, 230-242.

Abahnini, K., & Proteau, L., (1999). The role of peripheral and central visual information for the directional control of manual movements. *Canadian Journal of Experimental Psychology, 53*, 160-175.

Abrams, R.A., Meyer, D.E., & Kornblum, S. (1990). Eye-hand coordination: Oculomotor control in rapid aimed limb movements. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 248-267.

Adam, JJ., Nieuwenstein, J.H., Huys, R., Paas, F.G.W.C., Kingma, H., Willems, P., & Werry, M. (2000). Control of rapid aimed hand movements: The one-target advantage. *Journal of Experimental Psychology: Human Perception and Performance, 26*, 295-312.

Bard, C., Hay, L., & Fleury, M. (1985). Role of peripheral vision in the directional control of rapid aiming movements. *Canadian Journal of Experimental Psychology, 39*, 151-161.

Bard, C., Paillard, J., Fleury, M., Hay, L., & Larue., J. (1990). Positional versus directional control loops in visuomotor pointing. *European Bulletin of Cognitive Psychology, 39*, 151-161.

Bédard, P., & Proteau, L. (2001). On the role of static and dynamic visual afferent information in goal directed aiming movements. *Experimental Brain Research, 138*, 419-431.

Bédard, P., & Proteau, L. (2003). On the role of peripheral visual afferent information for the control of rapid video-aiming movements. *Acta Psychologica, 113*, 99-117.

Bédard, P., & Proteau, L. (2004). On-line vs. off-line utilisation of peripheral visual afferent information to ensure spatial accuracy of goal-directed movements. *Experimental Brain Research, 158,* 75-85.

Blouin, J., Bard, C., Teasdale, N., & Fleury, M. (1993). On-line versus off-line control of rapid aiming movements. *Journal of Motor Behavior, 25*, 275-279.

Bock, O. (1986). Contribution of retinal versus extraretinal signals towards visual localization in goal directed movements. *Experimental Brain Research, 64*, 476-482.

Canic, M., & Franks, I.M. (1989). Response preparation and latency patterns of tapping movements. *Human Movement Science, 8*, 123-139.

Carlton, L.G. (1981). Processing visual feedback information in movement control. *Journal of Experimental Psychology, 7*, 1019-1031.

Carlton, L.G. (1992). Visual processing time and the control of movement. In L. Proteau & D. Elliott (Eds.), *Vision and motor control* (pp. 3-31). Amsterdam: North-Holland.

Carlton, L.G., Carlton, M.J., & Newell, K.M. (1987). Reaction time and response dynamics. *Quarterly Journal of Experimental Psychology, 39A*, 337-360.

Carlton, M.J., Newell, K.M., & Carlton, L.G. (1984). Predicting individual discrete response outcomes from kinematic characteristics. *Journal of Human Movement Studies, 10*, 62-82.

Chamberlin, C.J., & Magill, R.A. (1989). Preparation and control of rapid multisegmented responses in simple and choice environments. *Research Quarterly for Exercise and Sport, 60*, 256-267.

Chua, R., & Elliott, D. (1993). Visual regulation of manual aiming. *Human Movement Science, 12*, 365-401.

Crossman, E.F.R.W., & Goodeeve, P.J. (1983). Feedback control of hand-movement and Fitts' Law. *Quarterly Journal of Experimental Psychology, 35A*, 251-278.

Danckert, J., & Goodale, M.A. (2001). Superior performance for visually guided pointing in the lower visual field. *Experimental Brain Research, 137*, 303-308.

Darling, W.G., & Cooke, J.D. (1987). Changes in the variability of movement trajectories with practice. *Journal of Motor Behavior, 19*, 291-309.

Elliott, D., Binsted, G., & Heath, M. (1999). The control of goal-directed limb movements: Correcting errors in the trajectory. *Human Movement Science, 18*, 121-136.

Elliott, D., Carson, R.G., Goodman, D., & Chua, R. (1991). Discrete vs continuous control of manual aiming. *Human Movement Science, 10*, 393-418.

Elliott, D., Chua, R., Pollock, B.J., & Lyons, J. (1995). Optimizing the use of vision in manual aiming: The role of practice. *Quarterly Journal of Experimental Psychology, 48A*, 72-83.

Elliott, D., Helsen, W.F., & Chua, R. (2001). A century later: Woodworth's two-component model of goal directed aiming. *Psychological Bulletin, 127*, 342-357.

Enright, J.T. (1995). The non-visual impact of eye orientation on eye-hand coordination. *Vision Research, 35*, 1611-1618.

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

Fleury, M., Bard, C., Audiffren, M., Teasdale, N., & Blouin, J. (1994). The attentional cost of amplitude and directional requirements when pointing to targets. *The Quarterly Journal of Experimental Psychology, 47A*, 481-495.

Franks, I.M., & Van Donkelaar, P. (1990). The effects of demanding temporal accuracy on the programming of simple tapping sequences. *Acta Psychologica, 74*, 1-14.

Garcia-Colera, A., & Semjen, A. (1988). Distributed planning of movement sequences. *Journal of Motor Behavior, 20*, 341-367.

Ghez, C., Gordon, J., Ghilardi, M.F., & Sainberg, R. (1995). Contributions of vision and proprioception to accuracy in limb movements. In M.S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 549-564). Cambridge, MA:MIT Press.

Glencross, D.J. (1980). Reponse planning and the organisation of speed movements. In R.S. Nickerson (Ed.), *Attention and Performance VIII* (pp. 107-125). Hillsdale, NJ: Erlbaum.

Gordon, J., & Ghez, C. (1987). Trajectory control in targeted force impulses III. Compensatory adjustments for initial errors. *Experimental Brain Research, 67*, 253-269.

Gordon, J., Ghilardi, M.F., & Ghez, C. (1994). Accuracy of planar reaching movements. I. Independence of direction and extent variability. *Experimental Brain Research, 99*, 97-111.

Greenhouse, S.W., & Geisser, S. (1959). On the methods in the analysis of profile data. *Psychometrika, 24*, 95-112.

Hale, T., Hodges, N., Khan, M.A., & Franks, I.M. (2000). A comparison of static and dynamic forms of augmented feedback on the acquisition of a rapid aiming task. *Journal of Human Movement Studies, 39*, 1-13.

Helsen, W.F., Adam, J.J., Elliott, D., & Beukers, M. (2001). The one-target advantage: A test of the movement integration hypothesis. *Human Movement Science, 20*, 643-674.

Henry, F.M. (1980). Use of simple reaction time in motor programming studies: A reply to Klapp, Wyatt and Lingo. *Journal of motor Behavior, 12*, 163-168.

Henry, F.M., & Rogers, D.E. (1960). Increased response latency for complicated movements and a "memory drum" theory of neuromotor reaction. *Research Quarterly, 31*, 448-458.

Immink, M.A., & Wright, D.L. (2001) Motor programming during practice conditions high and low in contextual interference. *Journal of Experimental Psychology: Human Perception and Perfromance, 27*, 423-437.

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

Ketelaars, M.A.C., Khan, M.A., & Franks, I.M. (1999). Dual-task interference as an indicator of online programming in simple movement sequences. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 1302-1315.

Khan, M.A., Elliott, D., Coull, J., Chua, R., & Lyons, J. (2002). Optimal control strategies under different feedback schedules. *Journal of Motor Behavior, 34*, 45-57.

Khan, M.A., & Franks, I.M. (2000). The effect of practice on component submovements is dependent on visual feedback. *Journal of Motor Behavior, 32*, 227-240.

Khan, M.A., & Franks, I.M. (2002). Critical sources of visual feedback in the production of component submovements. *Journal of Motor Behavior, 35, 285-295.*

Khan, M.A., Franks, I.M. & Goodman, D. (1998). The effect of practice on the control of rapid aiming movements: Evidence for an interdependency between programming and feedback processing. *Quarterly Journal of Experimental Psychology, 51A*, 425-444.

Klapp, S.T. (1975). Feedback versus motor programming in the control of aimed movements. *Journal of Experimental Psychology: Human Perception and Performance, 1*, 147-153.

Klapp, S.T. (1995). Motor response programming during simple and choice reaction time: The role of practice. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 1015-1027.

Klapp, S.T. (2003). Reaction time analysis of two types of motor preparation for speech articulation: Action as a sequence of chunks. *Journal of Motor Behavior, 35*, 135-150.

Klapp, S.T., Abbott, J., Coffman, K., Snider, R., & Young, F. (1979). Simple and choice reaction time methods in the study of motor programming. *Journal of Motor Behavior, 11*, 91-101.

Klapp, S.T., Anderson, W.G., & Berrian, R.W. (1973). Implicit speech in reading, reconsidered. *Journal of Experimental Psychology, 100*, 368-374.

Klapp, S.T., & Wyatt, E.P. (1976). Motor programming within a sequence of responses. *Journal of Motor Behavior, 8*, 19-26.

Klapp, S.T., Wyatt, E.P., & Lingo, W.M. (1974). Response programming in simple and choice reactions. *Journal of Motor Behavior, 6*, 263-271.

Klapp, S.T., & Rodriguez, G. (1982). Programming time as a function of response duration: A replication of "dit-dah" without possible guessing artefacts. *Journal of Motor Behavior, 14*, 46-56.

Messier, J., & Kalaska, J.F. (1997). Differential effect of task conditions on errors of direction and extent of reaching movements. *Experimental Brain Research, 115*, 469-478.

Messier, J., & Kalaska, J.F. (1999). Comparison of variability of initial kinematics and endpoints of reaching movements. *Experimental Brain Research, 125*, 139-252.

Meyer, D.E., Abrams, R.A., Kornblum, S., Wright, C.E., & Smith, J.E.K. (1988). Optimality in human motor performance: Ideal control of rapid aimed movements. *Psychological Review, 95*, 340-370.

Moreton, S. (2004). The effects of amplitude and the number of elements on reaction time. Unpublished MSc dissertation.

Paillard, J., & Amblard, B. (1985). Static versus kinetic visual cues for the processing of spatial relationships. In D.J. Ingle, M. Jeannerod, & D.N. Lee (Eds.), *Brain mechanism in spatial vision* (pp. 367-385). La Haye: Martinus Nijhoff.

Pélisson, D., Prablanc, C., Goodale, M.A., & Jeannerod, M. (1986). Visual control of reaching movements without vision of the limb. II: Evidence of fast unconscious processes correcting the trajectory of the hand to the final position of a double-step stimulus. *Experimental Brain Research, 62*, 303-313.

Person, E.S., & Hartley, H.O. (Eds), (1966). *Biometrika tables for statisticians* (Vol. 1) (3rd ed.). London: Biometrika Trustees.

Plamondon, R., & Alimi, A.M. (1997). Speed/accuracy trade-offs in target-directed movements. *Behavioral and Brain Sciences, 20*, 279-349.

Posner, M.I., Nissen, M.J., Klein, R.M. (1976). Visual dominance: An information processing account of its origins and significance. *Psychological Review, 83*, 157-171.

Prablanc, C., & Martin, O. (1992). Automatic control during hand reaching at undetected two-dimensional target displacements. *Journal of Neurophysiology, 67*, 455-469.

Proteau, L. & Marteniuk, R.G. (1993). Static visual information and the learning and control of a manual aiming movement. *Human Movement Science, 12*, 515-536.

Proteau, L., & Masson, G. (1997). Visual perception modifies goal directed movement: Supporting evidence from visual perturbation paradigm. *Quarterly Journal of Experimental Psychology, 50A*, 726-741.

Rosenbaum, D.A., Inhoff, A.W., & Gordon, A.M. (1984). Choosing between movement sequences: A hierarchical editor model. *Journal of Experimental Psychology: General, 113*, 372-393.

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

Smiley-Oyen, A.L., & Worringham, C.J. (1996). Distribution of programming in a rapid aimed sequential movement. *Quarterly Journal of Experimental Psychology, 49A*, 379-397.

Sternberg, S., Knoll, R.L., & Turock, D.L. (1990). Hierarchical control in the execution of action sequences: Tests of two invariance properties. In M. Jeannerod (Ed), *Attention and Performance XIII* (pp. 3-55). Hillsdale, NJ: Erlbaum.

Sternberg, S., Monsell, S., Knoll, R.R., & Wright, C.E. (1978). The latency and duration of rapid movement sequences: Comparisons of speech and typewriting. In G.E. Stelmach (Ed.), *Information processing in motor control and learning* (pp. 117-152). New York: Academic Press.

Stevens, J. (2002). Applied multivariate statistics for the social sciences (4th edition). Lawrence Erlbaum Associates, New Jersey.

Temprado, J.J., Vieilledent, S., & Proteau, L. (1996). Afferent information for motor control: The role of visual information in different portions of the movement. *Journal of Motor Behavior, 28*, 280-287.

Tremblay, L., & Proteau, L. (1998). Specificity of Practice: The case of powerlifting. *Research Quarterly for Exercise and Sport, 69*, 284-289.

Van Donkelaar, P., & Franks, I.M. (1991). The effects of changing movement velocity and complexity on response preparation: Evidence from latency, kinematic and EMG measures. *Experimental Brain Research, 83*, 618-632.

Vidal, F., Bonnet, M.L., & Macar, F. (1991). Programming response duration in a precueing reaction time paradigm. *Journal of Motor Behavior, 23*, 226-234.

Vince, M.A. (1948). Corrective movements in a pursuit task. *Quarterly Journal of Experimental Psychology, 1*, 85-106.

Woodworth, R.S. (1899). The accuracy of voluntary movement. *Psychological Review, 3*, (monograph supplement), 1-119.

Zelaznik, H.N., Hawkins, B., & Kisselburgh, L. (1983). Rapid visual feedback processing in single-aiming movements. *Journal of Motor Behavior, 15*, 217-236.