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The role of vision in the preparation and execution of multiple target movements

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THE ROLE OF VISION IN THE PREPARATION AND EXCUTION OF MULTIPLE TARGET MOVEMENTS

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SCHOOL OF SPORT, HEALTH AND EXERCISE SCIENCES

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CHAPTER 1

THESIS OVERVIEW

1.1 Background

Many everyday tasks involve multiple movements that require accurate and proficient motor control (e.g., typing on a keyboard, using a smart phone or tablet, placing a pen in a desk organiser or simply making a cup of tea). Researchers have adopted many approaches to understanding how these type of aiming movements in order to examine how they are prepared and executed. In fact as early as the 19^{th} century researchers were investigating the control of rapid target direct movements (Woodworth, 1899) and revealed that single target actions consist of at least two distinct components; the first is the initial impulse and assumed to be fast, ballistic, pre programmed movement designed to bring the limb into the vicinity of the target; the second is an error correction phase whereby vision (or proprioception) of the limb and target are used to make corrections to the limb trajectory in order to accurately reach the target. This notion of a two component model is still consistent with recent motor learning perspectives, which also point to a two-component with multiple processes model of goal-directed aiming (for a review, see Elliott et al., 2010).

Studies have found that rapid aimed hand movements take longer when the movement is directed at a second target rather than executed toward a single target (Adam et al., 2000; Chamberlin & Magill, 1989; Elliot, Helsen, & Chua, 2001; Lavrysen, Helsen, Elliott & Adam, 2002). This phenomenon is known as the 'one-target advantage' (OTA), the prominent explanations of which fall in one of three hypotheses; online programming (Chamberlain & Magill, 1989); movement constraint (Fischman & Reeve, 1992); movement integration (Adam et al., 2000). All three of these hypotheses adopt the notion of central programming and online processes in attempts to explain why and how movements within a two target aiming task are functionally dependent.

It has been suggested that the dependency/movement integration between segments is aided by the availability of vision (Helsen, Adam, Elliott, & Beukers, 2001) through the visual monitoring and regulation of actions (also see Khan , Lawrence, Franks, & Buckolz, 2006). In direct support for this is found in conditions where visual feedback is occluded, since participants have been reported take longer to initiate their movement (Lavrysen et al., 2002); presumably this increase in reaction time is to ensure that actions are accurate and can be integrated without the use of visual information. In light of the above, an issue with has been at the forefront of much theorising is the extent to which movement integration is dependent on the relative contributions of central planning and online processing together with the role that vision might take in this interplay.

1.2 Outline of the thesis

This thesis utilises a series of experiments in an attempt to investigate issues relating to the planning and control of multiple target actions under vision and no vision conditions. The first experiment focused on the movement variability or the accuracy equivalent of the OTA. The aim here was to investigate the role of visual feedback in the interaction between movement segments within a time constrained action. This allowed a more direct approach to testing the MCH and MIH hypotheses than previous research that have adopted paradigms where movement times that are free to vary. Over the course of 3 further investigations, the use of visual feedback in the interplay between planning and online integration was examined under full vision conditions and conditions where visual feedback was occluded at the end of the first movement. Here movement times were free to vary and the primary purpose was to investigate the effect of varying the location of the first target location under a non-perturbed (investigation 1) and unexpected perturbation (investigation 2) paradigms together with the effect of unexpectedly perturbing the location of the second target (investigation 3). The explanations of the OTA are both expanded and re-examined in light of the role of visual information plays in the integration between movement between movement segments.

1.3 Thesis Format

This thesis consists of a review of the literature, four research papers and general discussion. All four manuscripts are written as standalone research articles. The first manuscript has been published in the international psychology and motor control journal Acta Psychologica. The remaining manuscripts are currently in preparation for publication consideration. For consistency, all manuscripts are written in style adopted by the school of Sport, Health and Exercise Science, Bangor University, which is described in American Psychology Association Publication Manual 2009 (6th Edition) and current recommendations of the Bangor University for thesis preparation. For the same reason, all citations are included a single section and the end of this thesis and illustrations are numbered consecutively.

CHAPTER 2

THE LITERATURE REVIEW

2.1 Background

In many everyday tasks, actions comprise of several components that are executed in sequence (e.g., dialling a telephone, catching and throwing a ball, grasping and drinking a glass of water). Researchers have adopted numerous approaches to understanding how multiple segment movements are prepared and executed. While early research was devoted to understanding the relationship between reaction time (RT) and the number of response segments/elements (e.g., Henry & Rogers, 1960; Klapp et al., 1974, Sternberg et al., 1978), more recent efforts have focused on the execution of segments (see Adam et al., 2000). With regard to the latter, the typical finding is that movement times (MT) to the first target in a two target movement are longer than in single target movements. This phenomenon is known as the one-target advantage (OTA), and emerges regardless of participants' hand preference and hand used (Helsen et al., 2001; Lavrysen et al., 2003), is resistant to practice (Lavrysen et al., 2003) and the occlusion of vision (Lavrysen et al., 2002). In the following pages of this thesis I will present more details about this phenomenon and the theories that have been proposed in an attempt to explain it.

2.2 The One-Target Advantage (OTA)

In numerous times throughout life we have to perform single aiming movements (e.g., turn on /off the light) or two movements in a sequence (e.g., opening a door and then turning off a light switch upon existing a room). In these latter two target actions, movement time to target one takes longer compared to the same movement in a single target action. As previously mentioned this phenomenon is known as the OTA. This has been shown by comparing performance (i.e. movement time to the first target in a sequence) in two conditions: Participants are asked either to move as fast as possible to the first target and strike the first target and move on toward the second target, or to stop at the first target. Glencross (1980) was the first researcher who reported the difference in movement time (to the first target) between one-tap and two-tap conditions and since then numerous researchers have supported Glencross's observations (Adam et al., 1993, 2000; Chamberlin & Magill, 1989; Fischman & Reeve, 1992; Helsen et al., 2001; Khan et al., 2010; Lavrysen et al., 2002, 2003; Ricker et al., 1999). Understanding this OTA would provide insights into the planning and execution of target directed movements, especially in relation to the interdependency between movements within an action. In an attempt to describe this potential movement interdependency, the OTA literature has provided various explanations for the phenomenon, together with a number of factors that influence both its occurrence and magnitude. The ensuing pages of this thesis attempt to both detail and summarise these in a logical fashion. As such, the first sections are concerned with the various hypotheses proposed to explain the OTA, then, because many of these incorporate ideas associated both with response planning and online movement execution, the next sections aim to provide detailed background information regarding these processes. Finally, additional factors that have been shown to influence the OTA are discussed.

2.3 OTA explanations/hypotheses

Online programming Hypothesis

The Online programming Hypothesis (Chamberlain & Magill, 1989) is based on the notion that, in sequential aiming movements, the second movement is programmed during the execution of the first which results in an increase in the time required to execute the first movement. As such, Chamberlin and Magill (1989; see also Ricker et al .1999) attribute the one-target advantage to the online processes required to prepare the second movement while the first movement is in progress. In support of this, Fischman and Reeve (1992) tested this explanation of the OTA by allowing the performers to take as much as time they need in their initial movement whilst also reducing the difficulty of the second movement. They found that even with the smallest need for online programming (i.e., the lowest difficulty rating of movement two), the OTA remained present, suggesting that the reason for the lengthening of the first movement time in multiple target movements is due to the on-line programming of the second segment during execution of the first. This theory proposes that in sequential movements the planning is not completely prepared in advance. Thus, when responses are relatively complex (i.e., contain two movements), performers may use the RT interval to program the initial response segment (i.e., the movement to the first target) and then slow down this segment in order to allow sufficient time to accurately program the movement commands of the second segment in conjunction with executing the first.

Movement constraint hypothesis

According to the Movement Constraint Hypothesis (MCH) (Fishman & Reeve, 1992) the performer is constrained to prepare a more controlled movement to the first target before hitting the second one. That is, in order to hit the second target accurately, the performer has to be more precise and accurate in hitting the first target). In particular, a participant performing a two-element response might adopt a strategy of restraining the limb as it approaches the first target so as smoothly and quickly execute the second movement. It is possible that this strategy could be planned before movement initiation (Fischman and Reeve, 1992). The MIH based on the assumption that variability increases as movement distance increases (Schmidt, 1979; also see Khan et al., 2006 for a review). This means that in order to reduce impulse variability, the performer must reduce the accelerative impulse associated with the first movement, which will reduce endpoint variability associated with the first movement (Schmidt et al., 1979). Since both movement commands are hypothesised to be programmed prior to movement execution, this strategy allows a more accurate end point at the first target thus ensuring the pre-programmed commands of the second target require minimal trajectory adjustment as the limb approaches the second target. In sum, according to the MCH, the one target advantage is the result of a constraining motor control strategy which results in movements to a single target being categorised by relatively shorter deceleration phases and larger peak velocities than the corresponding movement in a two target response (Adam et al 1993).

The movement integration hypothesis

The movement integration hypothesis (MIH) was formulated by Adam et al. (2000), and similar to the MCH, combines planning and on-line control processes when explaining the OTA. However, whilst the MCH proposes that the latter segments within an action are subject to online movement programming (Chamberlain & Magill, 1989), the MIH proposes that the second movement is prepared in advance of response initiation (i.e., during the reaction time interval) and that the movement time cost associated with two versus single target actions resides in implementing the program commands for the second movement during execution of the first movement. Specifically, for two movement responses Adam et al. (2000) propose that both movements are programmed in advance of movement onset and that motor commands of the second movement are held in a buffer. The neuromuscular organisation and implementation of these commands are then implemented during the execution of the first at a time deemed appropriate to ensure that a smooth transition between movement segments is achieved. It is the cognitive processes involved in implementing the second movement whilst executing the first that creates interference with the first movement and results in a lengthening in the execution time of the first movement (i.e., the OTA).

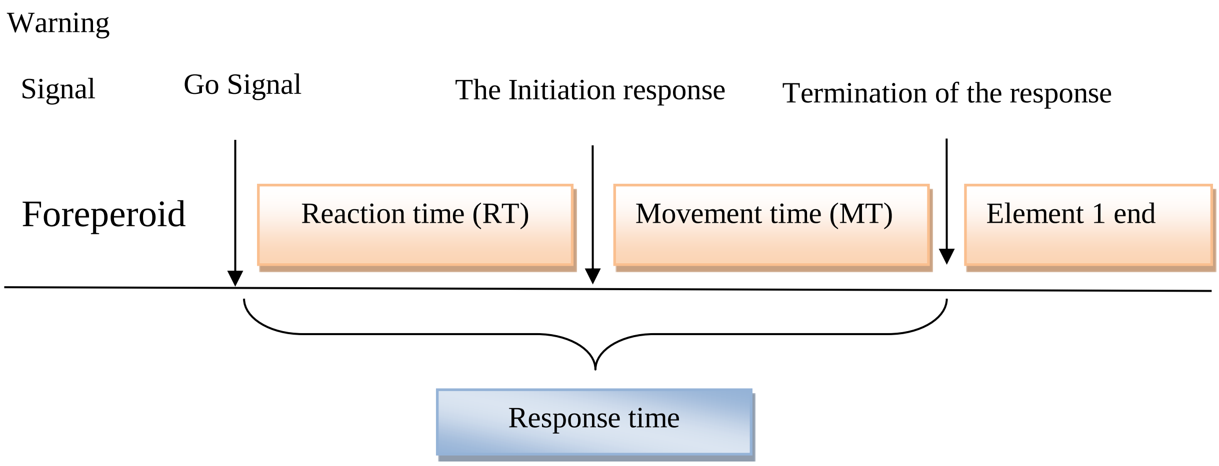
2.4 The Influence of Response Complexity on Reaction Time

Since all three of the aforementioned explanations of the OTA involve notions of motor planning, the following section aims to summarise research that has investigated motor planning in relation to the number of movements within a response. Henry and Rogers (1960) revealed that reaction time (RT) is clearly related to the number of elements within a response. They reported that RT for a finger lift off a key was faster compared to situations where this response was followed by subsequent actions (e.g., the grasping a ball.). This increase of RT as response complexity increases was attributed to the greater time needed to program more complex movements. According to Henry and Rogers, the quality of the response is associated with the availability of the information, and as the response gets more complicated the planning needs more stored information e.g., 'the coordination and direction into the eventual motor neurons and muscles in regard of neural impulses will require more time'. (p. 450).

The influence of complexity on RT has stimulated a great deal of interest in the field of motor control. The question of what aspect of response complexity is responsible for these increases in programming time has been a matter of much debate. As such researchers have investigated questions such as ‘does the response complexity have the same effect on RT when the person knows in advance what movement will be made (simple reaction time) compared to situations where the movement response is not known until stimulus presentation (Choice reaction time). In simple RT tasks, participants know which response to produce prior to the presentation of the stimulus (see Figure 1). In contrast, participants performing a choice RT task do not know the required response until stimulus presentation. With these differences, it is reasonable to suggest that some programming may be completed before the go signal or stimulus in a simple RT condition. Whereas in Choice RT pre programming cannot be performed since the response selection must occur during the RT interval. On this basis, one might not expect simple RT to increase as a function of response complexity since programming can be performed prior to the RT interval. In series of experiments using Morse code responses, 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 reaction time conditions.

This experimental design allowed an investigation into how the number of elements and response duration may have different effects on both simple and choice reaction time. Klapp showed that the duration of single-element response (e.g., dit – dah) had an influence on choice RT but not simple RT, whilst the number of elements increased simple RT (e.g., dit-dit,dah,dah,dit), but not choice RT. Klapp interpreted these results in a two-process model of response programming. The first part of the model is related to the duration of the internal features of individual elements to which he referred to as INT. The second part of the model concerns the ordering of the elements within a response which referred as SEQ. In simple RT conditions the programming of INT is said to take place before the presentation of the stimulus whereas the processes involved in SEQ occur during the RT interval. Thus, in simple RT conditions 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 reaction time task the participants cannot pre-program the movement since they do not know in advance of the stimulus what response is required. Therefore both INT and SEQ must occur during the RT interval. 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.

Simple RT



Choice RT

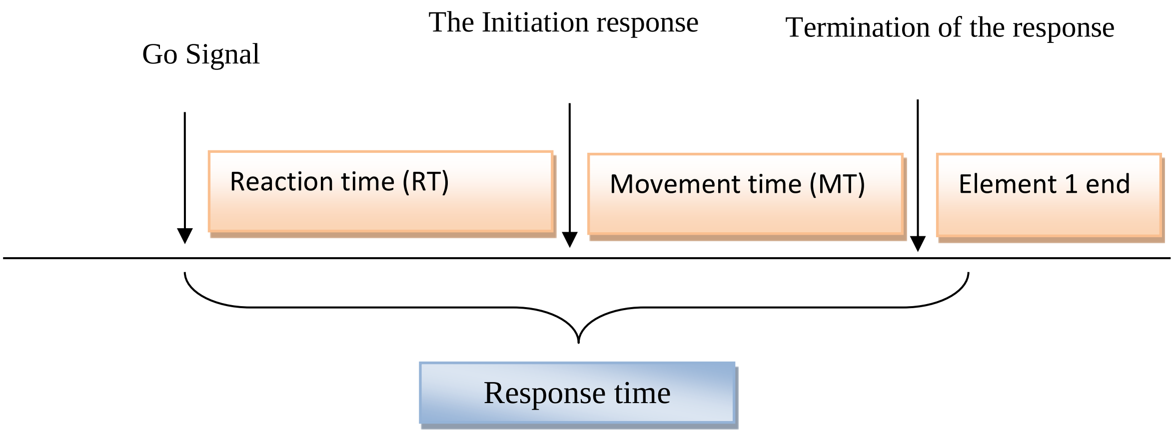


Figure 1 The differences between the events the involved in simple and choice RT.

Following a series of subsequent studies, Klapp (2003) extended his two process model of response programming based on the results that he obtained from speech articulation responses within both simple RT and choice RT conditions. He showed that choice RT increased as a function of the number of syllables (elements in the response) when the number (SEQ), but not nature (INT) of syllables was precued in advance of the stimulus. Interestingly, this finding was inconsistent with the original two process model of response programming. Therefore, Klapp modified the original model by suggesting that the order of the elements (SEQ) involved the planning and subsequent scanning a nonrepresentational time frame rather than the sequencing of actual elements. That is, the number and order of movements are loaded into a buffer prior to reaction time when SEQ is known in advance. This is then scanned to locate the starting point during the reaction time interval. Consequently, as the number of the segments increases the scanning process designed to locate the first segment of the sequence takes longer resulting in an increase in RT. As long as the number of elements is known prior to the stimulus being presented, the conceptual time frame can be loaded into a buffer and thus will influence RT in both Simple and Choice RT conditions when the number but not nature of response elements is known in advance. In situations where the number of elements is not indicated prior to stimulus presentation (e.g., complete Choice RT conditions) the nonrepresentational 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 a well-designed explanation for the differential effects of the number elements and response duration on simple and choice RT, it has been suggested that not all response programming occurs during the RT interval but rather programming of later movements can occur while an earlier movement is in progress (i.e. online during movement execution) (Glencross, 1980; Khan, Lawrence, Buckolz, & Franks, 2006); Smiley –Oyen & Worringham,1996). Researchers have provided some line of evidence to support this explanation for why the number of element with a response does not always influence RT. For example, Khan, et al., (2006) performed a series of experiments in which participant performed single-or-two target aiming responses. Participant were asked to move either toward a single target or two targets where the second target required a reversal direction to that of the first. Similar to Klapp (1995, 2003), Khan and colleagues found that simple RT was shorter for the single-target responses compared with two-target responses, however, the number of response elements did not affect choice RT. Since movements to the first target where subject to more online interference effects (i.e., increased probe RTs) in the choice compared to simple RT conditions, Khan et al. proposed that cognitive resources associated with online programming were occurring in the choice but not simple RT conditions. Of course, given the principles of both the MCH and MIH, it is possible that these greater online processes may have been a result of participants attempting to reduce the variability at the first target and/or accurately time the implementation of the second movement during the execution of the first. As such, the experiments within the present thesis aim to investigate these possibilities, amongst other

2.5 Visual Feedback

Visual regulation and visuo-motor delays

A factor that has been proposed to influence the online motor programming of movements (Khan et al., 2007), together with both constraining movement actions (see Khan et al., 2006 for a review) and monitoring actions in order to time the implementation of subsequent pre-programmed actions is the availability of visual information. As such, the following section aims to provide a detailed summary of the use of vision in both planning and executing movements. It is generally accepted that visual feedback plays an important role in ensuring movement accuracy and becomes more effective when movement durations are long enough to include visuo-motor delays (for reviews see Elliott et al., 2001; 2010, Khan et al., 2006). Researchers have acknowledged that the availability of visual feedback can enable both the ‘fine tuning’ of movement trajectories during action (i.e., online) and increase the accuracy of movement programming (i.e., offline) (e.g., Khan et al., 2003, 2004; Lawrence et al., 2011) Indeed, more than a century ago Woodworth (1899) suggested that, the control of goal directed movement involves central planning before movement initiation and processing of feedback to correct errors during movement execution. In his initial work on the accuracy of movement, Woodworth provided significant insights into the control of aiming movements and the relation between movement speed and accuracy. He reported that receiving visual feedback during movement execution results in an increase spatial accuracy and that as the time available to use this visual feedback is reduced so to does spatial accuracy. Woodworth instructed participants to draw lines to targets in a reciprocal motion using a pencil on a sheet of paper which was attached to a drum that rolled at a constant speed. Subject had to either terminate their endpoints as close as possible to preset targets or try to match the spatial endpoint of the previous trial. Vision was manipulated by having subjects open or close their eyes during the movement and the duration of movement was varied by instructed subjects pace their movement to the beat of metronome. Woodworth concluded that manual movement consisted of two phases; the first or initial adjustment phase where participants moved the hand toward the vicinity of the target as fast as possible, and the second or current control phase which was described as an error correction phase. This error correction or ‘homing in’ phase proposed the idea that during this portion of the movement the performer uses visual and other forms of feedback to reduce aiming error inherent in the first phase.

In order to investigate the time that it takes to process of visual information for use in the error correction phase, Woodworth (1899) sought to establish the shortest movement time where vision resulted in increased movement accuracy in comparison to the no vision (eyes closed) conditions. As he had expected, when the duration of a movement is very short no differences in accuracy were seen between the vision and no vision conditions. Interestingly the time to complete each movement in the sequence increased and the spatial errors decreased in the eyes open condition but remained similar in the no vision condition. In other words, the difference in the aiming error between the two conditions decreased as average MT decreased. Woodworth concluded from his vision and no vision comparisons that the time to process visual feedback was approximately 450ms.

Although Woodworth’s (1899) explanation of how limb movements are controlled is still prevalent in many of the visual feedback models today (see Elliott et al., 2010 for a review), his estimation of the time required for visual feedback processing is not without challenge. Indeed, as early as 1969 Keele and Posner reasoned that because Woodworth used reciprocal movements in his procedure, the duration of individual aiming movement included both the time needed to reverse the direction of the sliding movement at each of the target location and the time needed to travel between the two target lines. Consequently, they conducted a aiming study using only a single aiming protocol. Specifically, participants were asked to make an aiming movement from a start position to a small target at a specific movement duration (150, 250, 350 and 450ms) in both full vision and no vision conditions. In a full vision task, participants could see their limb and the target during the movement and this condition was like a practice to them. Whilst in no vision conditions, participants could see their limb and target during movement preparation but not during the movement execution (the room light went off before the movement initiation). Keele and Posner used 50% of the trials with vision and 50% with no vision randomly intermixed so the participant did not know whether the light would be off or not. They discovered the availability of vision resulted in greater movement accuracy when MTs were 260msec or greater but were not different in the short MT conditions (190msec). These results left Keele and Posner with an estimation of visual processing time somewhere between 190 and 260ms with later researchers estimating visual feedback processing time to be around 135ms (Carlton, 1981; Zelaznik, Hawkins & Kisselburg, 1983).

The paradigms and ensuing results from these early investigations into the use of visual feedback studies do not allow one to differentiate as to whether visual information is used to adjust movement trajectories during action (i.e., online) or used as a form of knowledge of results (KR) to improve the programming of subsequent movements (i.e., offline). This latter processing may occur when movements are relatively short and/or when visual feedback is presented too late during a movement to allow on-line corrections to be made (Khan et al., 2003a, 2003b, 2004; Lawrence et al., 2006; 2011). In a series of experiments that analysed movement variability throughout the entire movement trajectory Khan and colleagues revealed that in video aiming studies the use of visual information for online processes occurs at approximately 300msec and accuracy differences between vision and no vision conditions at MTs less than this are due to offline processes.

Since the early work of Woodworth (1899), the extensive body of literature surrounding visual feedback processing has revealed that vision is a very important element when ensuring movement accuracy of aiming movement, particularly when the movement duration is long enough to encompass visuomotor delays. The processes involved in the use of visual feedback during these movement times resides in the detection and correction of errors in the limb trajectory during movement execution (Elliott, Helsen, & Chua, 2001; Elliott et al., 2010; Khan et al., 2006) and more error corrections are made in vision compared to when no vision conditions. Whilst, researchers have examined the importance of vision by eliminating vision of moving limb upon movement initiation (e.g., Keele & Posner, 1986; Khan et al., 2003a, 2003b) or at various points in the movement trajectory of single aiming movements (Carlton, 1992; Chua and Elliott, 1993; Khan et al., 2004; Lawrence et al., 2006), Ricker et al. (1999) investigated the effect of occluding vision at various points during a two target aiming task. Specifically, movements were compared between full vision conditions and conditions where vision was occluded during the flight phase of the first movement or when vision was removed once the limb was in contact with the first target. Results revealed that the removal of vision following contact with the first target did not affect the time spent on the first target. This indicates that the two movements were planned interdependently and thus organised prior to the end of movement one. Furthermore, reaction times were shorter when vision was continually available indicating that vision prior to movement onset can be used offline to formulate a movement plan to both targets in a sequence. Similarly, Lavrysen et al., (2002) revealed that vision is important during trajectory the first movement in may be used online to aid in the integration between the various segments of a multiple target aiming action. Since this thesis is interested in the OTA phenomenon and thus the planning and control of multiple target directed and the factor that influence this processes, the programme of research includes visual manipulations in order to further investigate the role of vision in the OTA.

Kinematic characteristics of aiming movements and vision

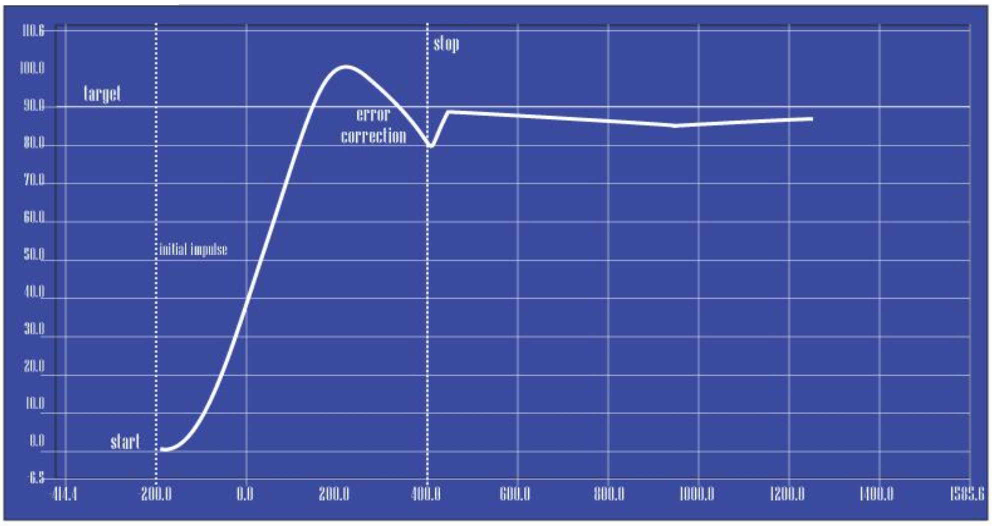
Speed-accuracy trade off explanations have focused on feedforward processes associated with the pre-planning of limb trajectories and the resultant increases in variability when programmed movement forces and durations increased (e.g., Schmidt et al., 1979; Plamondon and Alimi, 1997). Other researchers have determined the trade-off in relation to the utilisation of sensory information during execution to reduce the discrepancy between the limb position and the target location (e.g., Crossman and Goodeve, 1983) and more recent literature has focused on the role of both planning and execution when proposing models of speed-accuracy trade-off (for a review see Elliott et al., 2010).

Relevantly recent investigations examining the kinematics profiles of limb trajectories has played a significant role in shaping these speed-accuracy and visuo-motor control processes (Chua & Elliott, 1993; Elliott, Carson, Goodman, & Chua, 1991; Khan, Elliott, Coull, Chua & Lyons, 2002; Khan & Franks, 2000; Khan, Franks & Goodman, 1998). Specific kinematic landmarks can be determined and by analysed in order to gain specific information about the limb movement. These kinematic landmarks have been proposed to be linked to precise mental processes and therefore can be used to make inferences about the relative planning and execution contributions to visual aiming control. For example, kinematic markers from early in the trajectory have been used to describe the programmed phase of movement while operations implicated in the online regulation of movement have been inferred from kinematic information attained later in the trajectory (for a review see Khan et al., 2006). In line with these proposals, researchers utilised discontinuities in movement trajectory (the kinematic profiles) to parse movements into their programmed and sensory-based error correction phases (Chua & Elliott, 1993; Khan & Franks, 2000; Khan, Franks & Goodman, 1998).

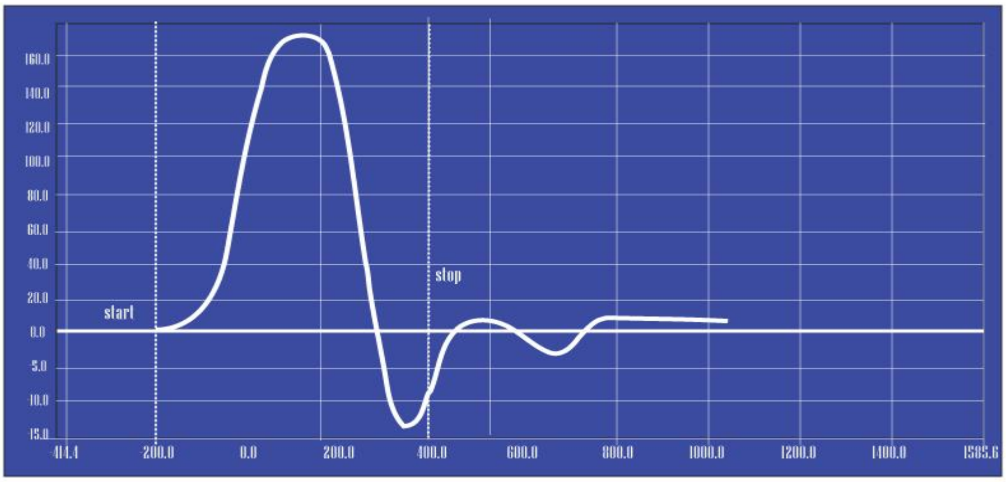
In general, this separation of trajectories into their programmed and error correction phases was achieved by first individualising profiles of displacement versus time in singular movement axes to obtain immediate velocity. These velocity profiles are then subjected to a second differentiation to obtain acceleration and in some cases, a third differentiation is performed to obtain jerk. Important information about how a movement is planned and controlled can then be obtained by applying criteria to these profiles to investigate any discrete adjustments via discontinuities in kinematic profiles i.e. reversals in the direction of movement, zero line crossings in accelerations, and significant deviations in acceleration profiles (Elliott & Khan, 2010; Khan et a., 2006). Figure (2) shows a typical position versus time profile in which primary positive acceleration and negative acceleration (deceleration) achieve the movement goal (i.e. the primary axis of movement for an aiming movement). In this example, the limb trajectory follows a relatively smooth, continuous movement from the starting position to the end of the movement on the target. This corresponds to normal bell shaped velocity profile in which the limb velocity increases at the beginning of the movement, reaches peak velocity at approximately 50% of the movement trajectory, and then decreases until the limb comes to rest on the target. The sinusoidal shape of the acceleration profile (consisting of the acceleration followed by a deceleration phase) then ensues as a result.

Following from Meyer, Abrams, Kornblum, Wright and Smith’s (1988) optimised submovement model, this type of trajectory reflects a movement with only a primary submovement and no corrective submovements. The initial impulse is ballistic in nature which by definition does not contain movement modification and is described by a clearly rapid continuous change in the position of the limb and smooth velocity and acceleration profiles this phase is assumed to be programmed to end at the location of the target (Meyer et al., 1988) or just short of the target (Elliott et al., 2004). The trajectory in figure(2) contains positive to negative shifts in velocity corresponding to reversals in direction of the movement The initial acceleration and deceleration phase of the movement results in a target overshoot, which is then corrected using a reversal in movement direction that brings the limb back to the target position. Figure(3) is more frequently observed trajectory (Khan et al., 1998), here a zero line crossing in acceleration reflects a situation where the primary movement undershoots the target and thus needs to be reaccelerated in the same movement direction in order to meet the target location demands. Figure (4) is fairly comparable to figure (3) except that the correction to the initial trajectory materialises earlier, before primary deceleration is complete or in a less discrete fashion. Here rather than an obvious change in acceleration, the profile contains a significant deviation in the absolute value of negative acceleration. In figures (2) through ,we have indicated where the primary submovement ends and the corrective process begins according to most movement phasing protocols (Elliott & Khan, 2010; Khan et al., 2006; Walker, Philbin, Worden, & Smelcer,1997).

Displacement



Velocity



Acceleration

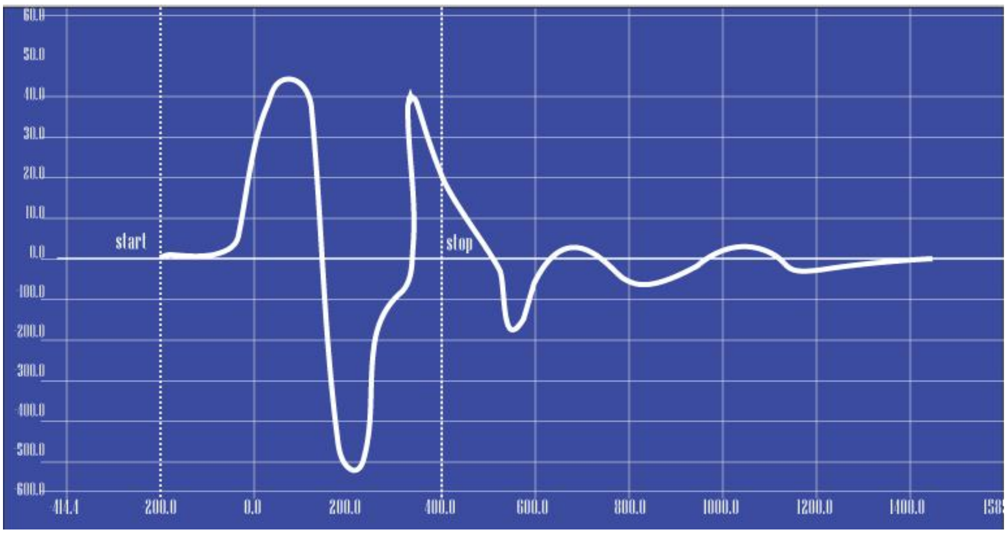
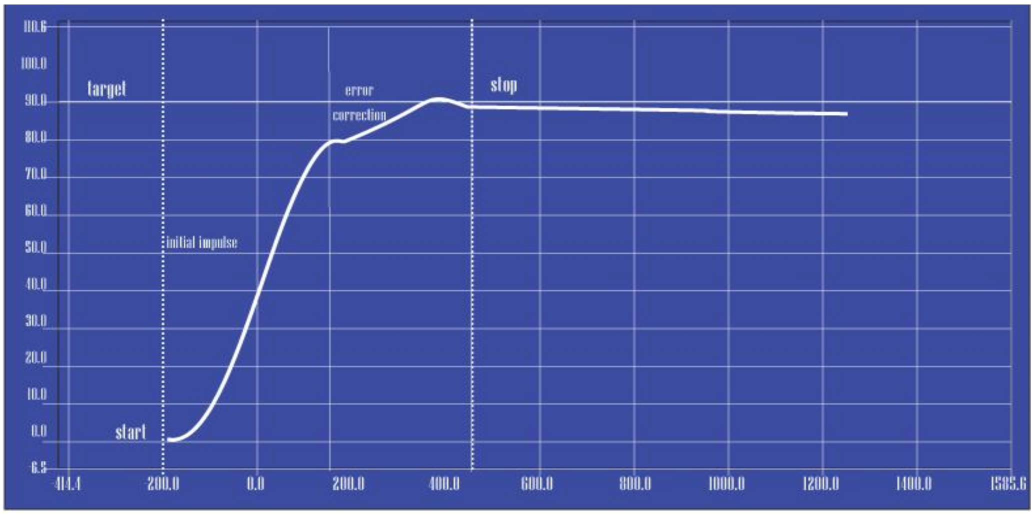
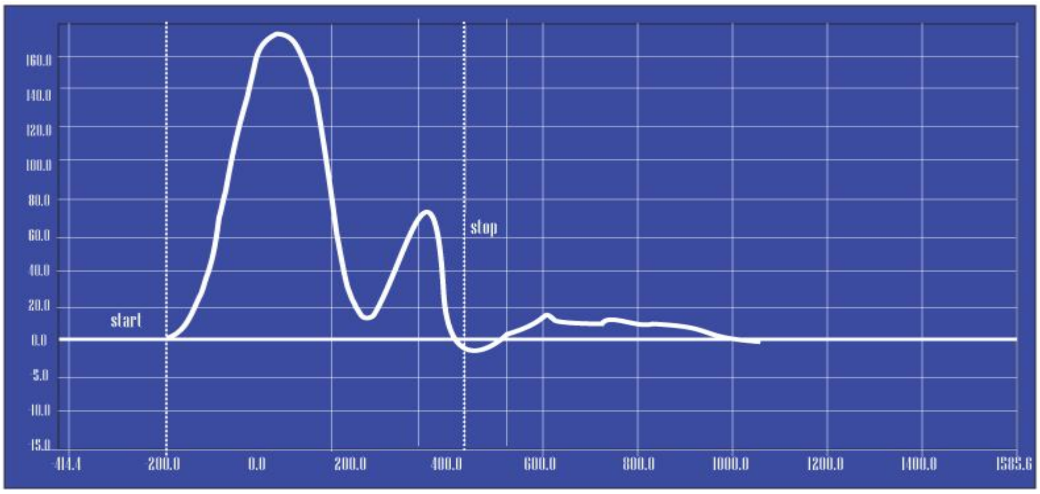


Figure 2 Sample of three kinematics profile (Displacement, Velocity, and acceleration) showing the stages of the initial impulse and error correction phases, for movement in zero line crossing in velocity.

Displacement



Velocity



Acceleration

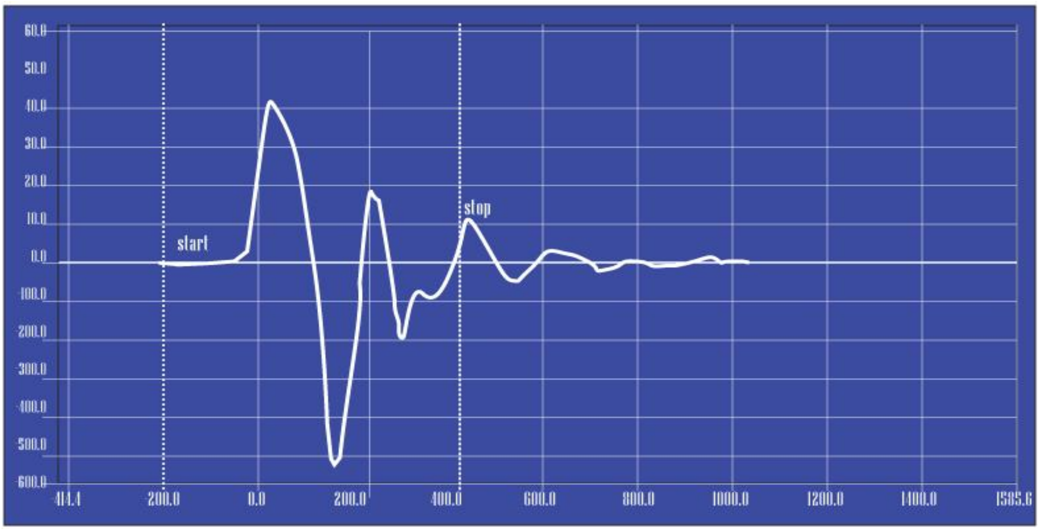
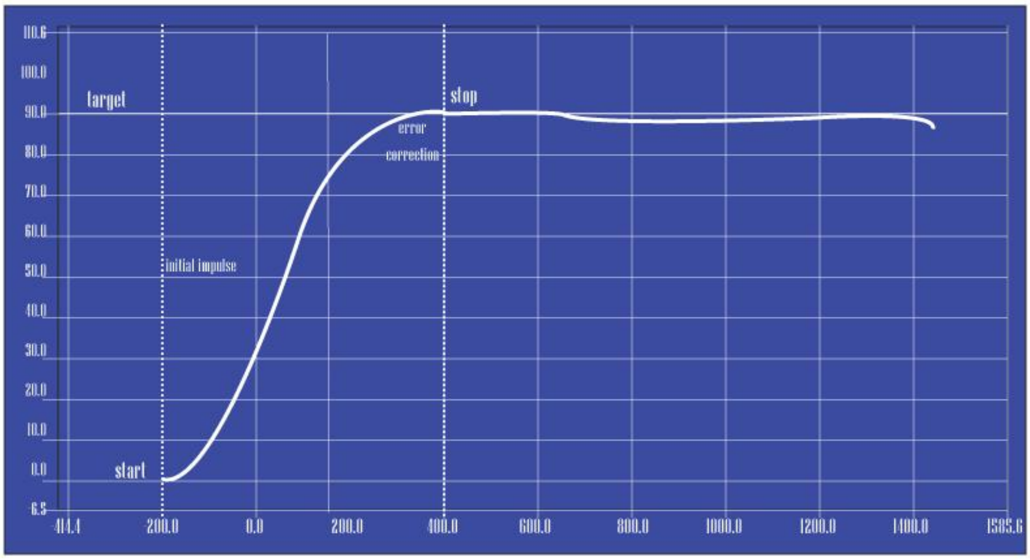
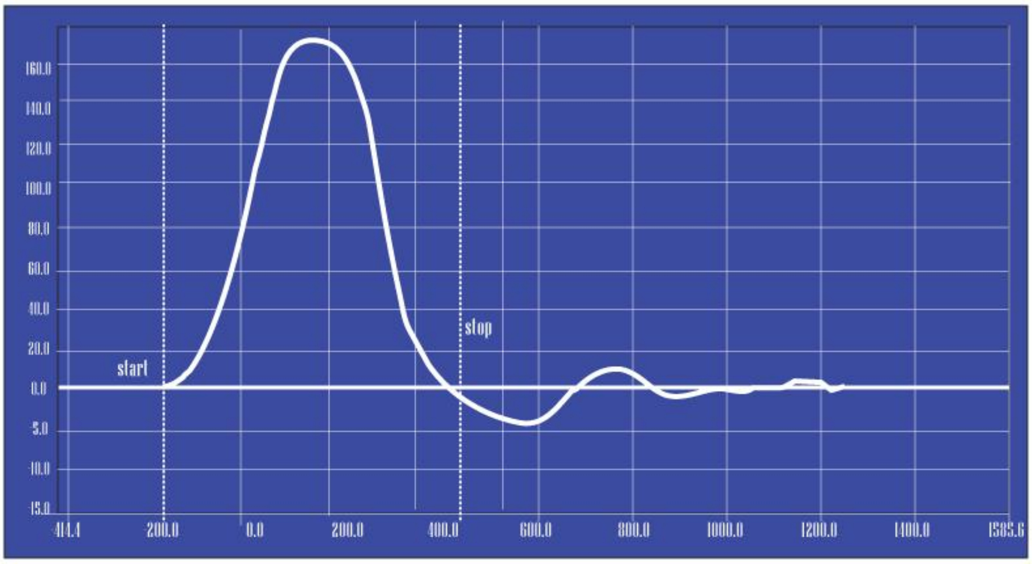


Figure 3 Sample of three kinematics profile (Displacement, Velocity, and acceleration) showing the stages of the initial impulse and error correction phases, for movement in zero line crossing in acceleration.

Displacement



Velocity



Acceleration

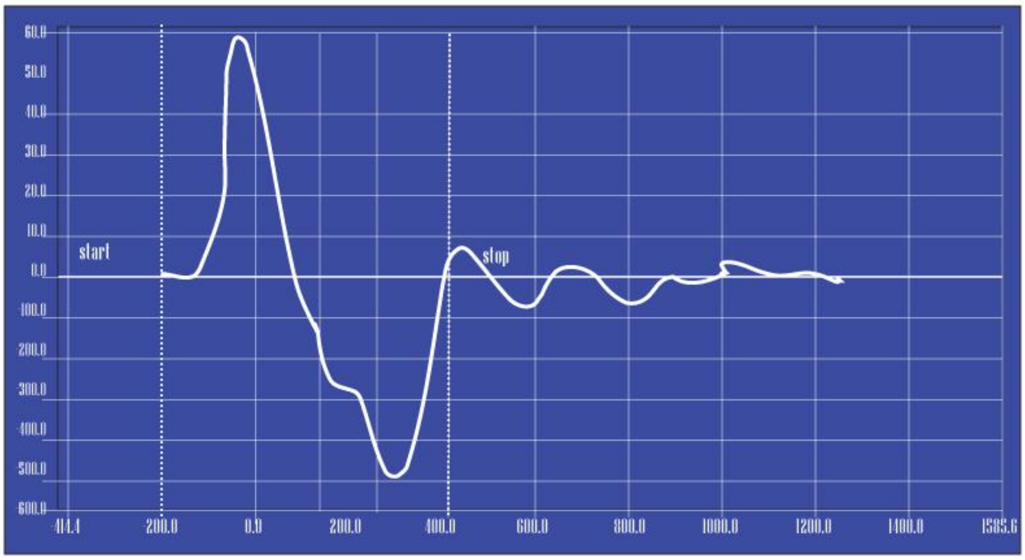


Figure 4 Sample of three kinematics profile (Displacement, Velocity, and acceleration) showing the stages of the initial impulse and error correction phases, for movement that shows a great deviation in acceleration.

Limb trajectory kinematics and vision regulation.

Research utilising trajectory discontinuities in order to determine the role of vision in target directed aiming have yielded conflicting results. Although discontinuities in the trajectory have reported to become more extensive as the accuracy requirements of the movement increase (Jagacinski,Repperger,Moran,Ward,&Glass,1980), some researchers have reported there are more discontinuities when vision is available (Chua & Elliott,1993; Khan & Franks, 2000) while others have not (Elliott, 1999, Meyer et al .,1988). These inconsistencies might be due to filtering procedures. That is, in order to obtain displacement, velocity and acceleration data the trajectory information obtained via data acquisition devices (i.e., 2D graphics tablets and 3D motion analysis systems) are passed through low frequency cut-off filters often with different Hz. The filtering process, together with the different cut-off frequencies may result in the loss of data or 'smoothing' of otherwise present discontinuities in kinematic profiles. Khan et al., (2006) investigated this possibility by passing the same displacement data through two different frequency filters (6Hz and 10Hz) and did not report any significant differences the subsequent kinematic data. However, the criteria for choosing the frequency of filters is not evident in the literature which leaves the question as to what is 'real' movement or movement noise (?) a relevant issue.

It has been reported that even after extended practice the primary submovement often undershoots the target (Khan et al., 1998) which may be a strategy of allowing any necessary and expected trajectory corrections to be the same direction of the initial impulse and thus less effortful than corrections that require a reversal in movement direction. The strategies that a participant adopts depends on what sensory information is available during practice. For example, when the vision is available participants can get to the target area more quickly by increases the velocity the primary impulse and then using the available movement time and visual information to make discrete error corrections to meet the accuracy demands of the target. On the other hand, when the vision is not available the primary movement is often programmed more carefully, executed slower and travels a greater distance, perhaps to reduce the need for the less effective proprioceptive based error corrections (Khan & Franks, 2000).

In order to investigate whether more extensive error corrections are indeed reflective of more effective trajectory corrections, Khan et al. (1998) developed the index of error correction effectiveness (IECE):

“IECE=AE(ii)-AE(ec)/AE(ii)+AE(ec)”

Here, AE(ii) is the absolute error at the end of the initial impulse phase, and AE(ec) is the absolute error after the error correction phase. The numerator gives an indication of how close the participants got to the target at the end of the initial impulse, whereas the denominator normalises for the proportion of the errors following the initial impulse and error correction phases. Data analysis of this index of error correction effectiveness has showed that the difference between both conditions (vision and no vision) in the initial impulse, error was decreased by following 60% when visual feedback was available compared to 20% when it was not, and that means the presence of discrete adjustment in kinematic profile is to a sizeable extent linked with sensory –based error correction rather than biomechanical characteristics of limb movement (Khan et al., 1998).

The use of discrete corrections in kinematic profiles to investigate online visual control was based on the hypothesis that visual feedback processing is discontinuous in so much that the initial impulse of movements are run to completion before visual control can take effect (Vince, 1948; for a review see Elliot, Helsen & Chua, 2001). Researches have shown that when aiming movements are subject to visual regulation movement trajectories contain more discrete corrections compared to when vision is unavailable (Chua & Elliot, 1993; Khan & Franks, 2000; Khan, et al., 1998). In addition, researchers have shown that when participants receive visual information the time spent both before (representative of movement planning) and after (representative of error correction) peak velocity is greater compared to when visual feedback is occluded (Abrams et al., 1990; Chua and Elliott, 1993; Khan and Franks, 2000; Meyer et al., 1988, Carson et al.,1990; Elliott et al 1991; Lyons et al., 1996). Sensory information might have played a role in lengthening these movement times, but discontinuities do not always differ between visual conditions despite longer movements times and lower endpoint error in vision compared to no vision conditions (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. These research discrepancies in the number of discrete corrections and the possibility that vision is utilised in a continuous rather than discrete fashion, highlights some potential limitations in the use of discrete discontinuities in kinematic profiles to infer online visual processing and highlights possible incorrect conclusions that movements are under the control of feed-forward processes when movement times are fast and/or discrete discontinuities are not present (Desmurget and Grafton, 2000; Desmurget et al., 2005, Khan et al., 2006).

Spatial Variability and movement performance.

Variability is inherent in human movement behaviour (Schmidt, 1979), however in order to reproduce movements accurately and consistently the temporal and spatial characteristics of movements remain relatively stable from one performance to the next (Sheridan, 1984). Although variability is inherent neural-motor noise, it is also often the response to a planning error, and thus with practice a person can learn to follow an optimal spatial-temporal path from an initial position of the target to reduce this variability. In this regard, Hansen et al. (2008) proposed that changes in variability over practice are associated with particular experimental conditions and that interferences can be made in relation to the most optimal of these conditions for terminal outcome. Thus, measuring movement variability over number of trials provides a good indication of the both central organisation (planning) and execution of the motor system. This rationale has recently been adopted by visual aiming researchers such that they have begun to analyse the data regarding the variability of the movement trajectories in order to provide new insights about accuracy planning and corrective behaviour (Khan et al.,2006; Scholz & Schoner,1999; Sidaway et al .,1995, Elliott & Khan, 2010; Lawrence et al., 2012).

The benefit of analysing spatial variability to elucidate the effect of target size and target location on movement planning and online control was demonstrated by Sidaway, Sekiya, Fairweather (1995). These researchers conducted two experiments which required participants to perform rapid movements to hit two targets as quickly and as accurately as possible. In the first experiment, the start position and the two targets were arranged in a straight line with the size of the first target being constant and the size of the second target varying from 6 cm & 1.5cm. The target sizes of the second experimental were the same as those in the first. However, the direction of movement was varied with participants required to make a 90 degree change in movement direction from target 1 to target 2. Results revealed that a increase in the terminal accuracy demands of the second target both increased programming time and resulted in reduced variability on contact with the first target i.e., the demand for movement constrains imposed by last target affected both reaction time and the variability of movement at the first target. It is possible the constraining of the first target movement was mediated to some effect by the use of visual feedback in order to minimise variability by maximising the error correction phase (Khan et al., 2006).

As mentioned previously, the use of variability to investigate the relative contributions of online and offline processing of visual feedback has resulted in the recent development of a method that involves calculating the within subject standard deviation in distance travelled (i.e., variability) at several kinematic landmarks (e.g. peak acceleration, peak velocity, peak negative acceleration and movement end) (Khan & Franks, 2002; Khan et al, 2003a, 2003b). The rationale here is that if movements are pre-programmed before the initial movement and not subject to online error corrections, then variability should increase (due to errors that occur early in the movement trajectory) as movement unfolds. However, when movements are subject to error correction during movement execution the shape of the variability profiles should deviate from those of the open loop pre-programmed movements described above (Khan et al., 2006). Research that has utilised this novel methodology has revealed that at fast movement times (< 250 ms) visual feedback is used offline as a form of KR in order to enhance the planning of subsequent actions, whereas for movement durations greater than 250msec visual feedback is used to reduce trajectory variability throughout movement execution (Khan et al., 2006).

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.

In support of the above Elliott et al. (1999) correlated the distance travelled at peak velocity was with the distance travelled from peak velocity to the end of the movement in a single target aiming task performed under both vision and no vision conditions. Negative correlations would imply that adjustments to the movement occurred during movement execution. For example, a large distance travelled at peak velocity would be compensated for by a shorter distance between peak velocity and the end of the movement. Results revealed that negative correlations existed between the distance at peak velocity and the distance between peak velocity and the end of the movement in both the vision and no-vision conditions. However, stronger correlations were evident when visual feedback was available providing evidence that visual afferent information was used to adjust movement trajectories planning error online.

The OTA has been explained by the MCH (Fishman & Reeve, 1992), an underlying assumption of which is that that variability increases as movement progresses and that variability at the first target is contingent on the accuracy demands of the second target (Sidaway et al., 1995). The present thesis will adopt methodologies to assessment movement variability during trajectory execution in order to investigate the role of visual feedback in constraining actions during two target aiming tasks.

Target perturbations and vision

In his classic study on the accuracy of voluntary movement, Woodworth (1899) found that the speed of movement to a target is composed of at least two distinct components, a notion consistent with more recent motor learning research findings, which also point to a two-component process in goal-directed aiming (Elliott et al., 2010). In order to investigate the time taken for the processing of visual information, Woodworth sought to establish the shortest movement time (MT) where vision was available. To detect or catch a moving target, we have to combine many different sources of information regarding the displacement of the target proportional to ourselves and to the nearby environment. As highlighted in the previous sections of the writing, visual information plays a major role in the acquisition of this information. Whilst the cited and discussed research in the previous sections centred around manipulating visual information before (Khan et al., 2003a) and throughout movement trajectories (Ricker et al., 1999; Khan et al., 2004; Layrsen et al., 2003), an alternative manipulation to investigate the use of visual information online involves unexpectedly perturbing target an already programmed target location. Relatively simple perturbations might involve a change in the size of the target (e.g. Heath et al., 1998), its position (e.g., Paulignan et al., 1991). Studies have shown that, the ability of movement trajectory adjustment in human performance materializes very rapidly even to a small perturbations (changes in target position, right or left, closer or further away from the performer’s body) even in situations where performer are unaware that the perturbation has occurred (Proteau, Roujoula, & Messier, 2009). The time that needed to make these online trajectory adjustments (when the target moves at the initiation of the movement) is estimated to be approximately 100ms (Hansen & Elliott 2009; Pelisson et al., 1986; Paulignan et al., 1991).

In terms of movement kinematics, the position of the target and the index of difficulty (ID; Fitts 1954) are processed during movement planning and thus considered to be reflected in the early part of the movement trajectory. On the other hand, the late parts of the trajectory are considered to reflect trajectory changes to any new target positions. This means that perturbations of a target affects both (mid and late) trajectory of the movement. Furthermore, whenever a target changes its position to a new location during the fast goal-directed movement, the performer tracks it to the latest position regardless of the conscious intention of the performer (Pisella et al., 2000). As such, adjustments to movement trajectories as a result of target perturbations are evident in goal directed aiming and often occur ouside of the performers consciousness (Proteau, Roujoula, & Messier, 2009).

According to Bruno et al (2008), adjustments to movements as a result of perturbations in target position are not confined to the actual displacement of a target, but also occur under illusory target and limb perturbations. Grierson and Elliott, (2009) introduced an illusionary paradigm (a moving background) at movement initiation to provide the illusion that the limb was moving faster or slower than expected. This paradigm resulted in a mismatch between the perceived velocity of the limb and the expected velocity of the limb and thus prompted an early adjustment to limb velocity. In addition, the Muller–Lyer illusion was used to influence the perceived position of the target and hence encourage a discrete correction late in the movement trajectory. Results revealed that the illusory perturbations impacted movement outcome in that the conditions where the moving background and Muller-Lyer created illusions that movements were faster and larger than reality resulted in participants terminating their trajectories sooner than necessary (the opposite was true in situations where perturbations created the illusion that the limb was moving faster than in reality). These findings indicate that the motor system can not only make adjustments to trajectories online in response to actual perturbations but also illusionary perturbations.

Purpose of the current thesis research programme

The first empirical chapter of this thesis was designed to investigate the possible mediative role that vision plays in the integration multiple target movements. Whilst traditionally, the OTA and integration of action has been investigated through the assessment of both reaction time and movement time, participants in the first experimental chapter were set a criterion movement time and the resulting errors and limb trajectory kinematics were examined under vision and no vision conditions. Constraining movement times would minimize the possibility of strategically redistributing planning and control processes when movement times are free to vary under manipulations of visual feedback. Hence, examining movement accuracy and limb trajectory kinematics with and without vision under time constrained conditions would offer a direct test of the role of visual feedback in sequential aiming and the underlying assumptions of both the movement constraint and movement integration hypotheses.

Chapters 4, 5 and 6 of this thesis were designed to investigate the integration of movements and the role of visual feedback when the distance to the first target, an unexpected perturbation at the first target and an unexpected perturbation at the second target are presented, respectively. In contrast to the first experimental chapter, movement times were free to vary in these experiments such that the relative planning and online control strategies involved in the integration of these perturbed movements could be investigated. Furthermore, assessment of both reaction time and movement time in conjunction with error corrections during movement execution allowed investigations into the flexibility of movement integration following unexpected target perturbation at both the first and second target.

CHAPTER 3

THE DUAL ROLE OF VISION IN SEQUENTIAL AIMING MOVEMENTS

3.1 Introduction

In many everyday tasks, actions comprise several components that are executed in sequence (e.g., dialling a telephone, catching and throwing a ball, and grasping and drinking a glass of water).Researchers have adopted numerous approaches to understanding how multiple segment movements are prepared and executed. While an initial surge of research was devoted to understanding the relation between reaction time (RT) and the number of response segments (or elements) (e.g., Henry & Rogers, 1960; Klapp, Wyatt, & Lingo, 1974; Sternberg, Monsell, Knoll, & Wright, 1978), more recent efforts have been focused on the time it takes to execute movements (e.g., Adam et al., 2000).With regard to the latter, the typical finding is that movement times (MT) to the first target in two target movements are longer than in single target movements. This one-target advantage in movement time (OTA) emerges regardless of participants' hand preference and hand used (Helsen, Adam, Elliott, & Buekers, 2001; Lavrysen et al., 2003), and is resistant to practice (Lavrysen et al.,2003) and the occlusion of vision (Lavrysen, Helsen, Elliott, & Adam,2002).

Different interpretations have been put forward in an attempt to explain the one-target advantage in movement time. These vary in the extent to which the lengthening of MT can be attributed to planning versus on-line control processes. According to the movement constraint hypothesis, movement to the first target is planned more precisely to reduce the variability of endpoints at the first target (Fischman & Reeve, 1992).Based on the assumption that variability increases as the action sequence progresses, the reduction in variability at the first target would ensure that the accuracy demands at the second target are met.

Other researchers have proposed an online programming explanation for the one-target advantage (e.g., Chamberlin & Magill, 1989). According to the online programming hypothesis, movement sequences are not prepared entirely prior to response initiation. When responses are relatively complex, participants may program the initial segments during RT but then delay the programming of later segments until after the RT interval, provided there is sufficient time during movement execution. Hence, MT increases due to the additional processing requirements of programming the second movement during the execution of the first movement.

By contrast, according to the movement integration hypothesis (Adam et al., 2000), program construction of the entire response is performed prior to response initiation. However, in order to facilitate a smooth and efficient transition between segments, the implementation of the second segment is performed online concur- rent with the execution of the first segment. The increased cognitive control associated with the implementation of the second segment during the production of the first segment in two target responses leads to interference and hence the lengthening of MT to the first target. An issue that is central to understanding how multiple target movements are prepared and executed is the extent to which individual segments are organized together or separately.

One factors that influences the degree of overlap between movement segments is the accuracy requirement of the task. It has been shown that reducing the size of the second target lengthens not only the movement times from the first to the second target but also the duration of the first movement segment (Rand & Stelmach, 2000; Ricker et al., 1999). This implies that sequential aiming movements are not controlled separately and that the control characteristics of one segment influences that of the other segment. However, the interdependency between segments is significantly reduced when the accuracy demands at the first target are high. When the size of the first target is relatively small, pause times are lengthened thereby disrupting the transition between the two movements (Adam & Paas 1996; Adam et al., 1995, 2000; Rand & Stelmach, 2000). In such cases, movements to targets are organized separately and independently, and hence there is little overlap of control processes.

The second factor that influences the organisation of multiple target aiming movements is the availability of visual feedback. When vision is occluded over the first movement segment, participants take longer to initiate their movement and movement times to the first target are increased (Lavrysen et al., 2002).It seems that when vision is not available, participants prepare more precise motor programs (i.e., more constrained) so that there is less reliance on online correction processes. Removing vision from the first movement segment has also been shown to increase pause times at the first target as well as movement times from the first to the second target (Ricker et al.,1999). These findings imply that the transition between the first and second elements was mediated by vision. When vision was removed from the first segment, there was less overlap between control processes and hence the implementation of the second element occurred during the dwell time at the first target rather than during the execution of the first segment. Interestingly, removing vision over the second movement segment has also been shown to increase movement times to the first target (Lavrysen et al., 2002). One implication of this finding is that producing a more constrained first movement would reduce the variability of endpoints at the first target. Hence, there would be a less need to adjust the parameters of the second segment since the initiation point of the second segment is more consistent. Also, increased movement times to the first target could reflect more precise planning of the second movement during the execution of the first segment. This would reduce the need to modify limb trajectories to the second segment when vision is occluded.

The primary purpose of the present study was to test the assumption that vision plays a dual role in the control of sequential aiming movements. Similar to single target movements, vision may be used within each movement segment to correct errors in the limb trajectory as the limb approaches the respective targets. In addition to its role in modifying limb trajectories within each segment, vision may be playing a critical role in the transition between segments. This could take the form of visually monitoring the endpoint location at the first target in order to adjust the parameters for the second movement (Khan, Lawrence, Buckolz, & Franks, 2006). For instance, in order to compensate for a longer distance travelled on the first movement, the amplitude of the second movement would have to be shortened, and vice versa. It is also plausible that visually based error corrections during the first segment would lower variability at the first target thereby making the implementation of the second segment more efficient because the need for modifying its parameters is minimized.

We investigated the role of visual feedback in sequential aiming movements from a slightly different angle to that of past research. In previous investigations, movements have been performed to targets of a finite size with the instruction to move as fast as possible (i.e., time minimization). In the current study, point targets were used and movement time to the first target was constrained (i.e., 450 ms). Hence, accuracy rather than movement time became our primary measure of interest. Many investigators have used time constrained movements to minimize tradeoffs between speed and accuracy (Khan et al., 2003; Proteau, Marteniuk, & Lévesque, 1992; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979; see Carlton, 1994 for a discussion of time minimization versus time constrained movements).

Also, constraining movement times would minimize the possibility of strategically redistributing planning and control processes when movement times are free to vary under manipulations of visual feedback. Hence, examining movement accuracy and limb trajectory kinematics with and without vision under time constrained conditions would offer a direct test of the role of visual feedback in sequential aiming and the underlying assumptions of both the movement constraint and movement integration hypotheses.The use of visual feedback in correcting errors in the limb trajectory within each movement segment was investigated by analysing the variability in limb position at peak velocity and at the end of each movement segment for vision and no vision conditions (Khan et al., 2006; also see Messier & Kalaska, 1997, 1999). Variability at peak velocity would give a reasonable indicator of the extent to which errors arise from programming processes (Elliott, Helsen, & Chua, 2001). Evidence for visually based movement modifications would be revealed from a greater reduction in limb trajectory variability from peak velocity to the end of the movement segment in the vision compared to no vision condition.

In order to assess the role of vision in the transition between movement segments, we adapted the correlation analysis used by Elliott, Binsted, and Heath (1999) for single target movements. In their study, the distance travelled at peak velocity was correlated with the distance travelled from peak velocity to the end of the movement. Negative correlations would imply that adjustments to the movement occurred during movement execution. For example, a large distance travelled at peak velocity would be compensated for by a shorter distance between peak velocity and the end of the movement. Elliott et al. showed that negative correlations existed between the distance at peak velocity and the distance between peak velocity and the end of the movement in both vision and no-vision conditions. However, stronger correlations were evident when visual feedback was available, thereby providing evidence for the important role of vision during movement execution. We modified the analysis of Elliott et al. (1999) for two segment movements by correlating the distance travelled on the first segment and the distance travelled on the second segment. If vision is being used to adjust and implement the parameters for the second movement, we would expect a negative correlation between the distances travelled on both elements.The underlying assumption of the movement constraint hypothesis is that variability increases as movement progresses and that variability at the first target is contingent on the accuracy demands of the second target (Sidaway, Sekiya, & Fairweather, 1995).

When participants are instructed to minimize movement time while being accurate, movement times to the first target are said to be lengthened in order to reduce variability at the first target so that the accuracy demands at the second target are met. Based on this explanation, we expected that when movement times to the first target are constrained and not allowed to vary, variability at the second target would be greater than at the first target when vision is not available. This is because participants would not have the flexibility to constrain the first segment through more precise movement planning (i.e., longer movement times) and hence variability increases would emerge at the second target. However, while we expected that variability would increase from the first to the second segment when vision is occluded, reductions in variability between peak velocity and the end of the first segment would curtail these increases in variability when vision is available. Along the lines of the movement integration hypothesis, the OTA arises due to interference caused from the increased cognitive demands associated with implementing the second element during the execution of the first segment. Hence, if movement times to the first target are constrained, the interference caused by the overlap of control processes during the first segment would result in increased errors and variability at the first target for the two compared to single target movements. In effect this finding would be the accuracy equivalent of the OTA. Again we would expect accuracy to be higher in the vision condition since visually based corrections may compensate for errors caused from overlapping control processes.

3.2 Method

Participants

Twenty four volunteers (males = 18 and females = 6; ages 18–32) participated in the study. All participants were self-declared right hand dominant, and had reported normal or corrected to normal vision. They all signed consent forms before taking part in the experiment and the study was carried out according to the ethical guidelines stated by the Ethics Committee of the School of Sport, Health and Exercise Sciences, Bangor University, for research involving human participants.

Apparatus

Participants sat at a table 75 cm above the ground. Aiming movements were performed on a computer monitor (19 in.) that was mounted horizontally and faced upwards in a cavity cut out from the table top (see Fig. 5). A sheet of plexi-glass 5 mm thick covered the monitor surface and was level with the table top.The start position was located 7 cm to the left of the right edge of the monitor. Target 1 was positioned 15 cm to the left of the start position while Target 2 was a further 15 cm to the left of Target 1. Participants were seated such that the body midline was aligned with Target 2. Both the start position and targets consisted of a small cross 10 mm in diameter. Participants performed aiming movements with a pen-like stylus held with their right hand. A micro-switch was mounted on the tip of the stylus. The position of the stylus was recorded from a small infrared- emitting diode (IRED) that was secured 5 mm from the tip of the stylus.The IRED was monitored using an Optotrak (Northern Digital Inc) three-dimensional movement analysis system at a sampling rate of 500 Hz. Participants wore a pair of liquid-crystal visual occlusion spectacles (Translucent Technologies, Toronto, Canada).

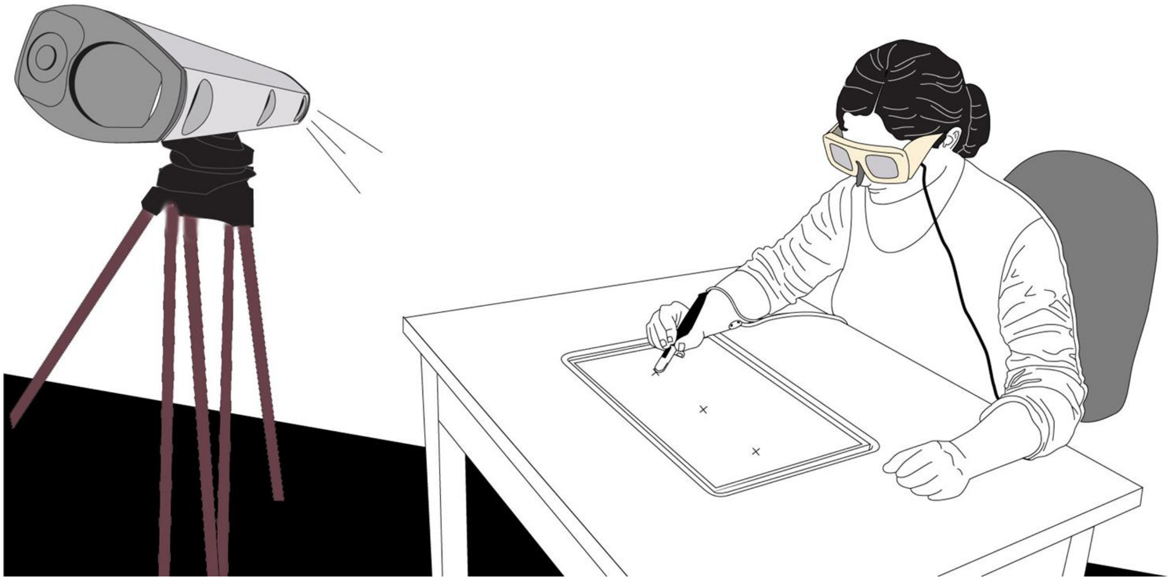


Figure 5 schematic representation of the experiment set-up .the aiming task was performed with a stylus to target displayed on a computer monitor that was mounted facing upwards in a cavity cut out from a table top. Movements were performed in the right to left direction.

Procedure

At the beginning of each trial, the start position and target(s) appeared on the monitor. Participants were first required to place the tip of the stylus at the start position. Once the stylus was steadily placed, a tone was presented signalling to participants to start their movement. In the one-target (1T) condition, participants raised the stylus from the start position and were required to touch down at Target 1. In the two-target condition (2T), participants moved to Target 1 and then to Target 2. Participants were instructed to perform their movement to Target1 in a movement time of 450 ms (± 100 ms).They were given feedback on their movement time after each trial in numerical form on the computer monitor. It was explained that reaction time was not important and that no restrictions were placed on their movement time from the first to the second target. The task had to be completed within 2 s at which time the targets disappeared.

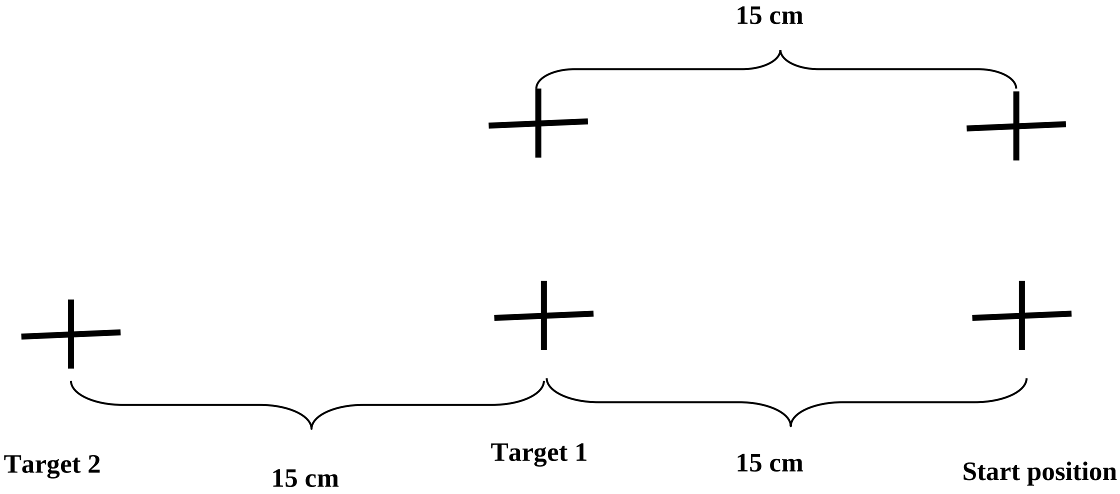


Figure 6 Diagram illustrating position of start, 1 target and 2 targets

Both the one and two-target movements were performed under two visual feedback conditions. In the vision condition, the occlusion goggles remained open throughout the trial. In the no vision condition, the goggles closed at the presentation of the stimulus tone and re-opened after 3 s. Since the targets had disappeared by this point in time, participants did not receive visual information of their endpoint accuracy.

Participants first performed 2 familiarization trials under each of the 4 combinations the 2 targets (1T and 2T) and 2 visual conditions (vision and no vision).They then performed a further 4 test blocks of 30 trials. The order of the trial blocks was counterbalanced between participants.The first 5 trials of each test block were designated as familiarisation trials and omitted from the analysis.Also, trials that were outside the movement time bandwidth were excluded. This amounted to less than 5% of the trials.

Data reduction

The 3D position data from the Optotrak were filtered using a second order, dual-pass Butterworth filter with a low pass cut-off frequency of 16 Hz. Position data were then filtered to obtain velocity Information.

	1T		2T	
	Vision	No vision	Vision	No vision
MT1 (ms)	458 (34)	454 (31)	449 (23)	446 (28)
CEy1 (mm)	0.5 (1.7)	— 2.0 (8.4)	0.9 (1.8)	7.6 (8.4)
CEx1(mm)	0.0 (1.4)	— 2.3 (5.7)	0.5 (1.5)	— 0.1 (4.0)
PT (ms)			209 (92)	244 (98)
MT2 (ms)			463 (39)	453 (38)
CEy2 (mm)			0.4 (2.6)	— 4.8 (12.5)
CEx2 (mm)			0.9 (2.4)	— 3.5 (6.6)

Table 1 Means (standard deviations) of movement time to the first target (MT1), y constant error at the first target (CEy1), x constant error at the first target (CEx1), pause time at the first target (PT), movement time from the first to the second target (MT2), y constant error at the second target (CEy2), x constant error at the second target (CEx2), for the one-target (1T) and two-target (2T) tasks in vision and no vision conditions.

Peak resultant velocity was identified for movements to each target. The start of movement to the first target was identified from working back from peak velocity to locate the first point in which velocity in the vertical direction (i.e., z-axis) was less that 15 mm/s.[1]

The end of the first movement was the point after peak velocity in which the

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[1] The velocity in the vertical direction was used to locate the start and end of movements since sliding of the stylus on the table top at the first target made it difficult to locate velocity zero crossings in the horizontal plane.

vertical velocity fell below 15 mm/s.This process was repeated to locate the start and end of the second movement for the two-target conditions. At the end of each movement segment and at peak resultant velocity for each segment we recorded the position coordinates in the primary direction of the movement (i.e., y-axis) and perpendicular to the primary direction of movement (i.e., x-axis).

Dependent measures

Our dependent measures consisted of movement time to the first target (MT1), movement time from the first to the second targets (MT2), pause time at the first target (PT), constant errors (i.e., signed difference between movement endpoints and the centre of the target) in the primary direction of the movement at the first and second targets (CEy1, CEy2) and in the direction perpendicular to the primary direction of movement (CEx1, CEx2). In the primary direction of the movement, a positive CE referred to an overshoot while a negative CE referred to an undershoot. In the direction perpendicular to the primary direction, a positive CE referred to movements to the right of the axis from the start position to the targets while a negative CE referred to movements to the left of this axis. As an overall measure of spatial variability in the x–y plane, we calculated ellipse areas at peak velocity and at the end of movement for each segment using the within-participant standard deviations of position along the y and x axes as the radii ($\pi \times SDy \times SDx$) (Hansen, Elliott, & Khan, 2008).

3.3 Results

For the first target, MT1, CEy1, and CEx1 were analysed using separate 2 Target (1 Target, 2 Targets) × 2 Vision Condition (vision, no vision) repeated measures ANOVAs. For two target movements, PT,MT2,CEy2 and CEx2 were analysed using repeated measures t-tests with vision as the independent variable. Interaction were broken down using Tukey post hoc tests ($p \leq 0.05$).Means and standard deviation are reported in(Table 1).

Movement time

The analysis of MT1 revealed no significant effects of Target ,$F_{(1,23)}=2.29$,$p=0.097$,or Vision $F_{(1,23)}=1.7$,$p=0.2$.There was also no interaction between target and vision, $F_{(1, 23)} = 0.1$, $p = 0.9$. Hence, any effects of vision condition on errors cannot be explained by differences in movement times to the first target. The analysis of MT2 also did not reveal a significant effect of vision, $t (23) = 1.6$, $p = 0.2$.

Pause time

There was a difference in PT at the first target between the vision and no vision conditions, $t_{(23)} = 9.5$, $p < 0.01$. Consistent with past research (Ricker et al., 1999), participants spent more time at the first target when vision was occluded.

Y-Error

The analysis of CEy1 revealed a significant main effect for target, $F_{(1, 23)} = 23.9, p < 0.001$, and an interaction between target and vision, $F_{(1, 23)} = 19.7, p < 0.001$. This interaction reflected small and similar overshoots for the 1- and 2-target conditions when vision was available, but a small undershoot in the 1-target condition and large overshoot in the 2-target condition when vision was not available. At the second target, a significant effect for vision on CEy2 indicated that participants tended to undershot the target when vision was removed, $t_{(23)} = 4.8, p < 0.05$.

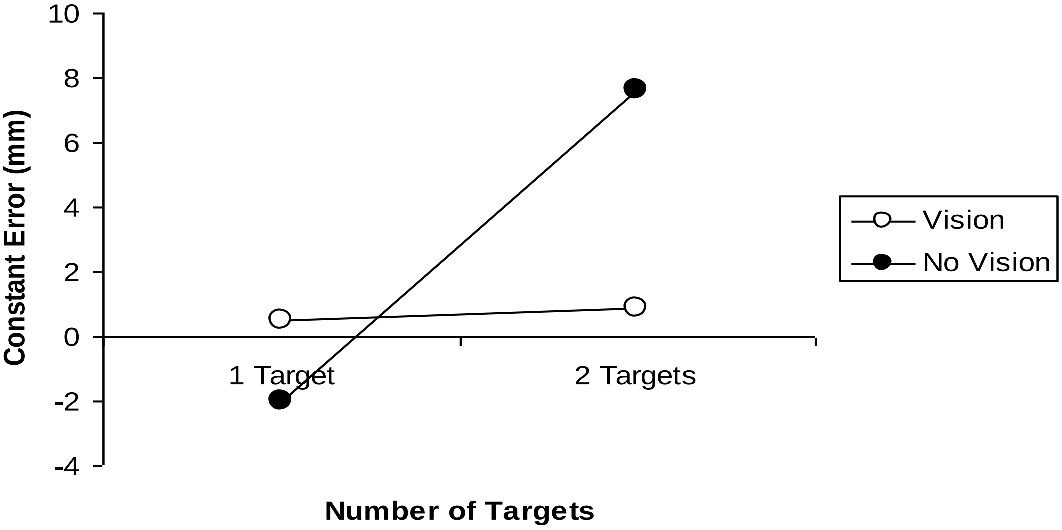

Figure 7. Constant Error (CE) at the first target for the single target (1T) and two-target responses under the vision and no vision conditions.

X-Error

The analysis of CEx1 revealed a significant main effect of target, $F_{(1, 23)} = 9.4, p \leq 0.01$, while the interaction between target and vision approached conventional levels of significance, $F_{(1, 23)} = 4.1, p = 0.053$. Overall, there was a small tendency for movement endpoints at the first target to be more leftward biased for the single than two target movements and this bias was greater in the no vision condition. At the second target, movements were also biased to the left when vision was not available, $t_{(23)} = 10.3, p \leq 0.01$.

Ellipse areas

In order to assess the role of vision within a movement segment we compared variability (i.e., area of ellipses in x–y plane) in stylus position at peak velocity and at the end of the movement at each target. Over the first movement segment, ellipse areas were analysed using a 2 target (1 Target, 2 Target) ×2Vision (vision, no vision) × 2 kinematic index (peak velocity, movement end) repeated measures ANOVA.

This analysis revealed significant main effects for target, $F_{(1,23)} = 9.3, p \leq 0.01$, vision, $F_{(1, 23)} = 118.5, p \leq 0.001$, and kinematic marker, $F_{(1,23)} = 22.1, p \leq 001$.

There was also a significant interaction between vision and kinematic index ,$F_{(1,23)} = 45.3, p \leq 0.001$.As shown in Fig. 8, variability ellipse areas decreased from $p \leq 0.001$.

Peak velocity to the end of the first segment in the vision condition for both single and two target responses. In the no vision condition, there was no significant difference in ellipse areas between peak velocity and the end of the movement. There was also a triple interaction between target, vision and kinematic index, $F_{(1, 23)} = 5.8, p \leq 0.05$. Breakdown of this interaction revealed that at peak velocity, there was no difference in ellipse areas between the single and two target conditions in the vision or no vision conditions. However, at the end of the first segment, ellipse areas were greater in the two than single target condition in the no vision but not vision condition.For the second movement segment, a 2 vision condition (vision, no vision) x2 kinematic index (peak velocity, movement end) repeated measures ANOVA revealed significant main effects for vision, $F_{(1,\ 23)}$ = 118.7, $p \leq 0.001$, and kinematic index, $F_{(1,\ 23)}$ =4.7, $p \leq 0.05$. The interaction between vision and kinematic index was also significant, $F_{(1,23)}$ = 6.2, $p \leq 0.05$. Breakdown of this interaction revealed that ellipse area decreased from peak velocity to the end of the movement for the vision but not the no vision condition (see Figure 8).

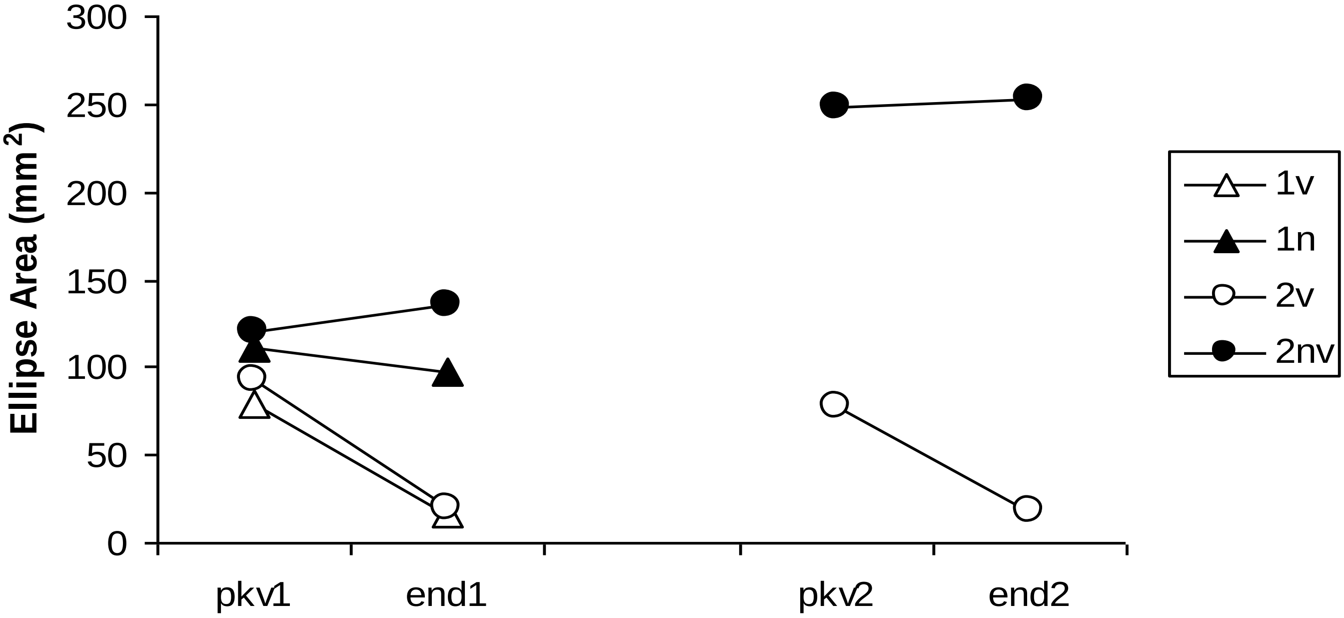

Figure 8. Ellipse areas for one-target (1T) and two-target (2T) tasks, in vision and no vision conditions at peak velocity of the first movement (pkv1), end of movement 1 (end1), peak velocity of the second movement (pkv2) and end of movement 2 (end2).

In order to compare variability between targets 1 and 2 for the two target movements, we performed a 2 targets (Target 1, Target 2) × 2 vision (vision, no vision) × 2 kinematic index (peak velocity, movement end) repeated measures ANOVA. This analysis revealed significant main effects for target, $F_{(1,23)} = 47.1$, $p < 0.001$,*vision*,$F_{(1,\ 23)} = 112.1, p \leq 0.001$, and kinematic index, $F_{(1,\ 23)} = 9.6, p \leq 0.01$.

Similar to the analyses mentioned above, a vision and kinematic index interaction, $F_{(1,23)} = 29.6, p < 0.001$, indicated that variability decreased from peak velocity to the end of the movement for the vision but not the no vision condition for both movement segments. In addition, there was a significant interaction between target and vision, $F_{(1, 23)} = 99.5, p \leq 0.01$. As shown in (Figure 8), there was a significant increase in ellipse areas from the first to the second segment in the no vision but not the vision condition.

Between segment correlations

In order to assess whether movement to the second target was adjusted depending on the characteristics of the first segment, we correlated the distance travelled in the primary direction on the first movement segment with the distance travelled on the second segment. A positive (or zero) correlation would indicate that adjustments were not made between the first and second segments while a negative correlation would imply that the second movement was modified to compensate for the distance travelled on the first segment. We found negative correlations between the distances travelled on the first and second segments for both vision (− 0.74) and no vision conditions (− 0.27). A t-test on the Z-transformations of these correlations revealed a stronger negative correlation in the vision compared to no vision condition, $t_{(23)} = 82.9, p \leq 0.01$.

3.4 Discussion

Past research has demonstrated that the execution of early segments in a multiple target aiming response is influenced by the presence and properties of later segments (Adam et al., 1995; Rand, Alberts, Stelmach, & Bloedel 1997; Rand & Stelmach, 2000). Based on this evidence, it has been suggested that individual components in an aiming sequence are not prepared and controlled independently. Whereas previous investigations have examined how movement times are influenced by factors such as the number of response segments, target size, and the availability of visual feedback, in the present study we constrained movement times and examined the resulting effects on accuracy and limb trajectory variability. In single target aiming, the use of time constrained movements has provided valuable insights towards the formulation of speed accuracy trade- offs (Schmidt et al., 1979). Although differences exist in the control characteristics between time minimization and constrained movements (Carlton, 1994), constraining the duration of the first segment of a two element response allowed us to directly test hypotheses relating to the use of visual feedback in sequential aiming movements.

Under the instruction to move as quickly as possible to defined target areas, movement times to the first target in multiple target aiming sequences are longer than in single target responses (i.e., one target advantage [OTA] in movement time). In the present experiment we found the accuracy equivalent of the OTA by constraining movement times to the first target. The locations of movement endpoints at the first target were more variable in the two compared to single target condition when vision was occluded. Hence, consistent with other studies that have shown that movement time to a target is influenced by the presence of a second target movement (e.g., Adam et al., 2000; Helsen et al., 2001), our results indicate that components of sequential aiming movements are not controlled independently. Along the lines of the movement integration hypothesis, it seems that under the time constraint conditions of the present study, the cognitive processes associated with implementation of the second element caused interference and hence a deterioration in movement accuracy at the first target. When visual feedback was available, participants were able to compensate for the interference caused by overlapping control processes and hence reduce variability at the first target compared to when vision was occluded.

Our results also indicate that variability of movement endpoints was greater at the second compared to the first target when vision was not available. When vision was available there was no difference in variability at the first and second targets. Hence, it seems that vision compensated for the natural increase in variability that occurs as movement progresses. As shown in (Figure 8), variability was significantly heightened at peak velocity of the second segment for the no vision condition and remained at an elevated level at the end of the movement when compared to the vision condition. According to the movement constraint hypothesis, the reason for the emergence of the OTA under time minimization instructions is that the first segment must be constrained in order to meet the accuracy demands of the second target. Our results indicated that when movement times to the first target are not allowed to vary, there was indeed an increase in variability at the second target compared to the first target. Hence, consistent with the movement constraint hypothesis, there is a need to reduce variability at the first target in order to meet high accuracy demands at the second target (Sidaway et al., 1995).Under time minimization conditions, this can be achieved through more precise movement planning resulting in longer movement times to the first target (i.e., OTA).When movement times are constrained but long enough to utilize visual feedback as in the present experiment (i.e.,450 ms), adjustments to the limb trajectory can be made to combat increases in variability as movement progresses.

Given the evidence supporting both the movement integration and constraint hypotheses, we have proposed that vision serves a dual purpose in sequential aiming movements. First, within each movement segment, vision is used to correct errors in the limb trajectory as the limb approaches the target. Evidence for this was provided by the analysis of limb trajectory variability that revealed a reduction in variability between peak velocity and the end of each segment for the vision but not the no vision condition.

This process is especially critical within the first movement segment in order to reduce variability at the first target so that the accuracy demands at the second target are met. Hence, in addition to planning processes prior to movement execution as postulated by the movement constraint hypothesis, online processing of visual feedback plays an important role in constraining limb trajectory variability provided that movement times are sufficiently long.

The second role played by vision is in the integration between response elements. Despite reductions in variability at the first target due to online corrections, the amplitude of the second element must be modified depending on the location of the movement endpoint at the first target. A longer distance travelled on the first target must be compensated by a shorter distance travelled on the second segment and vice versa. A correlation of the distance travelled on the first and second segments revealed a negative relation for both vision and no vision conditions. However, a stronger negative correlation emerged under the vision condition. Hence, vision mediated the transition between segments by providing information about the location of movement endpoints at the first target so that the parameters of the second segment could be modified. This is in accordance with an on-line programming interpretation of the one-target advantage (Chamberlin & Magill, 1989).

The availability of visual feedback also ensured a smooth transition between elements as indicated by shorter pause times under the vision compared to no vision condition (also see Ricker et al., 1999).This finding suggests that vision facilitates integration of first and second movements by moving forward the implementation of the second movement, as claimed by the movement integration hypothesis (Adam et al., 2000). According to this hypothesis, the entire movement sequence is prepared in advance of movement initiation but the implementation of the second movement does not wait on completion of the first movement. Evidence for the advance preparation of several segments comes from the finding that reaction time increases as the number of elements in the sequence increases (Khan et al., 2006, 2007, Khan, Mourton, Buckolz, & Franks 2007; Klapp 1995).

The results of the current experiment showed that vision played an important role in implementing the second segment by fine tuning the parameters of the second movement depending on the metrics of the first segment and by accelerating its implementation. Fine tuning and implementation of the second segment are likely based on a forward model of internal feedback loops whereby the endpoint of the first segment can be predicted in advance of its termination (see Desmurget & Grafton 2000).

Adam et al. (2000) have shown that the OTA was present under low accuracy demands but not under higher accuracy demands. It seems that under high accuracy constraints, movements to targets are organized separately and independently, and hence there is no overlap of control processes. Implementation of the second element then occurs during contact with the first target as indicated by an increase in dwell or pause times on the first target. It may be that when aiming movements are performed to small targets, the attention demands associated with the use of vision becomes so high that there is no capacity for preparing the second segment during execution of the first element. Khan et al. (2006) have also shown evidence that the use of vision in multiple target aiming is attention demanding. When participants knew in advance that a two segment response was required, the introduction of a secondary task during execution of a two target sequence caused significant deterioration in aiming accuracy at the first target. This deterioration in movement accuracy did not occur in the single target condition or when participants did not know in advance that a two element response was required. Hence, it seems that when participants know prior to the stimulus that a two target movement is required, the visuomotor system is prepared for a dual purpose of visually regulating movement to the first target and implementing the second segment. This high demand on the visual system is attention demanding and hence susceptible to dual- task interference.

Although we have suggested that the use of visual feedback is attention demanding, in the present experiment movement times were relatively long (i.e., 450 ms) compared to studies in which the OTA emerged under the instructions to minimize movement time (typically 150–400 ms).Hence, the attention demands associated with the use of visual feedback may have been consumed within the relatively long duration of the movement. This would have enabled participants to use vision in mediating the transition between movement segments without any noticeable deterioration in performance. It is likely that under shorter movement durations, accuracy decrements would emerge in two segment responses when vision is available since less time would be available to compensate for interference arising from the implementation of the second segment. In a recent study, Khan, Mottram, Adam, and Buckolz (2010) showed that the one-target advantage emerged when participants switched hands at the first target. It was reasoned that this finding could not be explained by the movement constraint hypothesis since the starting location of the second segment was fixed and hence not dependent on the endpoint of the first segment. However, the presence of the one-target advantage for sequential two-limb aiming does not rule out a movement constraint interpretation for single limb movements.

As we have shown here, constraining spatial variability is a critical component in the control of single limb sequential aiming movements. Hence, the similarities and differences between single and two limb sequential aiming are open to further debate. It may be that in addition to the role of visual feedback in modifying spatial parameters both within and between segments,the timing of implementation of the second segment may be a source of interference in sequential target aiming (Ketelaars, Khan, & Franks1999). Since the one-target advantage emerges in both single and two limb sequential aiming movements, the processes underlying the implementation of the second segment may have a central locus that is contingent on visual feedback when it is available or proprioceptive information when vision is occluded.

CHAPTER 4

THE EFFECT OF VARYING THE FIRST TARGET LOCATION ON MOVEMENT INTEGRATION: A NON-PERTURBED PARADIGM

4.1 Introduction

Whether in everyday life or in sporting circumstances, people need to perform a variety of motor skills quickly and accurately. One facet of movement that has been shown to consistently influence the speed of motor skill execution is the number of segments within an action. The work of Henry and Rogers (1960) revealed that reaction times are directly related to the number of response elements. This research motivated an extensive body of research aimed at further understanding the relationship between reaction time and the number of response elements (e.g., Klapp, 1995, 2003; Khan, Lawrence, Buckolz & Franks, 2006; Sternberg, Monsell, Knoll & Wright, 1978). More recently, researchers have focused their attention on how movement times are affected by the number of targets in an aiming sequence with findings revealing that movement times to the first target in a two-target sequence are slower than when a single target response is required (Adam et al., 2000; Chamberlin & Magill, 1989; Elliot, Helsen, & Chua, 2001; Khan et al., 2010; Lavrysen, Helsen, Elliott & Adam, 2002). This one-target advantage (OTA) is a robust phenomenon since has been shown to emerge when the two segments are performed both with the same limb and when the first and second segments are performed with different limbs (i.e., when there is a switch between limbs at the first target, see Khan et al., 2010), it also occurs under both left and right hand responses (Helsen et al., 2001; Lavrysen et al., 2003), with and without vision (Lavrysen, Helsen, Elliott, & Adam, 2002) and is resistant to practice (Lavrysen et al., 2003). Collectively, this body of research has indicated that individual segments in a targeted sequence are not prepared and executed independently (Adam et al, 2000). When the number of targets is known in advance, the preparation and execution of the targeted sequence is influenced by the properties of the individual segments as well as the relation between segments. The purpose of the current investigation was test how manipulating the distance to the first target at target onset influences the interdependency and integration between movement segments.

The interdependency between response segments in a targeted sequence has been explained via two hypotheses. The movement constraint hypothesis (MCH), (Sidaway, Sekiya & Fairweather, 1995) is based on the assumption that the variability of movement endpoints accumulates from one target to the next. Hence, in order to be accurate at a second target, movement to the first target must be constrained so that the accuracy demands at the second target are met. The constraining of movement endpoints at the first target is achieved through more precise movement planning and/or feedback processing during movement execution.This reduction in endpoint variability at the first target also allows for a more integrated and efficient transition between response segments (Khan et al,2010).

The movement integration hypothesis (Adam et al., 2000) poses that segments are programmed and stored in a buffer prior to response initiation. In order to facilitate a smooth and efficient transition between elements, the implementation of the second element is performed online concurrent with the execution of the first. This online implementation results in increased cognitive control during the production of the first element in two element responses and leads to interference. Hence, while the implementation of the second segment during the first segment facilitates the transition between segments, the increased interference during movement execution results in a lengthening of MT to the first target.

In support of both the movement integration and constraint hypotheses, the previous chapter revealed that vision plays a dual role in the control of sequential aiming movements. Specifically, data showed that when vision was available over the first segment, movements were adjusted as the limb approached the target thereby reducing endpoint variability. Also, a negative correlation between the distance travelled on the first and second segments implied that participants modified the second segment based on the distance travelled on the first segment. That is, a longer distance on the first segment was compensated by a shorter distance on the second segment and vice versa. Thus, online processing of visual feedback played an important role in constraining the limb trajectory of the first movement (i.e., supportive of the movement constraint hypothesis) while also playing a role in implementing the second segment by fine tuning the parameters of the second movement (i.e., supportive of the movement integration hypothesis).

Whilst the OTA has been shown to be robust, it does not emerge when the accuracy demands at the first target are relatively high (Adam et al., 2000). Movements to a small target are characterised by relatively long pause times between response segments thereby functionally separating the movements to both targets (Adam & Paas, 1996; Adam et al., 1995; Adam et al., 2000; Rand & Stelmach, 2000). Hence, the principles underlying the movement integration and constraint hypotheses do not apply since the two segments are controlled as separate units. In addition, it has been shown that reducing the size of the second target affects both movement times from the first to the second target and, importantly in relation to the OTA, the duration of the first movement segment (Rand & Stelmach, 2000; Ricker et al., 1999). These findings indicate that sequential aiming movements are controlled dependently and that the characteristics of either the first or second segment can influence that of the other segment.

The second additional factor that influences movement programming is the availability of visual feedback. When vision is occluded over the first movement segment, participants take longer to initiate their movement and movement times to the first target are increased (Lavrysen et al., 2002). It seems then that when vision is not available, participants prepare more precise motor programs (i.e. they are more constrained) so that there is less reliance on online correction processes. Removing vision from the first movement segment has also been shown to not only increase pause times at the first target, but also increase movement times from the first to second target (Ricker et al., 1999). These findings suggest that when vision was removed from the first segment, there was less overlap between control processes and hence the implementation of the second element occurred during the dwell time at the first target rather than during execution of the first segment. Interestingly, removing vision over the second movement segment has also been shown to increase movement times to the first target (Lavrysen et al., 2002).

Separate research has revealed that target size at both target one and target two together with the availability of visual feedback during both the execution of the first and second movement influences movement integration(Rand et al ., 1997;Cameron et al .,2007;Rand&Stelmach 2000;Ricker et al .,1999). However, the effect of movement distance to the first target under differing visual conditions has yet to be investigated within the OTA literature. As such, the primary purpose of the present study was to investigate the preparation and integration of multiple target actions when varying the location of first target location under both full vision conditions and when vision was occluded following impact at the first target.

4.2 Method

Participants

24 volunteers (males = 13 females = 11; ages 18-33) participated in the study. All participants were self-declared right hand dominant, and had reported normal or corrected to normal vision. They all signed consent forms before taking part in the experiment and the study was carried out according to the ethical guidelines stated by the Ethics Committee of the School of Sport, Health and Exercise Sciences, Bangor University, for research involving human participants.

Apparatus

Participants sat at a table 75 cm above the ground. Aiming movements were performed on a computer monitor (19 inch) that was mounted horizontally and faced upwards in a cavity cut out from the table top (see Figure 9). A sheet of plexi-glass 5 mm thick covered the monitor surface and was level with the table top. The start position was located 7 cm to the left of the right edge of the monitor. Target 1 was located to the left of the start position at one of three possible positions (8, 10 or 12 cm) while target 2 was a further 10 cm to the left of Target 1. Participants were seated such that the body midline was aligned with Target 2. The start position consisted of a small cross 10 mm in diameter while targets consisted of circles 1 cm in diameter. Participants performed aiming movements with a pen-like stylus held with their right hand. A micro-switch was mounted on the tip of the stylus. The position of the stylus was recorded from a small infrared-emitting diode (IRED) that was secured 5 mm from the tip of the stylus. The IRED was monitored using an Optotrak (Northern Digital Inc) three-dimensional movement analysis system at a sampling rate of 500 Hz. Participants wore a pair of liquid-crystal visual occlusion spectacles (Translucent Technologies, Toronto, Canada).

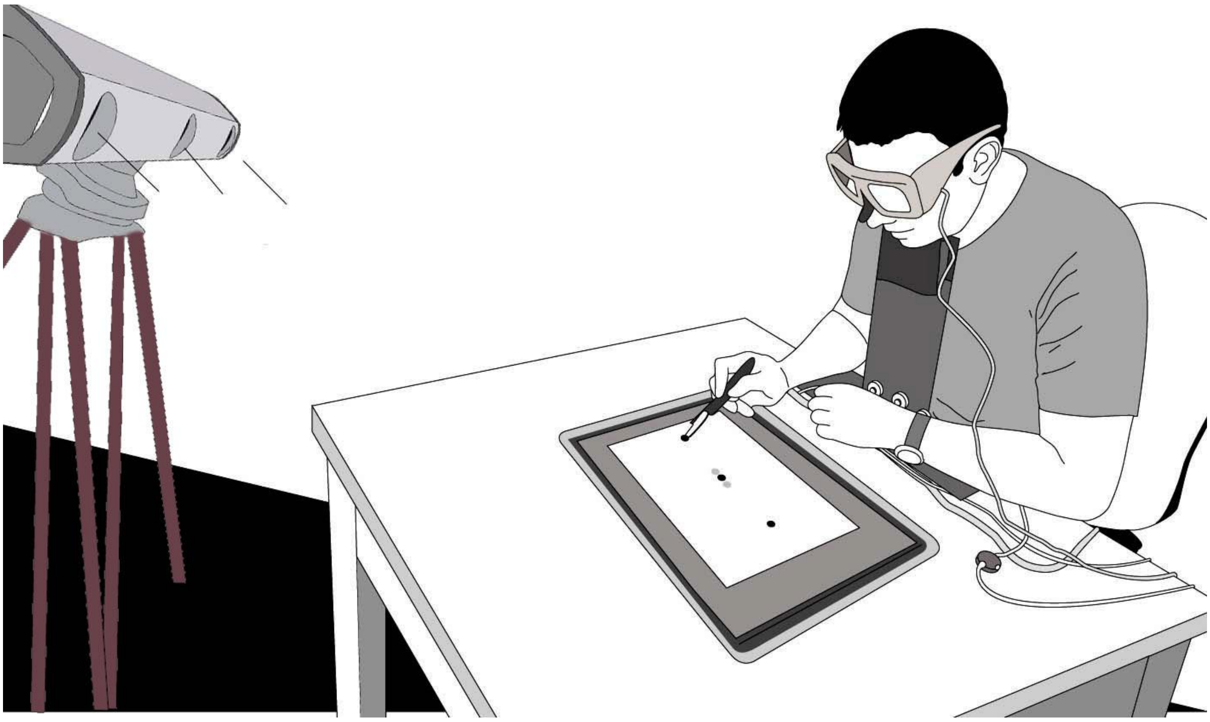

Figure 9 schematic representation of the experiment set-up .the aiming task was performed with a stylus to target displayed on a computer monitor that was mounted facing upwards in a cavity cut out from a table top. Movement were performed in the right to left direction.

Procedure

At the beginning of each trial, the start position and target(s) appeared on the monitor (see Figure 10). Participants were first required to place the tip of the stylus at the start position. Once the stylus was steadily placed, a tone was presented signalling to participants to start their movement. Participants performed three movement tasks. In the one-target task (1T), participants raised the stylus from the start position and were required to touch down at Target 1. In the two-target, vision task (2TFV), participants moved to Target 1 and then to Target 2. In the two-target, no vision task (2TNV), participants also moved to Target 1 and then to Target 2 but the occlusion goggles closed when the stylus made contact at the first target. Hence, vision was available on the first movement segment but not on the second segment. Participants were instructed to perform their movements as fast as possible while ensuring that they tip of the stylus touched down within the targets.

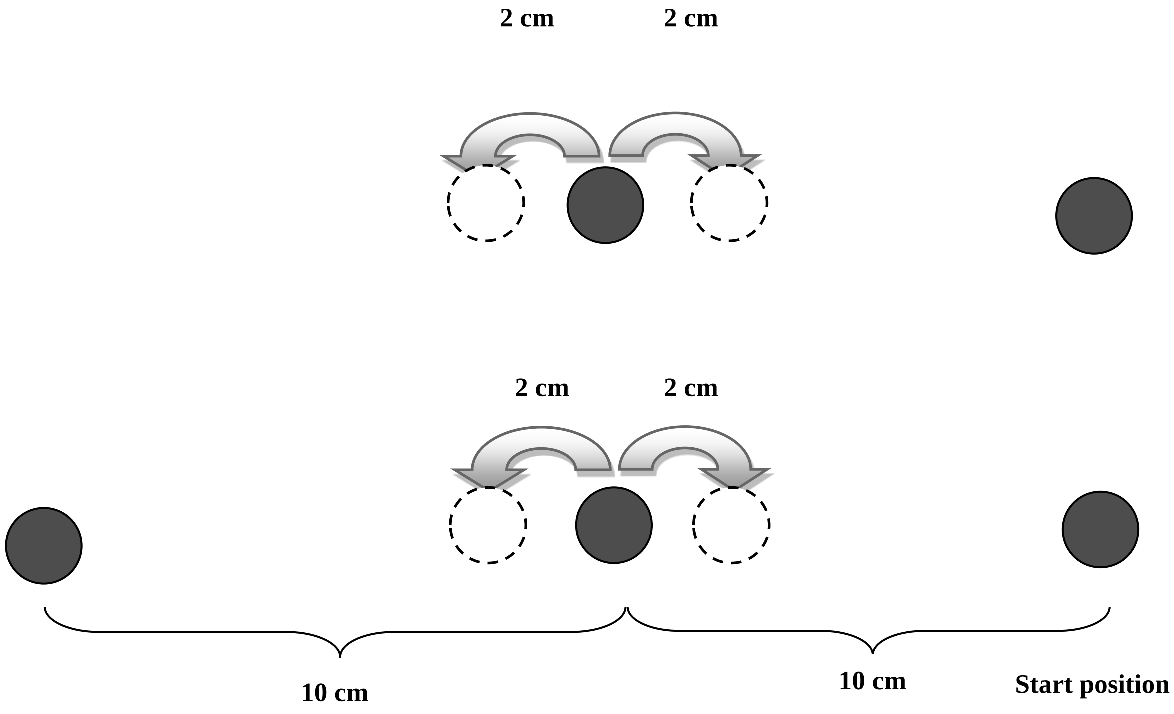

Figure 10 Diagram illustrating position of start, 1 target and 2 targets. In the first target vary (non-perturbed).

They were given feedback on their reaction time and movement time after each trial in numerical form on the computer monitor. The task had to be completed within two seconds at which time the targets disappeared. In the two target no vision condition, the goggles re-opened after 3 sec. Since the targets had disappeared by this point in time, participants did not receive visual information of their endpoint accuracy.

For each task, the position of the first target could appear in one of three positions; either 8cm (short; S), 10 cm (Neutral; N) or 12 cm (long; L) from the start location. Participants performed a block of trials for each of the three aiming tasks (1T, 2TFV, 2TNV). Each block consisted of 36 trials; 12 trials to each of the three possible target one location. The order of these blocks was counterbalanced between participants and the order of the target one locations was randomised within participants. Prior to each block of trials, participants performed 5 familiarization trials.

Data reduction

The 3D position data from the Optotrak were filtered using a second order, dual-pass Butterworth filter with a low pass cut-off frequency of 16 Hz. Position data were then filtered to obtain velocity information. Peak resultant velocity was identified for movements to each target. The start of movement to the first target was identified from working back from peak velocity to locate the first point in which velocity in the vertical direction (i.e., z-axis) was less that 15 mm/s. The end of the first movement was the point after peak velocity in which the vertical velocity fell below 15 mm/s.2 this process was repeated to locate the start and end of the second movement for the two-target conditions. At the end of each movement segment and at peak resultant velocity for each segment we recorded the position coordinates in the primary direction of the movement (i.e., y-axis) and perpendicular to the primary direction of movement (i.e., x-axis).

Dependent Measures

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[2] The velocity in the vertical direction was used to locate the start and end of movements since sliding of the stylus on the table top at the first target made it difficult to locate velocity zero crossings in the horizontal plane.

Our dependent measures consisted of reaction time (RT), movement time to the first target (MT1), movement time from the first to second targets (MT2), pause time at the first target (PT), constant errors (i.e., signed difference between movement endpoints and the centre of the target) in the primary direction of the movement at the first and second targets (CE1, CE2) and variable errors (i.e., the within participant standard deviation of the signed difference between movement endpoints and the centre of the target in primary direction of the movement at the first and second targets) (VE1,VE2).A positive CE referred to an overshoot while a negative CE referred to an undershoot. RT, MT1, CE1 and VE1 were analysed separately using 3 Tasks (1T, 2TFV, 2TNV) x 3Target Location (N,S,L) repeated measures ANOVAs, while PT, MT2, CE2 and VE2 were analysed using separate 2 Tasks (2TFV, 2TNV) x 3 Target Location (N,S,L) repeated measures ANOVAs

4.3 Results

Means and *SDs* for each dependent variable are reported in (Table 2). The analysis of RT revealed a significant main effect for Task ($F_{(2, 46)} = 15.87$, $p \leq .001$) together with a significant Task by Target Location interaction ($F_{(2, 46)} = 5.16$, $p \leq .01$). Specifically, whilst RTs were longer for the 2TNV task compared to the 1T and 2TFV tasks, RTs were only significantly different at each target location within the 2TNV task (see Figure 11).

	1T			2TFV			2TNV		
	L	N	S	L	N	S	L	N	S
RT(ms)	244	233	237	258	255	249	261	275	288
	(47.5)	(33.0)	(32.2)	(44.9)	(39.0)	(41.8)	(41.1)	(49.0)	(70.0)
MT1(ms)	257	249	233	271	259	233	261	253	244
	(44.8)	(52.4)	(52.1)	(62.3)	(61.8)	(50.0)	(46.5)	(58.1)	(48.4)
CEx1(mm)	0.5	0.4	0.3	0.5	1.8	1.0	1.0	0.8	1.7
	(2.1)	(2.0)	(1.8)	(1.9)	(2.1)	(3.0)	(2.6)	(2.5)	(2.4)
VE1(mm)	4.4	4.0	3.9	4.2	4.4	4.3	4.4	5.4	4.5
	(2.2)	(1.5)	(1.2)	(1.8)	(2.2)	(1.8)	(1.7)	(2.4)	(2.1)
MT2(ms)				241	257	272	216	237	253
				(60.2)	(64.5)	(61.6)	(39.6)	(54.6)	(54.6)
PT(ms)				43	44	38	37	45	57
				(36.8)	(40.0)	(34.4)	(32.8)	(39.6)	(69.2)
CEx2(ms)				-0.4	-0.3	-0.2	1.3	1.1	-0.7
				(3.7)	(2.9)	(3.5)	(10.4)	(11.7)	(13.6)
VE2(mm)				4.4	4.8	4.6	5.9	8.4	9.2
				(1.8)	(2.5)	(1.9)	(1.9)	(3.0)	(3.1)

Table 2 Means and SDs for all dependent measures as a function of task (1T = single task; 2TFV = two target full vision; 2TNV = two target no vision) and target location (S = short; N = neutral; L = long).

The analysis of MT1, revealed a significant main effect of Target location $(F_{(2, 46)} = 15.42, p \leq .001)$ with movement times to the short target being significantly faster than those to the long target (see Figure 12). Whilst the main effect of task was non significant ($p \geq .05$), the Task by Target Location interaction was significant $(F\ (_{4, 92}) = 1.31, p \leq .05)$. Specifically, whilst movement times were significantly greater in the long compared to short targets, these differences were significantly greater in the 1T and 2TFV conditions.

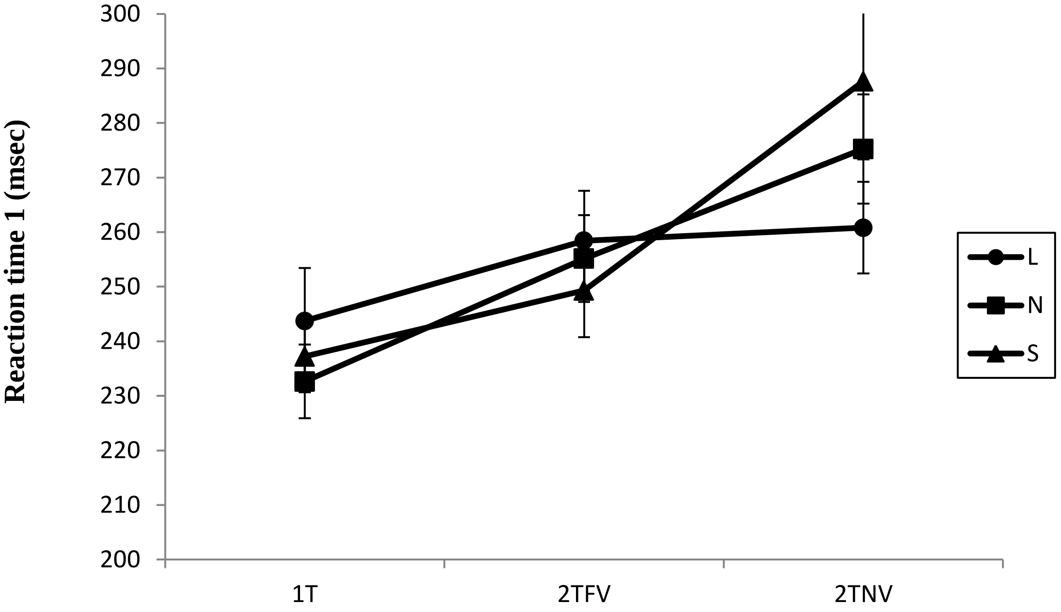

Figure 11 Reaction time as a function of task (1T = single task; 2TV = two target full vision; 2TNV = two target no vision) and target location (S = short; N = neutral; L = long).

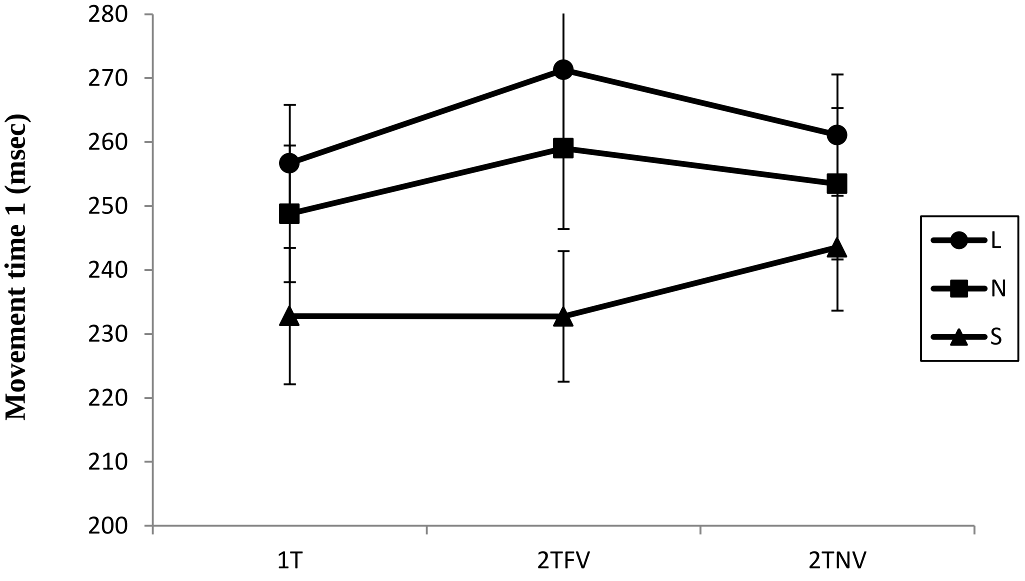

Figure 12 . Movement time as a function of task (1T = single task; 2TFV = two target full vision; 2TNV = two target no vision) and target location (S = short; N = neutral; L = long).

The analyses of target 1 accuracy revealed that there were no significant main effects or interactions (all *p's* ≥ .05) for CE1, although there was a tendency for movements to be more accurate in the single compared to two movement tasks ($F_{(2, 46)} = 2.27$, $p = .07$) (see Figure 13). For VE1, the analysis revealed a significant main effect for Task ($F_{(2, 46)} = 5.05$, $p \leq .001$) with the variability of movement endpoints at the first target being greatest when vision was not available over the second segment .No other significant main effects or interactions were observed ($p \geq .05$).

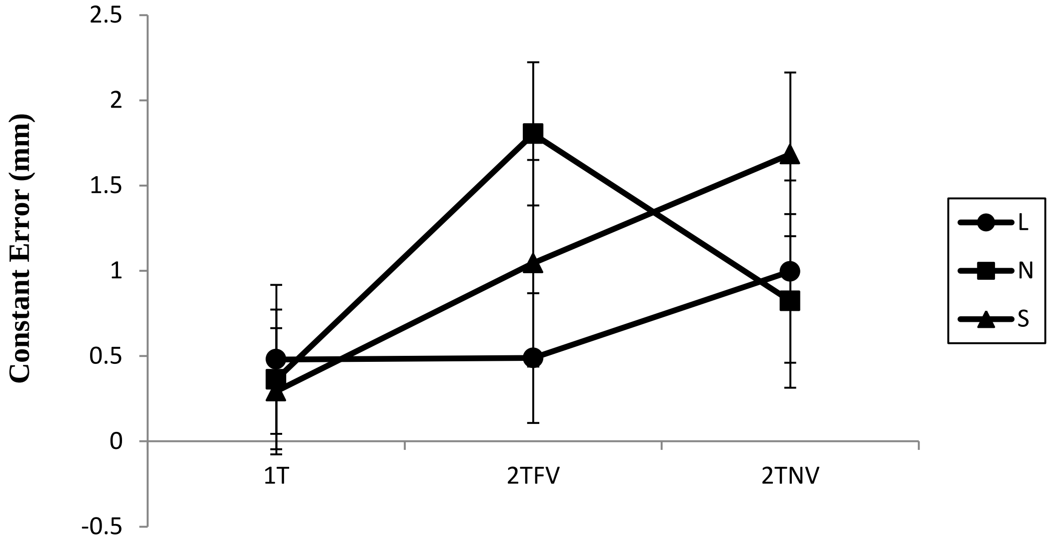

Figure 13 Constant error at target 1 as a function of task (1T = single task; 2TFV = two target full vision; 2TNV = two target no vision) and target location (S = short; N = neutral; L = long).

No main effects or interactions were evident within the pause time data (all *p's* ≥ .05), although the Task by Target Location interaction did approach conventional levels of significance ($F_{(2, 46)} = 4.71$, $p = .08$) with pause times tending to be greater in the short target locations of the 2TNV task compared to all other conditions (see Figure 15).

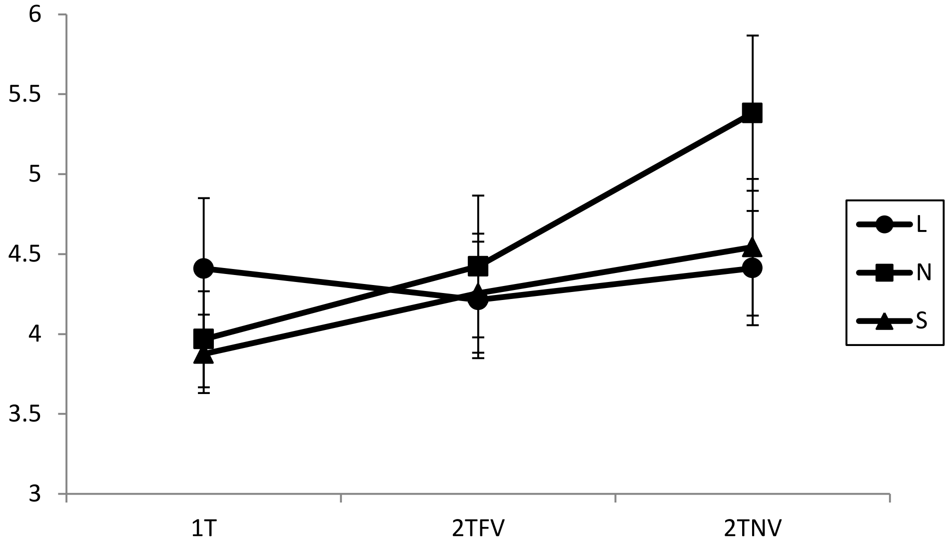

Figure 14 Variable error at target 1 as a function of task (1T = single task; 2TV = two target full vision; 2TNV = two target no vision) and target location (S = short; N = neutral; L = long).

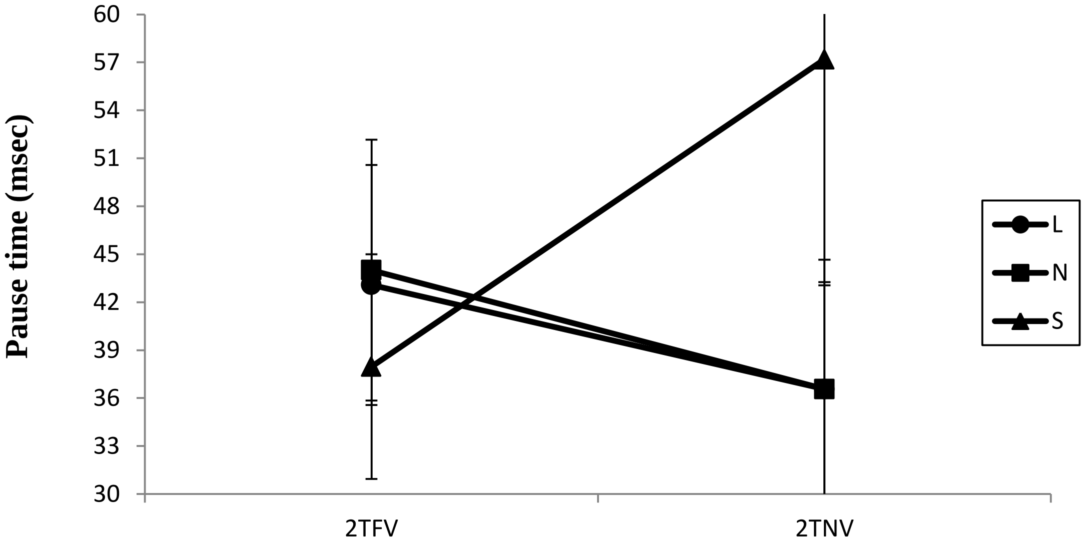

Figure 15 Pause times as a function of task (2TFV = two target full vision; 2TNV = two target no vision) and target location (S = short; N = neutral; L = long).

The analysis of MT2 revealed significant main effects for Task *(F* $_{(1, 23)}$ = 3.97, *p* ≤.05) and Target Location *(F* $_{(2, 46)}$ = 16.27, *p* ≤ .001). Movement times were significantly greater when vision was available and significantly increased as the distance to target 2 increased. That is, movement times were significantly different in all target locations with movement times being greatest in the short target location (i.e., when the distance required in movement two was the greatest).The analyses investigating accuracy at target 2 revealed non significant main effects or interactions for CE2 (all *p's* ≥ .05) whilst the VE2 data revealed that variability was significantly greater in the 2TNV compared to 2TFV tasks *(F* $_{(1, 23)}$ = 60.31, *p* ≤ .001) and in the neural and short target locations compared to the long target location *(F* $_{(2, 46)}$ = 13.21, *p* ≤.001. The significant Task by Target Location interaction *(F* $_{(2, 46)}$ = 6.81, *p* ≤ .001) revealed that the difference between the vision and no vision conditions was only significant in the backward and forward target locations (see Figure 17). The main effect for Target Location was non significant (*p* ≥ .05)

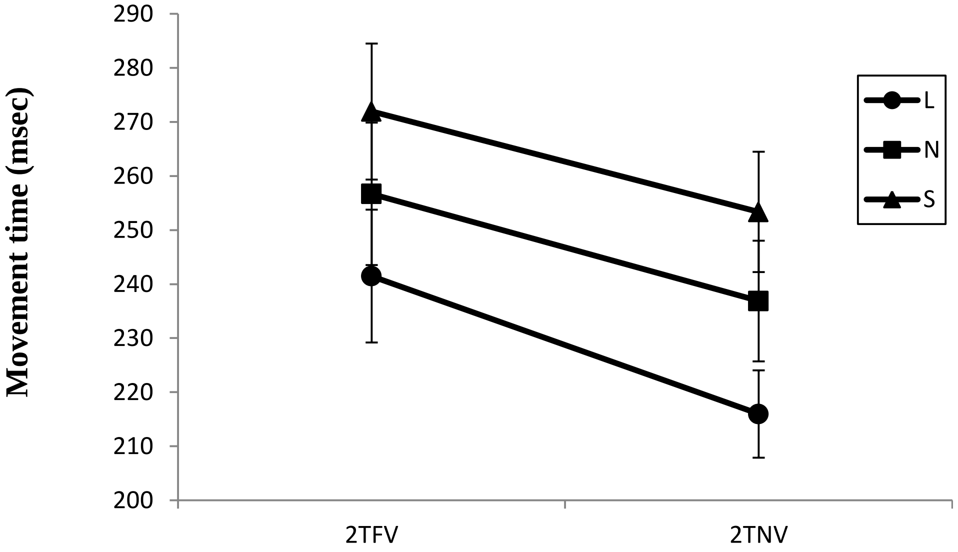

Figure 16 Movement time 2(MT2) as a function of task (2TV = two target full vision; 2TNV = two target no vision) and target location (S = short; N = neutral; L = long).

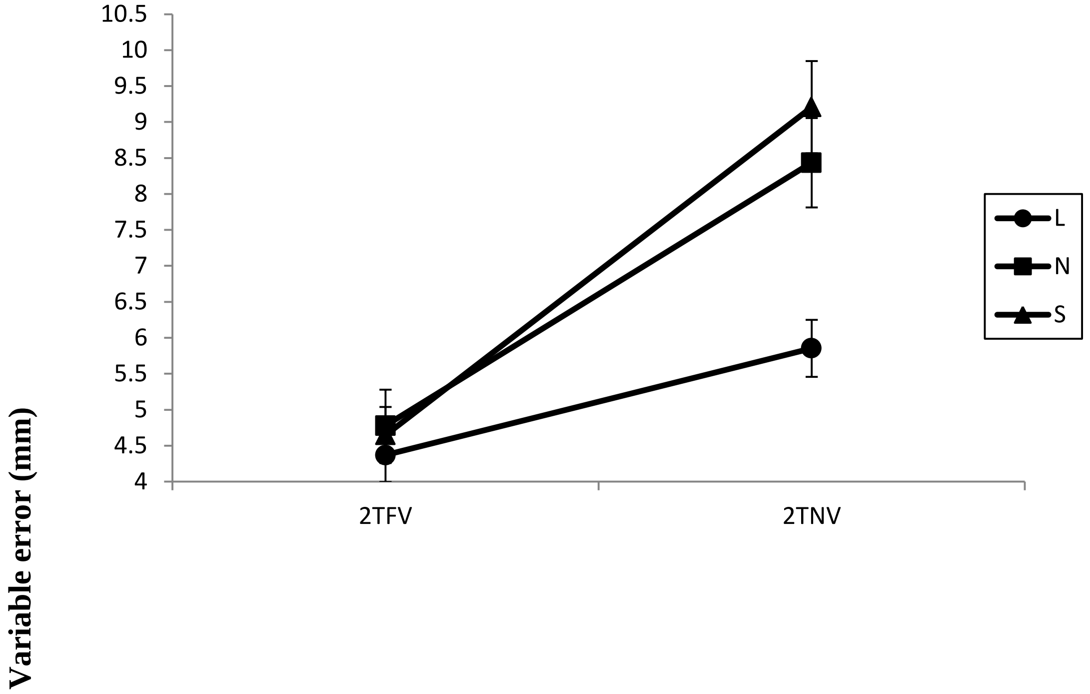

Figure 1.7 Variable error 2 (VE2) at the second target as a function of task (2TFV = two target full vision; 2TNV = two target no vision) and target location (S = short; N = neutral; L = long).

Additional analyses

In order to investigate the degree to which participants adjusted the distance travelled on the second segment to compensate for the different target locations and different visual conditions we correlated the distance travelled on the first segment with the distance travelled on the second segment (see Elliott, Binsted and Heath, 1999; Khan et al., 2010). The reasoning behind this analysis was that a shorter distance travelled on the first segment would have to be compensated by travelling a longer distance on the second segment, and vice versa. Hence, if adjustments are being made to the distance on the second segment based on the distance travelled on the first segment, the two distances should be negatively correlated. A two Task (2TFV, 2TNV) x 3 Target Location (N, S, L) repeated measures ANOVA performed on the Z-transformation of the correlation coefficients revealed a significant main effect of Task ($F_{(1, 23)} = 6.31$, $p \leq .02$) and a significant Task by Target Location interaction ($F_{(2, 46)} = 4.63$, $p \leq .05$).

As shown in (Figure 18), correlations were negative for all conditions but were significantly more negative when vision was available over the second segment compared to when vision was occluded. Furthermore correlations in the 2TFV were significantly more negative when the target was closer to the start position compared to the long and neutral positions. In the 2TNV task correlations were only negative in the short and long target locations and significantly different to those in the neural target location. The main effect for target location was non significant ($p \geq .05$).

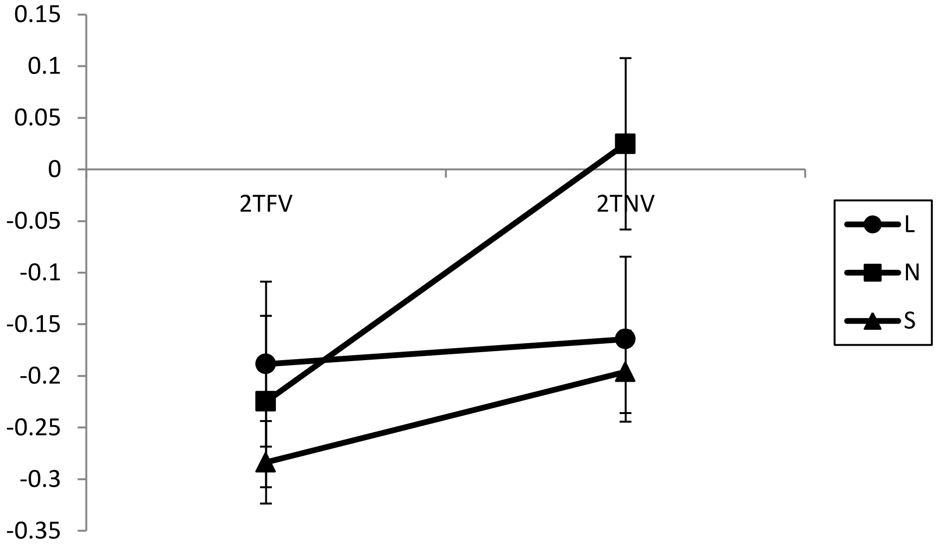

Figure 18 Z transformations for the correlations between the distance travelled at target 1 with the distance travelled at target two as a function of task (2TFV = two target full vision; 2TNV = two target no vision) and target location (S = short; N = neutral; L = long).

4.4 Discussion

Past research has revealed that the availability of visual feedback plays an important role in movement accuracy, and researchers have usually related this to the process of the correcting error in the limb trajectories during the movement execution. As we showed in the previous chapter of this thesis, the execution of early segments in a multiple target aiming response is influenced by the presence and properties of later segments (also see, Adam et al., 1995; Rand, Alberts, Stelmach, & Bloedel 1997; Rand & Stelmach, 2000). Based on this evidence, it has been suggested that individual components in an aiming sequence are not prepared and controlled independently. The primary purpose of the present study was to investigate the effect of varying the first target location under a non perturbed paradigm. In addition, similar to the first experimental chapter of this thesis, we continued to test the assumption that vision of the second movement has an effect on the preparation and integration of the first movement.

Our results showed that a longer distance travelled on the first target must be compensated by a shorter distance travelled on the second segment and vice versa. Specifically, the correlation of the distance travelled on the first and second segments revealed negative values for both the vision and no vision conditions. Nevertheless, a stronger negative correlation emerged under the vision condition indicating that visual feedback was used to make online movement adjustments to the second segment to more effect than the afferent information available under the no vision conditions. Furthermore, movement times to the first target (and second target) were longer, variable error was less, and pause times tended to be shorter in the 2TFV compared to 2TNV conditions. Collectively, these findings indicate that the availability of visual feedback throughout the entire action also ensured greater transition between elements. That is, similar to the findings of the previous chapter, vision of both movement one and two facilitates integration of these movements by reducing endpoint variability (supporting the MCH, Fishman & Reeve, 1992) and monitoring the first segment in order to the accurately time the implementation of the second movement (MIH, Adam et al., 2000).

According to the MIH (Adam et al., 2000), when responses require two movements, both of these are programmed in advance of movement initiation. Furthermore, research has suggested that this pre-programming is mediated by the knowledge of the available visual feedback (Lavrysen et al., 2002). The results of the present investigation offer further support for these proposals, since reaction times were longer in the 2 target compared to single target responses and longer still in the 2TNV compared to 2TFV and single target conditions. Of more interest, is the finding that reaction times were only significantly affected by target location in the 2TNV task. Specifically, RTs increased in relation to an increase in the movement distance of the second segment (i.e., RT's were longer when target one was closer to the start position [S] in comparison to when the same target was further away from the start position [L]). This suggests that the more careful programming seen under the no vision conditions was mediated by the movement distance of the second movement. These findings are likely due to the fact longer movements result in greater movement variability (Khan et al., 2006; Schmidt, 1979) and thus require more accurate planning when not subject to online visual feedback adjustment (see also Khan et al., 1998). Thus, because participants were aware that visual feedback was unavailable during the second segment in the 2TNV conditions they adopted a strategy of more carefully planning the responses where the distance of the second movement was longest.

In line with this, movement times between the first and second targets were significantly shorter when visual feedback was unavailable, suggesting that participants adopted movement planning and execution strategies that were not dependent on the use of afferent information for online movement corrections. Further support for this proposal can be seen in the variability at target 2. Here variability was significantly greater in the 2TNV compared to 2TFV conditions. However, this difference was only significant when the distance to the first target was manipulated (i.e., the short and long target locations). These manipulations resulted in the requirement of different movement distances between the first and second targets in comparison to the neutral target locations (8 cm and 12 cm for the short target location; 12 cm and 8 cm for the long target locations; 10 cm and 10 cm for the neutral target location). As such, it is possible that the manipulation required greater use of cognitive recourses in an attempt to both monitor movement one in order to reduce variability at target one and to accurately time the implementation of the second movement whilst also ensuring that the motor program of the second movement was accurate because any discrepancies between the limb and target position were not subject to online visual feedback correction. These strategies would explain the more careful planning (e.g., longer reaction times), less available resources for the use of visual feedback to make online corrections during the first movement (e.g., greater variability at the first target) together with the longer movement times and greater endpoint variability for the second segment in the 2TNV compared to the 2TFV conditions. In conclusion, it appears that both the processes involved in the planning and execution phases of multiple target movements are mediated by the availability of visual feedback and the required movement distance to the first target.

CHAPTER 5

THE EFFECT OF VARYING THE FIRST TARGET LOCATION ON MOVEMENT INTEGRATION: A PERTURBED PARADIGM

5.1 Introduction

Simple tasks such as pointing or reaching and grasping, together with more complex tasks such as a whole body gymnastics routine or a ground stroke in tennis, all require the performer to plan, execute and integrate multiple movements into a coordinated and efficient action. Researchers have adopted numerous approaches in order to understand how the multiple segment movements in actions are prepared and executed. While initial research was devoted to understanding the relationship between reaction time and the number of response segments/elements (e.g. Henry & Rogers, 1960; Klapp, Wyatt & Lingo, 1974; Sternberg et al., 1978), more recent efforts have focused on the time it takes to execute movements within a response (e.g., Adam et al., 2000). With regard to the former, the typical finding is that reaction time (RT) is negatively influenced by the number of elements within a response. In their seminal article, Henry and Rogers (1960) reported that RT for a simple finger lift response was faster than when this response was followed by further actions, such as grasping a ball. This increase in RT as response complexity increased was attributed to the greater time needed to program more complex movements. Since some aspects of muscularity need to be pre-programmed before the execution, reaction time provides information about movement planning for impending movement (Rosenbaum, 1980; Klapp, 1995).

With regard to the latter aspect (i.e. movement times), as discussed in the first experimental chapter of this thesis, movement times to the first target in a multiple target sequences are typically longer than movement times to a single target. This phenomenon has become known as the ‘one-target advantage’ (OTA). It has been proposed that this lengthening of movement time is a consequence of additional control processes associated with the implementation of the second segment during execution of the first segment (see Glencross, 1980; Chamberlin & Magill, 1989; Adam et al., 2000; Fischman & Reeve, 1992). A fundamental question in multiple target actions is the extent to which movements within a sequence are planned and executed in relation to each other. In the first study of this thesis, we have shown evidence that suggests that individual components in an aiming sequence are not prepared and controlled independently. Furthermore, it was concluded that vision plays a dual role in mediating the mechanisms responsible for this inter-dependency. That is, vision serves to; 1) make online movement corrections during the first movement such that the variability at that target has a minimal impact of the accuracy of the second; 2) allow continuous monitoring of the first movement such that the implementation of the second movement is produced at a time that allows optimal integration between the two movements. This dual role of vision supports the proposed processes of both the movement constraint hypothesis (Sidaway et al., 1995), where there is a need to reduce variability at the first target in order to meet the accuracy demands at the second target, and the movement integration hypothesis (Adam et al., 2000) whereby the careful monitoring of the first movement allows for increased accuracy leading to optimal integration and a reduction in the interference associated with the implementation to the second movement during the execution of the first.

Early research investigating the accuracy of voluntary movement revealed that there are at least two components involved in target aiming movements (Woodworth, 1899), and more recent motor learning and control research is consistent with this notion (for a review see Elliott et al ,2010) The first component is deemed as a fast, ballistic pre-programmed action designed to bring the limb into the vicinity of the target. Following this component, the limb enters a correction phase whereby afferent information regarding the position of the limb in relation to the target is used to decrease any discrepancies between the two and thus ensure accuracy.

An obvious factor that influences both the planning and correction phases of target directed movements is the availability of visual information. Research has revealed that when movement durations are long enough to encompass visuomotor delays (approximately > 100 msec, Carlton, 1992) visual information can be utilised both to detect errors in limb trajectories and then perform movement corrections based on this information during movement execution. However, in situations where movement times are faster than those necessary to encompass visuomotor delays, vision still plays an important role in movement accuracy. Here, vision regarding the endpoint of movements is utilised 'offline' in order to more accurately plan subsequent actions (Khan et al., 2003, 2004).

In addition to investigating the use of vision for online and offline processes during in single movement tasks, Ricker et al. (1999) investigated the effect of occluding vision at various points during a two target aiming task. Specifically, movements were compared between full vision conditions and conditions where vision was occluded during the flight phase of the first movement or when vision was removed once the limb was in contact with the first target. Results revealed that the removal of vision following contact with the first target did not affect the time spent on the first target. This indicates that the two movements were planned interdependently and thus organised prior to the end of movement one. Furthermore, reaction times were shorter when vision was continually available indicating that vision prior to movement onset can be used to formulate a movement plan to both targets in a sequence.

Whilst research utilising visual occlusion paradigms has revealed that vision is used to both plan and correct movement trajectories, similar findings have been observed in experiments that utilise perturbation paradigms. Relatively simple perturbations might involve a change in the size of the target (e.g. Heath et al., 1998) and its position (e.g., Paulignan et al., 1991). Studies have shown that the ability for movement trajectory adjustment in human performance materialises very rapidly, even in response to a small perturbation (such as changes in target position i.e. right or left, closer or further away from the participant's body), without the performer realising that the target had moved (Proteau, Roujoula, & Messier, 2009). These findings suggest that online error corrections are based on automatic and reflexive processing of afferent information and the time required for this type of adjustment has been estimated to be 100 ms when the target object is moved at the time of movement initiation (Pélisson et al., 1986; Paulignan et al., 1991; Hansen & Elliott, 2009).

Adjustments to limb trajectories following perturbations of the target are not restricted to situations where actual ‘real’ perturbations occur, since there is some evidence for the influence of an illusory change in target or limb position on trajectory control (Bruno et al., 2008; Grierson & Elliott, 2009). Grierson and Elliott, (2009) introduced an illusionary paradigm (a moving background) at movement initiation to provide the illusion that the limb was moving faster or slower than expected. This paradigm resulted in a mismatch between the perceived velocity of the limb and the expected velocity of the limb and thus prompted an early adjustment to limb velocity. In addition, the Muller–Lyer illusion was used to influence the perceived position of the target and hence encourage a discrete correction late in the movement trajectory. Results revealed that the illusory perturbations impacted movement outcome in that the conditions where the moving background and Muller-Lyer created illusions that movements were faster and larger than reality resulted in participants terminating their trajectories sooner than necessary (the opposite was true in situations where perturbations created the illusion that the limb was moving faster than in reality). These findings indicate that the motor system can not only make adjustments to trajectories online in response to actual perturbations but also illusionary perturbations.

Whilst the majority of previous perturbation paradigms have utilised single target designs (Grierson and Elliott, 2009; Heath et al., 1998; Paulignan et al., 1991), a limited amount of research has investigated perturbations within two target aiming movements (Cameron et al., 2007; 2009). Here results revealed that in the two target conditions, the hand movements showed less flexibility in response to target jumps than in the single target conditions. Also, a perturbation in the position of a single target was shown to have an influence on movements to both targets. The purpose of the present investigation was to further investigate the impact of target perturbations during two target movements whilst also including the manipulation of visual information. Specifically, the interdependency between the planning and execution of multiple target movements together with the role that vision plays in mediating this integration was investigated during a perturbation paradigm in order to examine to what extent this interdependency can be adjusted during movement execution. To achieve this, participants were instructed to complete a two-target aiming movement where target one was unexpectedly perturbed either towards or away from the start position on 17% of the trials. They were required to perform these movements in both full vision conditions and conditions where vision of the limb was occluded following contact with target one. In the first experimental chapter of this thesis, movements were performed to targets of a finite size with the instruction to move to the first target in a constrained movement time (i.e. 450 msec). The results revealed that when vision was available, participants adjusted the distance on the second segment depending on the distance travelled on the first. In contrast, in this study, reaction time and movement time were investigated by instructing the subjects to move as quickly and as accurately as possible. Given both the findings of the first experimental chapter of this thesis and those of Rikker et al., 1999, it was expected that the availability of vision during the whole movement would result in greater accuracy and faster reaction times compared to conditions where vision was occluded following contact with target one. In addition, it was expected that if both movements of a two-target response are planned and integrated prior to the termination of movement one, then a forward or backward perturbation of target one would result in the overshooting or undershooting of target two, respectively; if movement integration is not subject to visual regulation. Finally, it was expected that adjustments to a perturbation would result in a shorter distance travelled on the first movement having to be compensated for by travelling a longer distance on the second movement, and vice versa. Therefore, if these compensations occur during the execution of the second (rather than the first) movement then we expected to observe positive correlations between the distance travelled at the first target and the distance travelled at the second target in the no vision condition.

5. 2Method

Participants

24 volunteers (males = 12, females = 12 ages 18-32) participated in the study. All participants were self-declared right hand dominant, reported normal or corrected to normal vision and were naïve to the research hypothesis. All signed consent forms before taking part in the experiment and the study was carried out according to the

ethical guidelines stated by the Ethics Committee of the School of Sport, Health and Exercise Sciences, Bangor University, for research involving human participants.

Apparatus

Participants sat at a table 75 cm above the ground with their chin on a chinrest. Aiming movements were performed on a computer monitor (19 inch) that was mounted horizontally and faced upwards in a cavity cut out from the table top (see Figure 19).

A sheet of plexi-glass 5 mm thick covered the monitor surface and was level with the table top. The start position was located 7 cm to the left of the right edge of the monitor. Target 1 was positioned 10 cm to the left of the start position while target 2 was a further 10cm to the left of Target 1. Participants were seated such that the body midline was aligned with Target 2. The start position consisted of a small cross 10 mm in diameter and targets consisted of circles 10mm in diameter. Participants performed aiming movements with a pen-like stylus held with their right hand. A micro-switch was mounted on the tip of the stylus. The position of the stylus was recorded from a small infrared-emitting diode (IRED) that was secured 5 mm from the tip of the stylus. The IRED was monitored using an Optotrak (Northern Digital Inc) three-dimensional movement analysis system at a sampling rate of 500 Hz. Participants wore a pair of liquid-crystal visual occlusion spectacles (Translucent Technologies, Toronto, Canada).

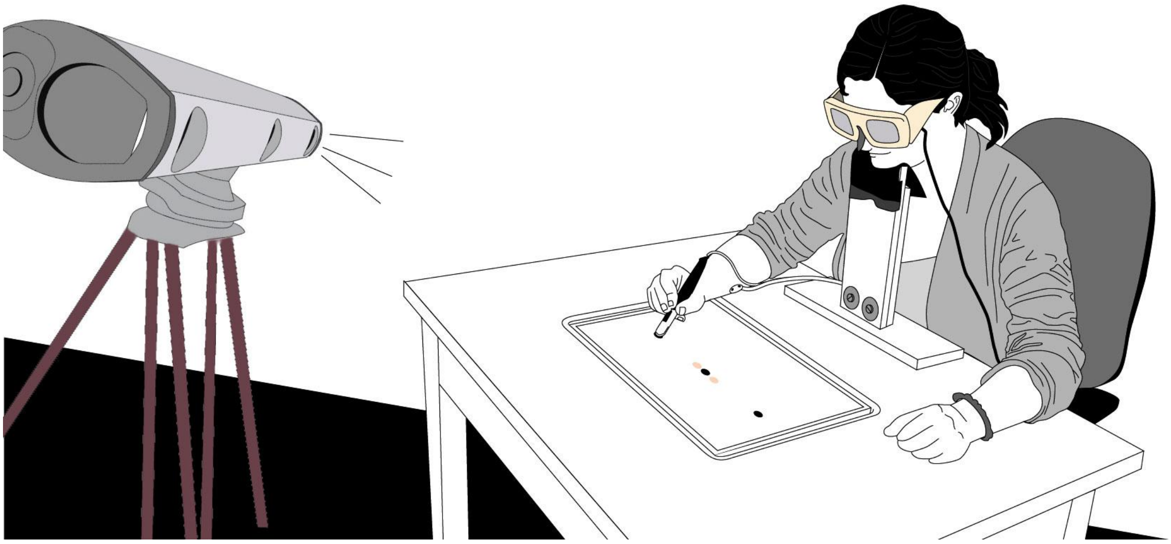

Figure 19. Schematic representation of the experimental set-up. The aiming task was performed with a stylus to targets displayed on a computer monitor that was mounted facing upwards in a cavity cut out from a table top. Movements were performed in the right to left direction to either one or two targets (i.e., y-axis). The motion of the stylus was recorded using an Optotrak 3D motion capture system.

Procedure

At the beginning of each trial, the start position and target(s) appeared on the monitor (see Figure 20). Participants were first required to place the tip of the stylus at the start position. Once the stylus was steadily placed, a tone was presented signalling to participants to start their movement. Participants performed three movement tasks. In the one-target task (1T), participants raised the stylus from the start position and were required to touch down at Target 1. In the two-target, vision task (2TFV), participants moved to Target 1 and then to Target 2. In the two-target, no vision task (2TNV), participants also moved to Target 1 and then to Target 2 but the occlusion goggles closed when the stylus made contact at the first target. Hence, vision was available on the first movement segment but not on the second segment. Participants were instructed to perform their movements as fast as possible while ensuring that they tip of the stylus touched down within the targets.

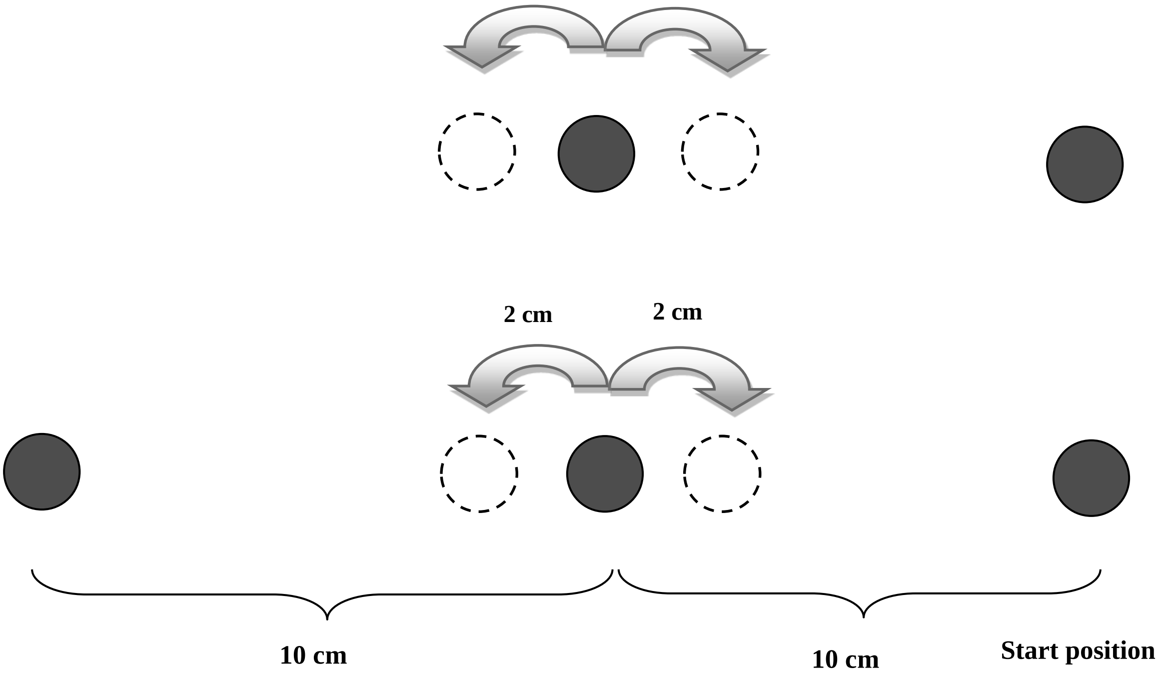

Figure 20 Diagram illustrating position of start, target 1 and target 2. And target position in perturb condition for target 2.

They were given feedback on their reaction time and movement time after each trial in numerical form on the computer monitor. The task had to be completed within two seconds at which time the targets disappeared. In the two target no vision condition, the goggles re-opened after 3 sec. Since the targets had disappeared by this point in time, participants did not receive visual information of their endpoint accuracy.

For each task, the position of the first target was perturbed randomly. The first target either remained in its original location (non-perturbed [NP]) or shifted to the right by 2cm (backward shift [BS]) or left by 2cm (forward shift [FS]) when the stylus left the start position. On those trials in which the position of the target was shifted, participants were required to adjust their movements as quickly as possible in order to be as accurate at the new target location.

Participants performed a block of trials for each of the three aiming tasks (1T, 2TFV, 2TNV). Each block consisted of 72 trials. For 48 trials the first target was not perturbed (N), while the target shifted backward on 12 trials, and forward on 12 trials. The order of these blocks was counterbalanced between participants. Prior to each block of trials, participants performed 5 familiarization trials.

Data reduction

The 3D position data from the Optotrak were filtered using a second order, dual-pass Butterworth filter with a low pass cut-off frequency of 16 Hz. Position data were then filtered to obtain velocity information. Peak resultant velocity was identified for movements to each target. The start of movement to the first target was identified from working back from peak velocity to locate the first point in which velocity in the vertical direction (i.e., z-axis) was less that 15 mm/s. The end of the first movement was the point after peak velocity in which the vertical velocity fell below 15 mm/s.[3] This process was repeated to locate the start and end of the second movement for the two-target conditions. At the end of each movement segment and at peak resultant velocity for each segment we recorded the position coordinates in the primary direction of the movement (i.e., y-axis) and perpendicular to the primary direction of movement (i.e., x-axis).

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[3] The velocity in the vertical direction was used to locate the start and end of movements since sliding of the stylus on the table top at the first target made it difficult to locate velocity zero crossings in the horizontal plane.

Dependent Measures

Our dependent measures consisted of reaction time (RT), movement time to the first target (MT1), movement time from the first to second targets (MT2), pause time at the first target (PT), constant errors (i.e., signed difference between movement endpoints and the centre of the target in the primary direction of the movement at the first and second targets (CE1, CE2),and variable errors (i.e., the within participant standard deviation of the signed difference between movement endpoints and the centre of the target in primary direction of the movement at the first and second targets) (VE1,VE2). A positive CE referred to an overshoot while a negative CE referred to an undershoot.

RT,MT1,CE1,VE1 were analysed separately using 3 Tasks (1T,2TV,2TNV) x 3 Target Location (FS ,N,BS) repeated measures ANOVA while PT,MT2,CE2,VE2 were analysed using 2 Tasks (2TFV,2TNV) x 3 Target Location (FS, N,BS) repeated measures ANOVAs .

The analysis of RT revealed a significant main effect for Task, $F_{(2, 46)} = 3.8, p \leq .05$. RTs were longer for the 2TNV task (280 ms) compared to the 1T (263 ms) and 2TV (262 ms) tasks. Although the main effect for Target Location was significant, $F_{(2, 46)} = 2.9, p \leq .05$, the difference between conditions was only 7 ms (NP = 273 ms, BS = 266 ms, FS = 266 ms). There was no interaction between Task and Target Location, $p \geq .05$ (see Figure 21).

5.3 Results

	1T			2TFV			2TNV		
	FS	NP	BS	FS	NP	BS	FS	NP	BS
RT(ms)	261.7	266.3	260.1	261.3	269.1	254.8	274.0	283.3	283.1
	(58.3)	(58.0)	(53.2)	(54.5)	(51.5)	(48.0)	(52.9)	(61.5)	(59.8)
MT1(ms)	293.0	262.8	285.3	276.3	264.0	256.3	280.5	271.7	272.9
	(60.0)	(47.9)	(55.9)	(78.8)	(55.3)	(50.2)	(69.8)	(49.5)	(55.3)
CE1(mm)	-4.9	1.0	8.1	-6.3	4.1	13.1	-6.1	3.9	11.9
	(4.9)	(1.6)	(5.7)	(6.5)	(3.9)	(8.9)	(7.0)	(3.2)	(7.4)
VE1(mm)	6.2	4.6	5.1	6.9	4.7	5.7	7.6	4.9	6.6
	(2.4)	(1.5)	(2.0)	(2.7)	(2.0)	(2.8)	(2.5)	(1.7)	(2.2)
MT2(ms)				249.9	239.8	270.6	253.0	237.4	258.0
				(56.8)	(52.0)	(69.4)	(59.5)	(47.3)	(55)
PT(ms)				34.0	35.8	49.5	42.5	37.7	53.9
				(36.0)	(31.6)	(43.7)	(41.0)	(31.2)	(46.9)
CE2(ms)				2.2	-0.8	0.3	4.0	-0.1	-0.7
				(3.8)	(3.1)	(3.3)	(9.0)	(8.0)	(9.6)
VE2(mm)				5.0	5.0	4.5	8.9	8.0	8.4
				(2.6)	(1.9)	(1.8)	(3.8)	(2.4)	(2.7)

Table 3 . Means (standard deviations) of the reaction time(RT) ,movement time to the first target (MT1), y constant error at the first target (CE1), Variable error (VE1), pause time at the first target (PT), movement time from the first to the second target (MT2), y constant error at the second target (CE2),variable error of the second target (VE2).

Overall, a main effect of Target Location indicated that movement times to the first target were longer when the target shifted forward. Although the main effect of Task was not significant, $F_{(2, 46)} = 1.5$, $p \geq .05$, there was a significant interaction between Task and Target Location, $F_{(4, 92)} = 4.4$, $p \leq .05$. Breakdown of this interaction revealed that MT1s were longest in the one target task compared to the 2 target tasks for both the backward and forward target shifts (see Figure 22). In the non-perturbed condition, there was no difference in MT1 between the Tasks.

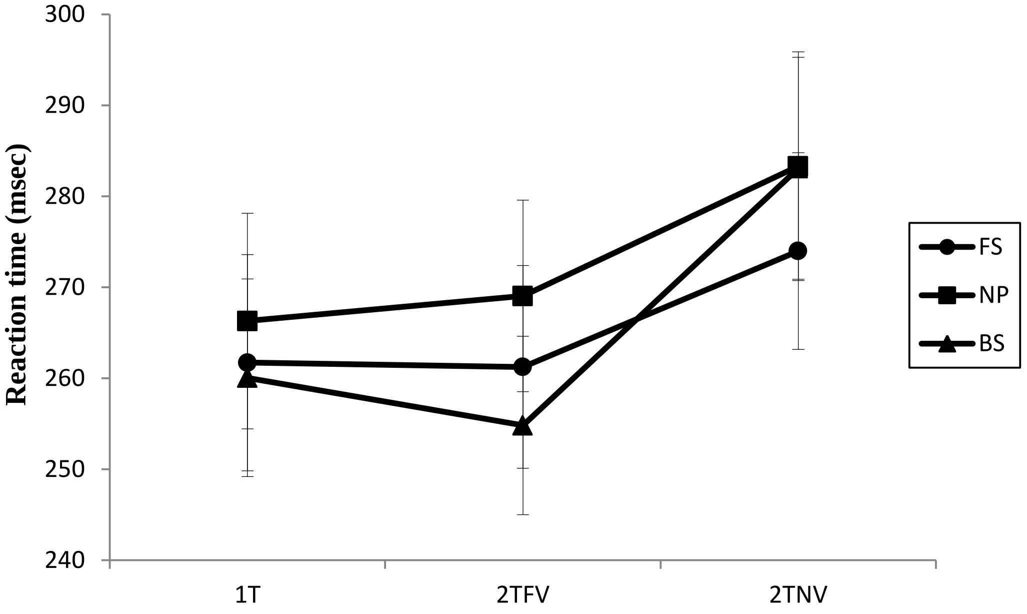

Figure 21 . Reaction times (RT) for Single Target (1T), Two-Target aiming .for different target locations, forward shift (FS), Non-perturb (NP) and backward shift (BS).

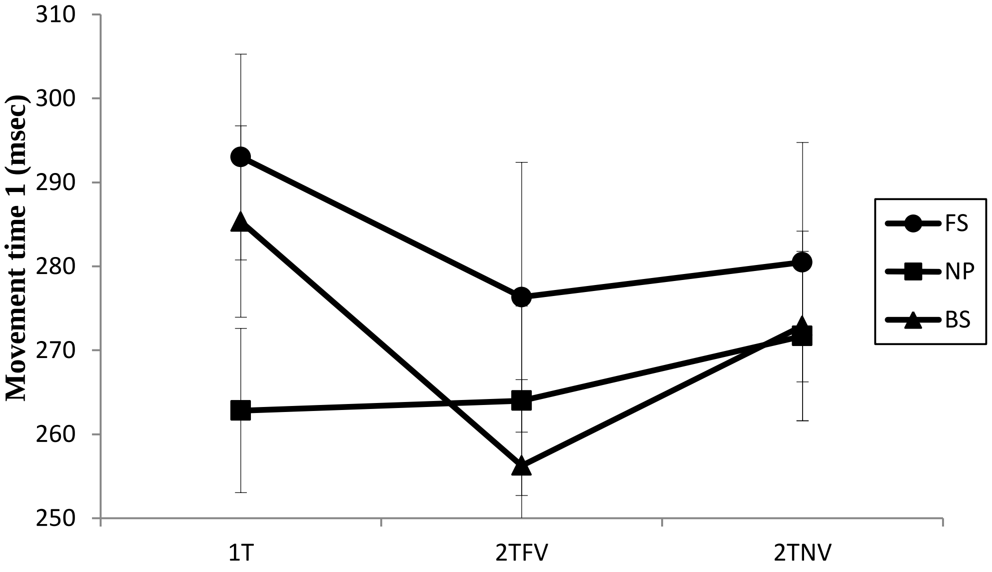

Figure 22 . Movement time 1 (MT1) for Single Target (1T), Two-Target aiming task for different target locations, Forward shift (FS), none-perturb (NP) and backward shift (BS).

The analyses of CE1 revealed significant main effects of Task, $F_{(2, 46)} = 9.3, p \leq .01$, and Target Location, $F_{(2, 46)} = 53.8, p \leq .001$, while the interaction between Task and Target Location approached conventional levels of significance, $F_{(4, 92)} = 6.6, p = .05$. Specifically, biases were in the opposite direction to the perturbation and greater in the two compared to single target tasks (see Figure 23).

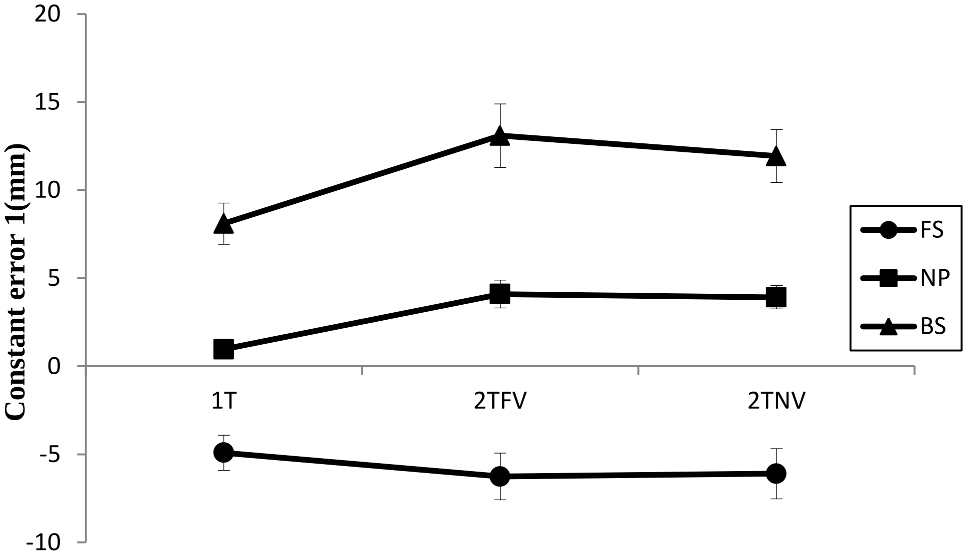

Figure 23 Constant error 1 (CE1) for Single Target (1T), Two-Target aiming .for different target locations, forward shift (FS)non-perturb (NP) and backward shift (BS).

The analysis of VE1 revealed main effects for Task, $F_{(2, 46)} = 6.3, p < .01$, and Target Location, $F_{(2, 46)} = 14.7, p \leq .001$. The variability of movement endpoints at the first target was greatest when vision was not available over the second segment (1T = 5.3 mm, 2TFV = 5.8 mm, 2TNV = 6.4 mm). Also, VE1 was greatest when the target location shifted forward compared to when it shifted backwards or was not perturbed (NP = 4.7 mm, BS = 5.8 mm, FS = 6.9 mm).

Pause times at the first target were significantly longer when the target shifted backwards compared to when there was a forward shift or no shift in target location, $F_{(2, 46)} = 11.4, p \leq .01$. No other effects on pause time were significant, $p \geq .05$. Similarly, movement times to the second target were longest when the first target was shifted backwards, $F_{(2, 46)} = 7.0, p \leq .01$. Again, no other effects on MT2 were significant, $p \geq .05$.The analysis of CE2 revealed a main effect of Target Location, $F_{(2, 46)} = 9.6, p \leq .01$. When the first target shifted forward, there was a bias towards overshooting the centre of the second target (3.1 mm). This bias was not present in the non-perturbed (- 0.4 mm) and backward shift (- 0.2 mm) conditions. The variability of movement endpoints at the second target was greater when vision was not available (8.4 mm) compared to when vision was available (4.8 mm), $F_{(1, 23)} = 73.9, p \leq .01$. No other effects on CE2 and VE2 were significant.

Additional analyses

When the location of the first target was perturbed, movement times to the first target were longer in the single compared to two target conditions (see Figure 22). Accompanying this result was mean error scores tended to be lower in the single compared to two target conditions (see Figure 23). In order to further assess speed-accuracy trade-offs when correcting for target perturbations, linear regressions of MT1 versus CE1 were performed for each participant. For backward shifting target locations, the expectation was that the degree to which participants overshoot the target would be less as movement times increase. Hence, the y-intercept of the regression equation would be positive but the gradient would be negative. Similarly, for forward shifting target locations, it was expected that the degree of undershooting the target would be less as movement times increase. In this case, the y-intercept is negative but the gradient is positive. The y-intercepts and gradients of the resulting regression analyses were submitted separately to 3 Tasks (1T, 2TFV, 2TNV) x 3 Target Location (FS ,NP, BS,) repeated measures ANOVAs. The analysis of the gradients revealed a significant effect of Target Location, $F_{(2, 46)} = 39.1, p \leq .01$. Gradients were indeed negative when the target shifted backwards and positive when the target shifted forwards. There was no difference in the magnitude of the gradients between the single and two target conditions, $p \geq .05$. The analyses of the y-intercepts did reveal a significant interaction between Task and Target Location, $F_{(4, 92)} = 3.5, p \leq .01$. As shown in (Figure 24), the magnitude of the y-intercepts was greater in the 2TNV condition than the 1T condition.

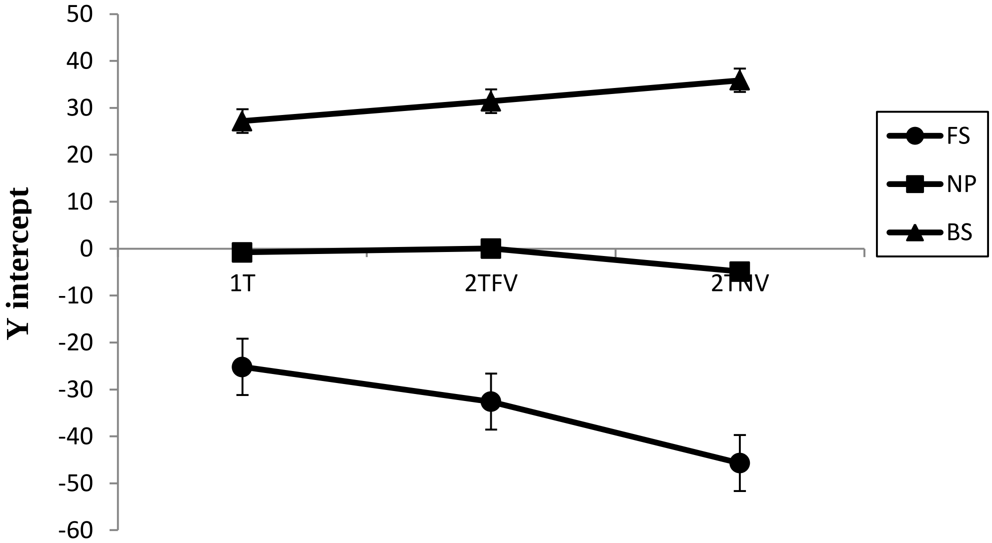

Figure 24. The analyses of the y-intercepts between Task and Target Location

In order to investigate the degree to which participants adjusted the distance travelled on the second segment to compensate for shifts in the location of the first target, we correlated the distance travelled on the first segment with the distance travelled on the second segment (see Elliott, Binsted and Heath, 1999; Khan et al., 2010). The reasoning behind this analysis was that a shorter distance travelled on the first segment would have to be compensated by travelling a longer distance on the second segment, and vice versa. Hence, if adjustments are being made to the distance on the second based on the distance travelled on the first segment, the two distances should be negatively correlated. A two Task (2TFV, 2TNV) x 3 Target Location (FS ,NP, BS,) repeated measures ANOVA performed on the Z-transformation of the correlation coefficients revealed main effects of Task, $F_{(1, 23)} = 46.9, p \leq .001$, and Target Location, $F_{(2, 46)} = 13.6, p \leq .001$.

As shown in (Figure 25), correlations were negative for all conditions but were more negative for the two perturbation conditions compared to the non-perturbed condition. Also, correlations were more negative when vision was available over the second segment compared to when vision was occluded.

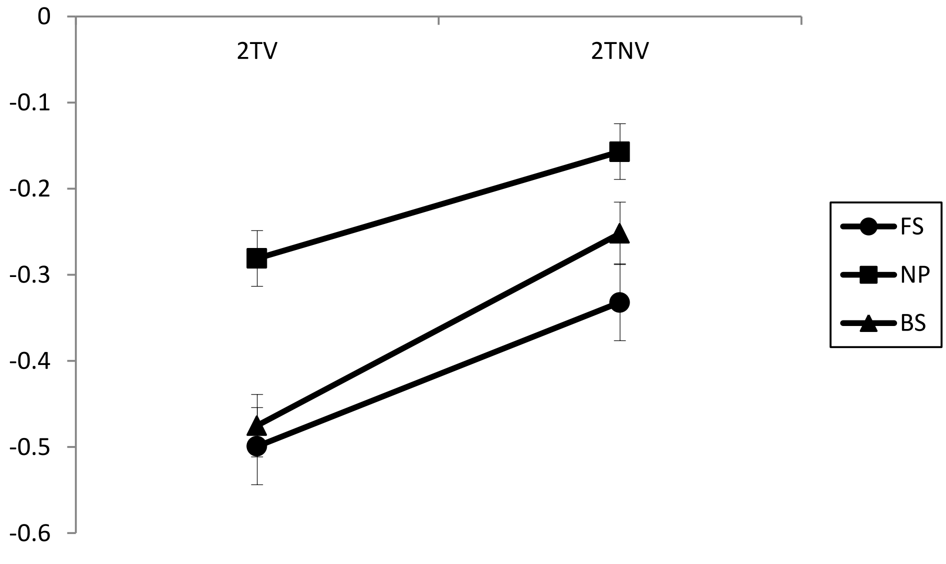

Figure 25 the Z-transformation of the correlation coefficients of the Task condition and target locations.

5.4 Discussion

Research has shown that a movement time cost is incurred when a movement has to be executed to multiple targets versus a single target (Adam et al., 2000; Chamberlain & Magill, 1989, Helsen et al., 2001; Lavrysen et al., 2002, 2003). Whilst there are competing explanations for this phenomenon e.g., the online programming (Chamberlain & Magill, 1989), the movement constraint (Fishman & Reeve, 1992), and movement integration hypothesis (Adam et al., 2000), previous research has shown that vision influences this cost (Helsen et al., 2001; Ricker et al., 1999) by reducing target variability and mediating the transition between movements in multiple target actions (see chapter 3 of this thesis). The purpose of the present investigation was to further investigate the role of vision in the planning, execution and integration of multiple target movements during a perturbation paradigm in order to examine to what extent the interdependency between movements can be adjusted during movement execution. Results indicated greater reaction times in the no vision compared to vision conditions, an increase in movement time to the first target in the two target perturbed conditions, greater variability at the first target when vision was not available in the second movement, and greater limb trajectory adjustments between the first and second movements in the perturbed conditions compared to non perturbed and when vision was available during the second movement compared to when it was occluded at target one. Collectively, these findings indicate that multiple targets are planned and executed in an interdependent fashion, that this interdependent programme can be adjusted online following a perturbation and that both the planning of multiple target movements together with the online adjustments are more efficient when vision is available over the whole action compared to when it is removed at the first target.

The reaction time data revealed that the knowledge that vision was removed at target one increased the time required to plan the multiple target action. This supports previous literature within single target actions highlighting that participants adopt different programming strategies under vision and no vision conditions (Elliott, Chua, Pollock & Lyons, 1995; Khan, Franks, & Goodman, 1998; Khan, Elliott, Chua, & Lyons, 2002). In accordance with these proposals, we suggest that when vision was removed at target one participants spent significantly longer to plan their actions in order to ensure the accuracy of the second segment. This strategy was likely adopted because participants were aware that this component of action could not be adjusted during execution based on visual afferent information (Elliott et al., 1995; Khan et al., 1998).

Past literature investigating multiple target actions has consistently revealed the one-target advantage (an increase in movement time to the first target when a second target directed movement is required) (Adam et al., 2000; Helsen et al., 2001, Lavrysen et al., 2002, 2003; Khan et al., 2010) and the results of the present investigation supported this phenomenon in conditions when target one was unexpectedly perturbed in either a forward to backward direction. These findings suggest that the individual elements in the two target responses were not programmed or executed independently and that the movement commands of the second segment were likely programmed, adjusted and implemented during the execution of the first segment. This strategy subsequently resulted in an inference and increase in the time required to execute the first movement (see Adam et al., 2000). In support of this suggestion, mean error scores tended to be lower in the single compared to two target perturbed conditions indicating that the increased interference reduced the accuracy at the first target. Further investigation of this speed-accuracy trade-off was conducted via performing linear regressions of movement time at target one with error at target one for each participant. The expectation for the backward perturbation was that the degree to which participants overshot the target would be less as movement times increased, thus the y-intercept of the regression equation would be positive but the gradient would be negative. Similarly, for forward shifting target locations, it was expected that the degree of undershooting the target would be less as movement times increase. In this case, the y-intercept is negative but the gradient is positive. Results supported these expected pattern of results with gradients being negative when the target shifted backwards and positive when the target shifted forwards. This finding supports previous proposals that visual information is utilised to correct for unexpected target perturbations and that this process is subject to experiencing sufficient movement time in which to use afferent visual information.

In addition, the y intercept was significantly greater in the 2TNV condition (i.e., when vision was removed at target one) compared to the single target condition. This result indicates that in order to achieve similar levels of accuracy in the 2TNV condition as in the single target condition, participants needed to reduce their movement speed to the first target. We propose that this increase in movement time was due to participants in the 2TNV condition utilising greater cognitive resources and visual processes compared to the single target condition in order to both monitor the first movement to reduce movement variability and to accurately time the implementation of the second movement during the execution of the first. The strategy of using these time consuming processes to a greater extent was due to the knowledge that the second movement was not under visual control and thus could not easily be adjusted during movement execution. Therefore, the need to ensure an accurate endpoint of movement one together with accurate implementation of the second movement was essential if accuracy at the second target was to be achieved. In comparison, movement times to the first target in the two target full vision condition did not need to be reduced in order to meet the same levels of accuracy at target one because participants could utilise afferent visual information to correct movement trajectories during the second segment. Therefore the need to both reduce variability at target one whilst simultaneously implementing the movement commands of movement two was less important compared to conditions were vision of the second movement was unavailable. However, since variability at target one was significantly less in the 2TFV compared to 2TNV conditions, in line with the results of the first experimental chapter and the proposals of the movement constraint hypothesis (Fischman and Reeve, 1992) participants were still utilising visual information during the first movement in order to reduce variability at target one when vision was available during the second segment. Thus, we propose that participants in the 2TNV conditions were utilising visual information to both reduce variability and monitor the trajectory to accurately time the implementation of the second segment whilst also considering the accuracy of the movement plan associated with the second movement.

This additional processing resulted in both a reduction in movement speed and an increase in the variability at movement target one in comparison to conditions where vision was available during the second segment.

In support of the above proposal (i.e., participants in the 2TNV condition increased the visual information processing of the first movement in comparison to the 2TFV condition), the correlations between the distance travelled on the first segment with the distance travelled on the second segment revealed significantly greater negative correlations in the two perturbed conditions compared to non perturbed condition together with greater negative correlations in the full vision conditions compared to when vision was occluded at target one. These findings indicate that in order to ensure movement accuracy at target two greater movement adjustments were made during movement execution when vision was available and when the target was perturbed at the first target. Since these adjustments were not as effective in the 2TNV condition, it is possible that participants compensated for the lack of visual information by adopting a strategy of monitoring the trajectory of movement one together with using the available visual information to accurately time the implementation of movement two to a greater extent than in the 2TFV conditions. This finding would suggest that visual information during the first segment is utilised to a greater extent to mediate the integration between movements when vision is unavailable during the second segment.

The findings of the regression data between movement time towards and error at target one suggested that the use of visual information to correct errors at target one was more effective when participants had greater time in which to process the afferent information and the pause time data lend further support this suggestion. Pause times at targets are indicative of reduced integration between movement segments since there is a reduction in the smooth transition between movements (Adam et al., 2000). The pause times of the current experiment were increased as the movement distance decreased. That is, they were greater in the backward shifting perturbations compared to the non perturbed and forward shifting conditions. Since the distance required to travel to the backward shifting targets was less than that of either the non perturbed or forward shifting targets, the time available to utilise visual information to mediate the integration between segments was less than in the other conditions and thus resulted in the requirement to pause between segments to a greater extent.

In conclusion, the findings of the current experiment indicate that the integration of movements in multiple target responses is greater when vision is available and, in line with the first experimental chapter of this thesis, visual information appears to be used to mediate the transition between segments. This mediation occurs through visual information being used to both reduce endpoint variability at target one and accurately time the implementation of the second segment of the movement. Furthermore, when participants are aware that vision is unavailable during the second movement they likely adopt strategies associated with movement integration that ensure the second segment is programmed as accurately as possible and that the first movement is visually monitored so that the second segment is implemented at an appropriate time for the pre-programmed movement distance (i.e., visual information during the first segment is utilised to a greater extent to mediate the integration between movements when vision is unavailable during the second segment). This additional monitoring of the first movement (in comparison to conditions where vision of the second movement is available) actually results in a reduction in the accuracy at the first target.

Finally, the finding that the one target advantage existed between the single movement and two movement perturbation conditions and the finding movements were accurately adjusted following perturbations indicates that pre-planned segment integration can be adjusted during movement execution following unexpected perturbations of the first target.

CHAPTER 6

THE EFFECT OF VARYING THE SECOND TARGET LOCATION ON MOVEMENT INTEGRATION: A PERTURBED PARADIGM

6.1 Introduction

As shown in previous chapters in this thesis, movement times to the first target in a multiple target sequence are typically longer than movement times to a single target. It was also proposed that this lengthening of movement time is a consequence of additional control processes associated with the implementation of the second segment during execution of the first segment (see also Glencross, 1980; Adam et al., 2000; and Elliott & Adam, 2002). The first chapter of the thesis revealed that vision plays a dual role in mediating the integration between segments in multiple target directed movements by reducing movement variability at the first target and through monitoring the first movement in order to aid in timing the implementation of the second movement during the execution of the first. The previous chapter showed the OTA when target one was unexpectedly perturbed at movement onset and suggested that the mediative role of vision also occurs in these situations. Furthermore, the data revealed that movement trajectory adjustments were evident following perturbations in both the full vision condition and the condition where vision was removed at the first target. These findings indicate that pre-planned segment integration can be adjusted during movement execution following unexpected perturbations at target one.

The present experiment focused on the impact of unexpectedly perturbing the second target during the same two target movements and visual conditions as the previous experiment. Specifically, the experiment allowed further investigation into the interdependency between the planning and execution of multiple target movements together with the role that both vision and an unexpected change in the location of the second target plays in this integration.

The paradigm used in the present experiment contained an unexpected perturbation at the second target during a two target aiming movement. The results of previous research investigating movement control in multiple target directed aiming tasks, have revealed that the characteristics of the second movement influence both the execution of the first movement and the integration between the first and second movement. For example, Sidaway et al. (1995) showed that variability at the first target was reduced when the accuracy demands at the second target are increased (i.e., target size is reduced). Similarly, movements to the first target are typically characterised by relatively long pause times at the first target when the accuracy demands of the second target are increased (Adam & Paas, 1996; Adam et al., 1995; Adam et al., 2000; Rand & Stelmach, 2000). The reduced variability at target one (achieved via adjustments to movement trajectories) and the long pause times at this location indicate that increased accuracy demands of the second target result in the functional separation of movement segments.

The present study further investigated the costs associated with adjusting movement trajectories following manipulation of the second target. However, as opposed to changing the accuracy characteristics of the second target (Adam & Paas, 1996; Adam et al., 1995; Adam et al., 2000; Rand & Stelmach, 2000) we unexpectedly changed the location of the second target at movement onset. Participants performed aiming movements to a single target; two-target movements in which vision was available for both segments; and two-target movements in which vision was occluded at the end of the first segment. In contrast to Experiment 3, for each aiming task the location of the first target remained fixed while the second target was perturbed at movement onset. In perturbed trials, the second target was shifted either closer to or further from the first target.

Cameron et al. (2007) showed that a second target location perturbation influenced the movement to a stationary first target. Specifically, horizontal movement endpoint at target 1 was biased in the direction of the horizontal shift of target 2. It is possible that this influence was due to the online programming and/or online implementation of the second movement during the execution of the first. Since these processes involve cognitive resources, Cameron et al. (2007) suggested that both conscious and unconscious visual processing is resource limited and thus subject to interference in multiple target actions.

As in the previous chapter, the present experiment used linear regressions of error versus movement time on perturbed trials. It was expected that the results would demonstrate that aiming movements in a sequence are not controlled independently and that error correction processes during the first movement are subject to competition from overlapping processes concerned with the implementation of the second element during execution of the first. Based on these predictions and the suggestions of Cameron et al. (2007), we expected that the occlusion of vision during the second movement would result in the requirement of more resource intensive programming and implementation in order to meet the accuracy demands of the second target. That is, the programming and/or the timing of the implementation of the second movement in the two target conditions would need to be more accurate in no vision condition compared to full vision condition because the second movement is not subject to visual based online feedback adjustment. Consequently, we expected the influence of the second movement on the execution of the first would be greater in the 2 target NV perturbation conditions compared to the 2 target full vision perturbation conditions.

6.2 Method

Participants

Twenty four volunteers (males = 10, females = 14; ages 18-31) participated in the study. All participants were self-declared right hand dominant, and had reported normal or corrected to normal vision. They all signed consent forms before taking part in the experiment and the study was carried out according to the ethical guidelines stated by the Ethics Committee of the School of Sport, Health and Exercise Sciences, Bangor University, for research involving human participants.

Apparatus

The set up of the experimental apparatus can be seen in (Figure 26). Participants sat at a table 75 cm above the ground resting his chin on a chinrest. Aiming movements were performed on a computer monitor (19 inch) that was mounted horizontally and faced upwards in a cavity cut out from the table top. A sheet of plexi-glass 5 mm thick covered the monitor surface and was flush with the table top. The start position was located 7 cm to the left of the right edge of the monitor. On all trials, Target 1 was positioned 10 cm to the left of the start and was located directly in front the midline of the participants, while target 2 was a further 10, 12, or 8 cm to the left of Target 1. The three possible locations of the second target were determined by the perturbation at this target (see Figure 27). On non perturbed trials, target 2 was located 10cm centre to centre from target 1, on forward perturbation trials target 2 shifted forward 2cm (thus was now located 12cm centre to centre from target 1) and on backward perturbation trials target 2 shifted backward 2cm (thus was now located 8cm centre to centre from target 1). Both the start position and targets consisted of a small cross 10 mm in diameter. Participants performed aiming movements with a pen-like stylus held with their right hand. A micro-switch was mounted on the tip of the stylus. The position of the stylus was recorded from a small infrared-emitting diode (IRED) that was secured 5 mm from the tip of the stylus. The IRED was monitored using an Optotrak (Northern Digital Inc) three-dimensional movement analysis system at a sampling rate of 500 Hz. Participants wore a pair of liquid-crystal visual occlusion spectacles (Translucent Technologies, Toronto, Canada).

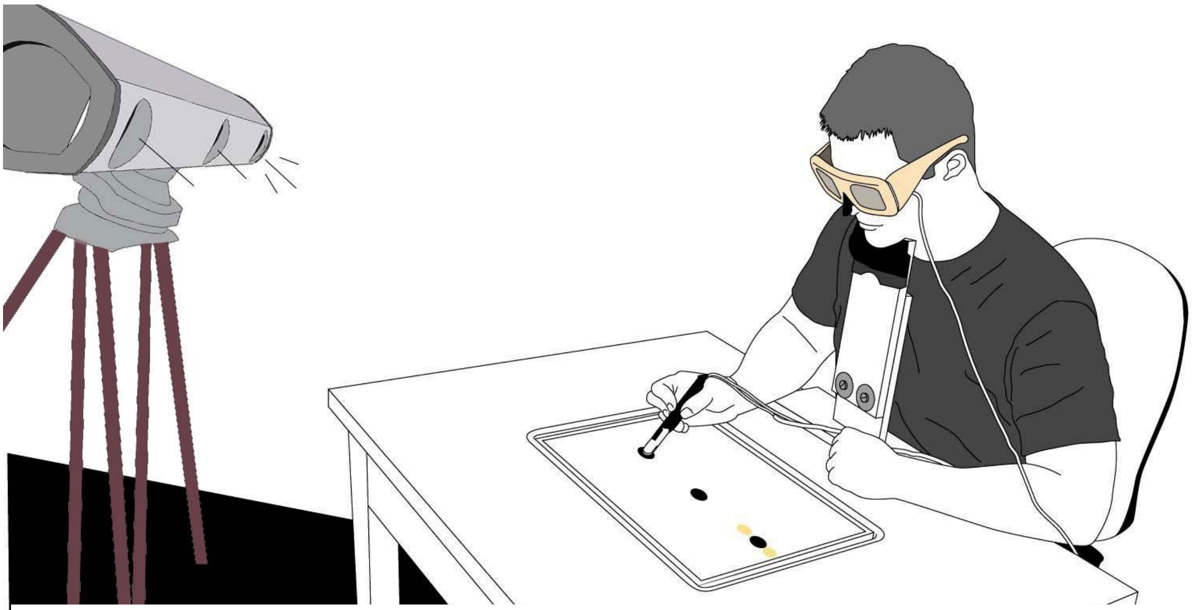

Figure 26 .Schematic representation of the experimental set-up. The aiming task was performed with a stylus to targets displayed on a computer monitor that was mounted facing upwards in a cavity cut out from a table top. Movements were performed in the right to left direction to either one or two targets (i.e., y-axis). The motion of the stylus was recorded using an Optotrak 3D motion capture system.

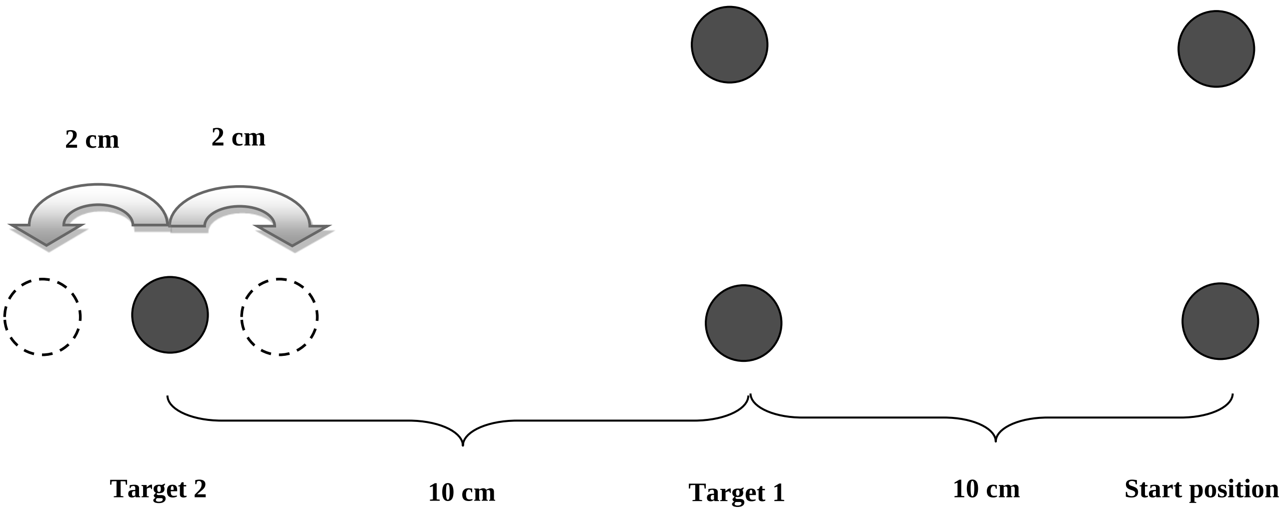

Figure 27 Diagram illustrating position of start, 1 target and 2 targets and the two possible target perturbation locations at target 2 (i.e., a 2cm forward or backward shift).

Procedure

At the beginning of each trial, the start position and target(s) appeared on the monitor. Participants were first required to place the tip of the stylus at the start position. Once the stylus was steadily aligned, a tone was presented signalling participants to start their movement. As in the previous experimental chapter, participants were required to perform three movement tasks. In the one-target task (1T), participants raised the stylus from the start position and were required to touch down at Target 1. In the two-target, vision task (2TFV), participants moved to Target 1 and then to Target 2. In the two-target, no vision task (2TNV), participants also moved to Target 1 and then to Target 2 but the occlusion goggles closed when the stylus made contact at the first target. Hence, vision was available on the first movement segment but not on the second segment.Participants were instructed to perform their movements as fast as possible while ensuring that the tip of the stylus touched down within the targets. They were given feedback on their reaction time and movement time after each trial in numerical form on the computer monitor. The task had to be completed within two seconds at which time the targets disappeared. In the two target no vision condition, the goggles re-opened after 3 sec . Since the targets had disappeared by this point in time, participants did not receive visual information of their endpoint accuracy.

For each of the two target tasks (2TFV, 2TNV), the location of the second target was perturbed at random. Specifically, when the stylus left the start position the second target either remained in its original location (non-perturbed [NP]) or shifted to the right by 2cm (backward shift [BS]) or left by 2cm (forward shift [FS]) (See Figure 27).

On those trials in which the position of the target was shifted, participants were required to adjust their movements in order to be as accurate as possible at the new target location.

Participants performed a block of trials for each of the three aiming tasks (1T, 2TFV, 2TNV). For the 1T task participants performed 48 trials. For each of the two-target tasks (2TFV, 2TNV) participants performed 72 trials; 48 where the second target was not perturbed (N); 12 when the target shifted backward; 12 when the target shifted forward. The order of these blocks was counterbalanced between participants. Prior to each block of trials, participants performed 5 familiarization trials.

Data reduction

The 3D position data from the Optotrak were filtered using a second order, dual-pass Butterworth filter with a low pass cut-off frequency of 16 Hz. Position data were then filtered to obtain velocity information. Peak resultant velocity was identified for movements to each target. The start of movement to the first target was identified from working back from peak velocity to locate the first point in which velocity in the vertical direction (i.e., z-axis) was less that 15 mm/s. The end of the first movement was the point after peak velocity in which the vertical velocity fell below 15 mm/s. This process was repeated to locate the start and end of the second movement for the two-target conditions. At the end of each movement segment and at peak resultant velocity for each segment we recorded the position coordinates in the primary direction of the movement (i.e., y-axis) and perpendicular to the primary direction of movement (i.e., x-axis).

Dependent Measures

Our dependent measures consisted of reaction time (RT), movement time to the first target (MT1), movement time from the first to second targets (MT2), pause time at the first target (PT), constant errors (i.e., signed difference between movement endpoints and the centre of the target) in the primary direction of the movement at the first and second targets (CE1, CE2) and variable errors (i.e., the within participant standard deviation of the signed difference between movement endpoints and the centre of the target in primary direction of the movement at the first and second targets) (VE1,VE2). A positive CE referred to an overshoot while a negative CE referred to an undershoot.

In order to investigate the differences between the 1T and 2TFV and NV tasks, each of the RT, MT1, CE1 and VE1 dependent variables data were submitted to separate One way Repeated Measures ANOVAs with 7 levels (1T, 2TFV FS, 2TFV NP, 2TFV BS, 2TNV FS, 2TNV NP, 2TNV BS). In order to examine the effect of vision during the second movement together with location perturbation at the second target we submitted all dependent variables RT, MT1, CE1, VE1, PT, MT2, CE2, VE2) to separate 2 Tasks (2TFV,2TNV) x 3 Target Location (NP,FS,BS) repeated measures ANOVAs .

6.2 Results

	1T	2TV			2TNV		
	NP	FS	NP	BS	FS	NP	BS
RT(ms)	250.8	269.4	275.9	264.8	279.6	282.8	272.8
	37.6	50.1	48.1	51.0	38.5	43.1	43.3
MT1(ms)	268.1	268.6	268.4	264.2	262.1	263.4	261.7
	60.9	46.4	47.1	46.3	53.5	52.2	50.4
CE1(mm)	-0.4	0.5	0.2	-0.2	0.9	0.8	0.5
	1.0	2.0	1.9	2.2	3.2	3.5	3.5
VE1(mm)	11.5	4.1	4.2	3.8	4.7	4.8	4.2
	1.5	1.3	1.3	1.3	2.3	1.5	1.4
MT2(ms)		279.7	261.9	242.8	288.7	258.6	234.6
		35.4	35.3	34.8	55.7	42.5	34.6
PT(ms)		53.3	55.0	55.4	50.7	50.1	50.1
		36.5	38.0	38.9	38.3	37.7	38.7
CE2(ms)		-2.4	-0.8	-0.5	7.7	6.1	4.3
		3.1	3.9	5.5	12.0	10.3	11.1
VE2(mm)		5.1	4.9	3.8	13.0	10.9	8.1
		1.6	2.3	1.2	5.0	3.3	2.7

Table 4 Means and SDs for all variables as a function of task (1T = one target; 2TV = two target full vision; 2TNV = two target no vision) and target perturbation (FS = forward shift; NP = non perturbed; BS – backward shift).

One-way ANOVAs

RT, CE1 and VE1 all revealed significant mean differences $F_{(6, 1\,38)} = 4.37, p \leq .001, F_{(6, 1\,38)} = 2.16, p \leq .05,$ *and* $F_{(6, 1\,38)} = 100.5, p \leq .001,$ respectively) whilst there was no significant mean differences for the MT1 data (*p* ≥05). Specifically, reaction times were significantly less in the 1T compared to 2T conditions (see Figure 28), errors were negatively biased in the 1T and significantly different to the typically positively biased errors of the 2T conditions (see Figure 29), variability at the first target was significantly greater in the 1T compared to 2T conditions.

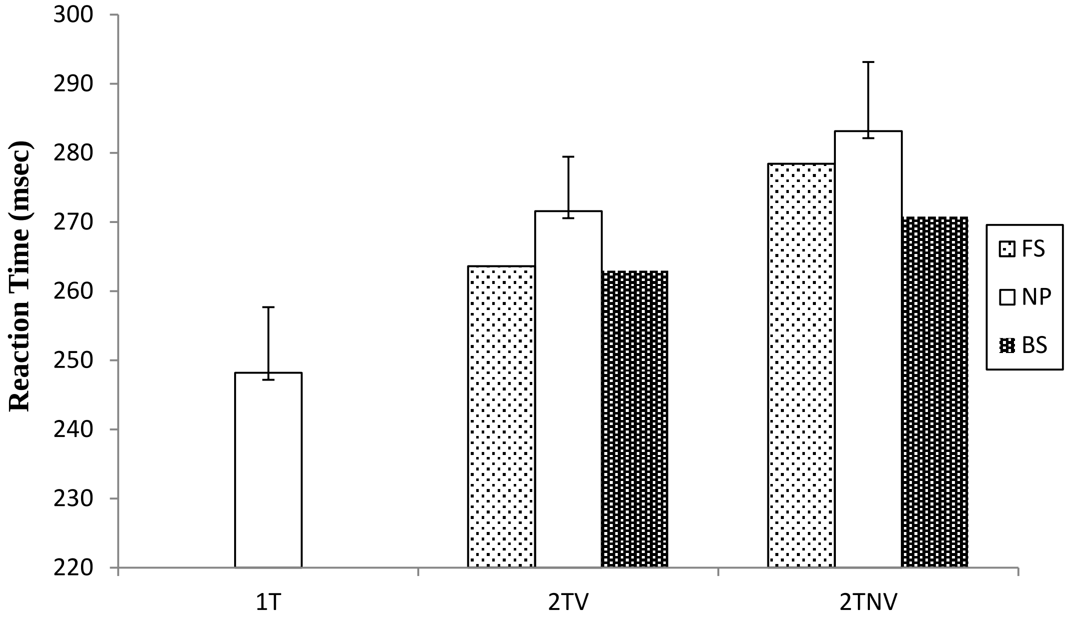

Figure 28. mean of the reaction time as a function of task and perturbation. (RT) for Single Target (1T), Two-Target aiming .for different target locations, forward shift (FS), non-perturb (NP) backward shift (BS).

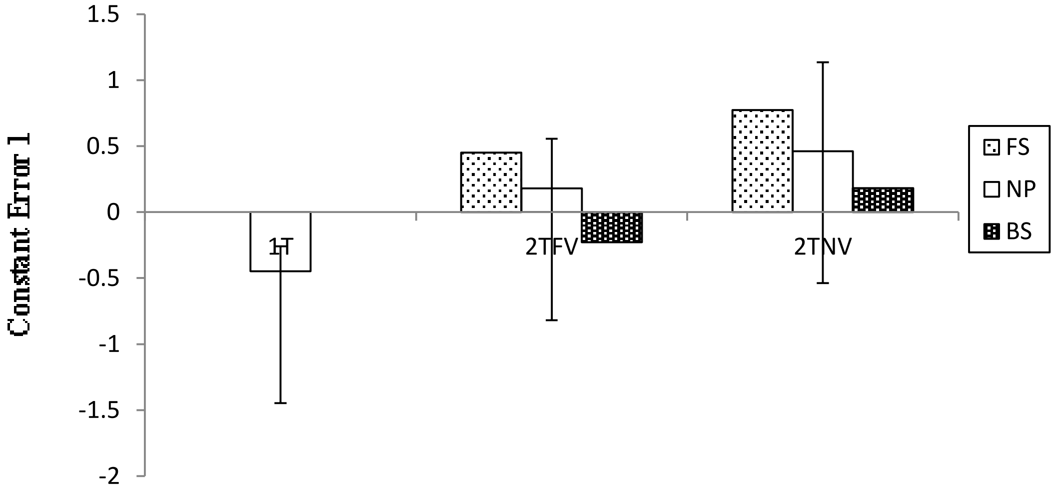

Figure 29 mean of constant error (CE1) as a function of task and perturbation (CE1) for Single Target (1T), Two-Target aiming .for different target locations, forward shift (FS), non-perturb (NP)and backward shift (BS).

2 Tasks x 3 Target Location repeated measures ANOVAs

The analysis of RT revealed a significant main effect for Target location ($F_{(2, 46)}$ =4,77 , $p \leq .01$) and a non significant main effect for both Task and the Task by Target

Location interaction (*p* >.05). As shown in (Figure 28), reaction times were significantly longer when vision was occluded at the first target (2TNV) compared to the full vision condition.

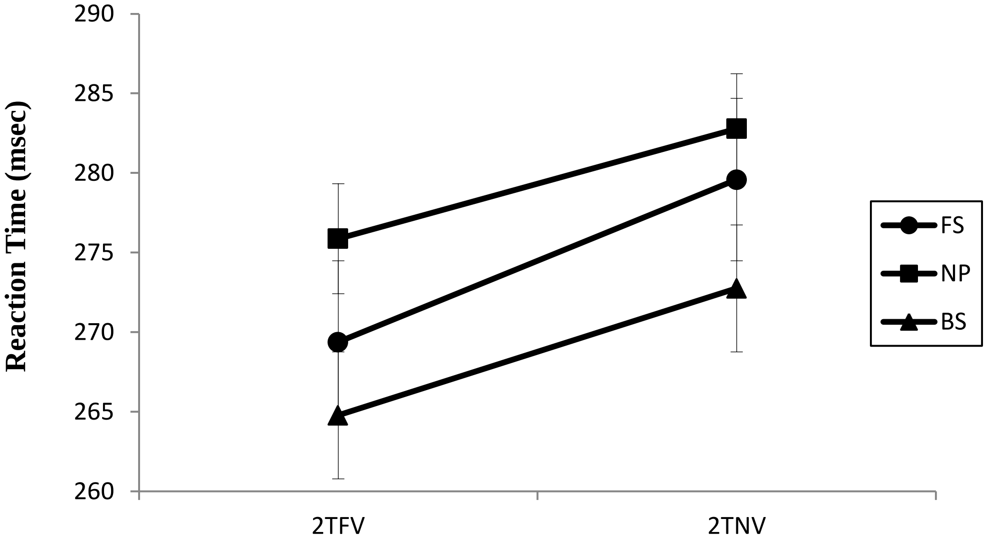

Figure 30 Reaction times (RT) as a function of task and perturbation for different target locations, forward shift (FS), none-perturb (NP),and backward shift (BS).For both conditions with vision and with no vision.

MT1 data revealed no significant main effects or interactions *($p \geq .05$).* The analyses of CE1 revealed only a significant main effect for target location *($F_{(2, 46)} = 3.51$, $p \leq .01$)* with errors in the backward shifting location conditions being significantly less than those in the forward shifting location conditions (see Figure 29). The analysis of VE1 revealed no significant main effects or interactions ($p \geq .05$) although there was a trend for variability at target 1 to be higher in the forward shifting compared to backward shifting location conditions $F_{(2, 46)} = 2.57$, $p = 0.08$) .

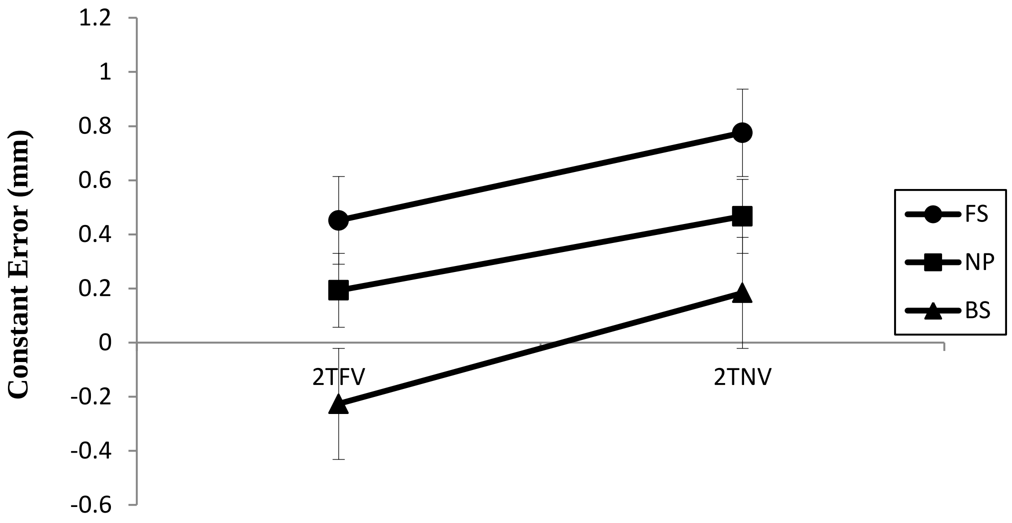

Figure 31 Constant error 1 (CE1) as a function of task and perturbation for different target locations, forward shift (FS), none-perturb (NP), and backward shift (BS). For both conditions, with vision and with no vision.

The analysis of PT revealed no significant main effects or interactions *($p \geq .05$).* Whereas the analysis of MT2 revealed both a significant main effect for Target Location, *($F_{(2, 46)} = 109.98, p \leq .01$)* and a significant Task by Target Location interaction ($F_{(2, 46)} = 6.02, p \leq .05$). Specifically, movement times were significantly faster in both the full vision and no vision backward shifting conditions compared to both the full vision and no vision forward shifting conditions. The analysis of both CE and VE at target 2 revealed significant main effects of Task *(*$F_{(1, 23)} = 13.83$, $p \leq .05$; $F_{(1, 23)} = 83.4$, $p \leq .001$, respectively) with error and variability being significantly less in the vision compared to no vision conditions. Furthermore, the analysis of VE also revealed a significant main effect of Target Location *(*$F_{(2, 46)} = 23.18$, $p \leq .001$) together with a significant Task by Target Location interaction ($F_{(2, 46)} = 8.28$, $p \leq .01$). Specifically, whilst variability was not different between the differenet target locations within the vision condition, variability in the no vision condition was significantly different between all target locations.

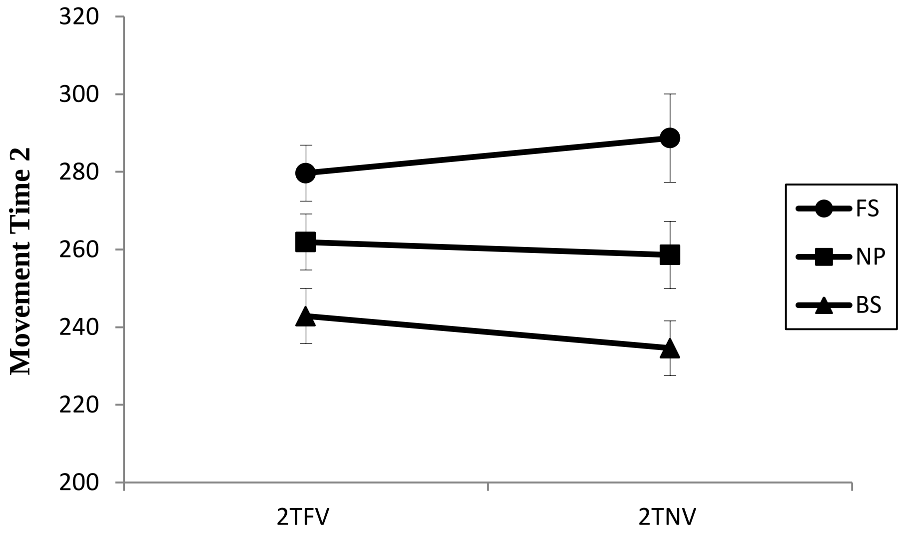

Figure 32 Movement time 2 (MT2), as a function of task and perturbation for different target locations, forward shift (FS),none-perturb (NP),and backward shift (BS). For both conditions (with vision and with no vision).

Additional analyses

Similar to the previous experimental chapter, in order to assess possible speed-accuracy trade-offs when correcting for target perturbations, linear regressions of MT2 versus CE2 were performed for each participant. For backward shifting target locations, the expectation was that the degree to which participants overshoot the target would be less as movement times increased. Hence, the y-intercept of the regression equation would be negative but the gradient would be positive. Similarly, for forward shifting target locations, it was expected that the degree of undershooting the target would be less as movement times increased. In this case, the y-intercept is negative but the gradient is positive. The y-intercepts and gradients of the resulting regression analyses were submitted separately to 2 Task (2TFV, 2TNV) x 3 Target Location (FS, NP, BS) repeated measures ANOVAs. The analysis of the gradients revealed a significant main effect of the Task, $F_{(1, 23)} = 17.16$, $p \leq .01$ with gradients in the full vision conditions being significantly less than those in the no vision conditions. Gradients were indeed positive when the target shifted backwards and close to zero when the target shifted forwards but there was no significant difference in the magnitude of the gradients between the two conditions and no Task by Target Location interaction was observed ($p \geq .05$). The analysis of the y-intercepts revealed both a significant main effect for Task ($F_{(1, 23)} = 11.16$, $p \leq .01$) and Target Location $F_{(2, 46)} = 3.77$, $p \geq .05$). As shown in (Figure 33), the magnitude of the y-intercepts was significantly greater in the 2TNV condition than the 2TFV condition and significantly greater in the forward shifting compared to backward shifting target locations. No significant Task by Target Location interaction was observed ($p \geq .05$).

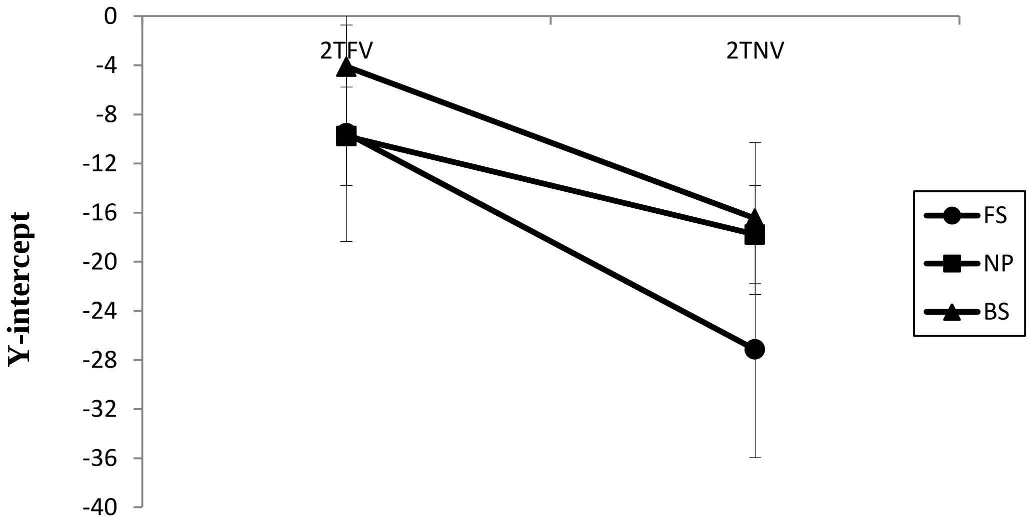

Figure 33 the analyses of the y-intercepts between Task and Target Location for both conditions, with vision and with no vision.

In order to investigate the degree to which participants adjusted the distance travelled on the second segment to compensate for shifts in the location of this target, we correlated the distance travelled on the first segment with the distance travelled on the second segment (see Elliott, Binsted and Heath, 1999; Khan et al., 2010).

The reasoning behind this analysis was that since the first target location was fixed, a perturbation at the second target would require a shorter or longer distance depending on the direction of the perturbation. Furthermore, shorter distance travelled on the first segment would have to be compensated by travelling a longer distance on the second segment, and vice versa in the non perturbed conditions. Hence, if adjustments are being made to the distance on the second movement based on the distance travelled on the first segment or the perturbation at the second target, the two distances should be negatively correlated. A two Task (2TFV, 2TNV) x 3 Target Location (FS,NP, BS,) repeated measures ANOVA performed on the Z-transformation of the correlation coefficients revealed a significant main effects of Task ($F_{(1, 23)} = 83.68$ $p \leq .001$). Specifically, correlations were negative for all conditions but were more negative for the 2TFV compared to the 2TNV condition (see Figure 34). No other significant main effects or interactions were observed ($p \geq .05$).

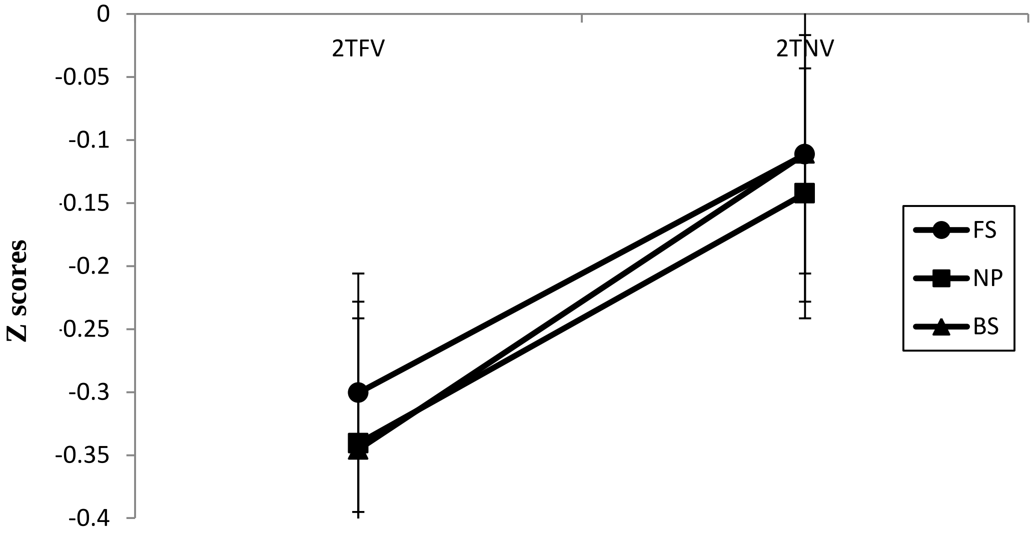

Figure 34 the Z-transformation of the correlation coefficients of the Task condition and target locations.

6.3Discussion

As shown in previous research together with the earlier chapters in this thesis, there is a cost in the control of the first movement (movement time and/or accuracy) when a movement has to be executed to multiple targets versus a single target (Adam et al., 2000; Chamberlain & Magill, 1989, Helsen et al., 2001; Lavrysen et al., 2002, 2003). The findings of both Helsen et al. (2001) and Ricker et al. (1999) have shown that vision influences this cost and the findings of the first experimental chapter of this thesis indicated that vision reduced target variability and mediated the transition between movements in multiple target actions. Furthermore, the previous chapter suggested that the mediative role of vision also occurs in situations where target one was unexpectedly perturbed at movement onset. These findings indicate that pre-planned segment integration can be adjusted during movement execution following unexpected perturbations at target one. The aim of the current experiment was to further investigate the interdependency between the planning and execution of multiple target movements and the role that both vision and an unexpected change in the location of the second target plays in this integration.

Similar to Chapter 4 and 5, the analysis of RT revealed a longer RT for the 2 target compared to the single target conditions. This is consistent with the notion that increasing the number of elements in a response results in an increase in the time taken to prepare and program that response (Henry and Rogers, 1960; Khan et al., 2006, 2007; Klapp, 1995; 2003). These results also support the first of the underlying principles of the movement integration hypothesis (MIH) (Adam et al., 2000), whereby the implementation of the second segment during the execution of the first is dependent on both segments being programmed prior to movement initiation. Specifically, the MIH states that both movements are programmed in advance and that the second movement is implemented during the execution of the first at a cost of increasing movement time of the first movement. Whilst the movement integration and the interdependency between segments in multiple target actions has received considerable empirical support (Adam et al., 2000; Helsen et al., 2001; Khan et al., 2010; Larysen et al., 2002, 2003; Rikker et al., 1999), there is still a debate regarding the exact nature of the interdependency and possible mediators of this (i.e., the knowledge of the availability (or not) of visual information and the location/characteristics of the second target). In line with this, the results revealed that response planning took longer in the no vision compared to full vision conditions indicating that participants more carefully planned 2 target responses when vision was unavailable during the second movement further suggesting that vision acts to mediate the interdependency between movements. In addition, error at the first target was influenced by the target perturbation of the second movement. This finding indicates that shifting the location of the second segment after movement programming influenced the execution of the first movement and provides evidence of the interdependency of multiple target movements and the possible mediating role played by the location shift of the second target.

As detailed in the earlier chapters of this thesis, vision acts to mediate the interdependency between movements by 1) allowing online movement corrections during the first movement in order to ensure variability at the first target has a minimal impact on the accuracy of the second and 2) allowing continuous monitoring of the first movement such that the implementation of the second movement can be produced at a time that allows optimal integration between the two movements. This dual role of vision supports the proposed processes of both the movement constraint hypothesis (Sidaway et al., 1995), where there is a need to reduce variability at the first target in order to meet the accuracy demands at the second target, and the movement integration hypothesis (Adam et al., 2000) whereby the careful monitoring of the first movement allows for increased accuracy leading to optimal integration and a reduction in the interference associated with the implementation to the second movement during the execution of the first. The current experiment revealed that accuracy was increased and variability reduced at target two when vision was available compared to when vision was occluded suggesting that vision also aids online movement corrections of the second movement in multiple target aiming.

Whilst target location did not impact upon the variability at either target 1 or 2 in the vision condition, it did significantly affect variability at the second target in the no vision condition. Specifically, variability was greater in the forward shifting location compared to the non perturbed location and backward shifting location. Since, impulse timing theory (Schmidt, 1979) proposes that variability increases as a function of movement distance (also see Khan et al., 2003a; Khan et al., 2003b; Khan et al., 2006) it is not surprising that these effects were observed in the absence of visual feedback. That is, under conditions where online visually based movement trajectory corrections are not possible.

In order to investigate possible speed accuracy trade-offs when correcting for target perturbations, linear regressions of MT2 versus CE2 were performed for each participant. The expectation for the backward perturbation was that the degree to which participants overshot the target would be less as movement times increased, thus the y-intercept of the regression equation would be positive but the gradient would be negative. Similarly, for forward shifting target locations, it was expected that the degree of undershooting the target would be less as movement times increase. In this case, the y-intercept is negative but the gradient is positive. Gradients in the full vision conditions were significantly less than those in the no vision conditions and were indeed positive when the target shifted backwards and close to zero when the target shifted forwards. Whilst the gradients of the target shifts were not statistically significant from one another, the y-intercepts revealed the magnitude of the intercepts was significantly greater in the 2TNV condition than the 2TFV condition and significantly greater in the forward shifting compared to backward shifting target locations. These findings indicating that more time was needed in the no vision conditions in order to reach similar accuracy levels (presumably due to the more time needed to process and utilise proprioceptive feedback during movement execution) to the full vision conditions.

In order to further investigate the degree to which participants adjusted the distance travelled on the second segment to compensate for shifts in the location of this target, we correlated the distance travelled on the first segment with the distance travelled on the second segment. The reasoning behind this analysis was that since the first target location was fixed, a perturbation at the second target would require a shorter or longer distance depending on the direction of the perturbation. Furthermore, shorter distance travelled on the first segment would have to be compensated by travelling a longer distance on the second segment, and vice versa in the non perturbed conditions. The correlations revealed significantly greater negative correlations in the full vision conditions compared to when vision was occluded at target one. These findings indicate that in order to ensure movement accuracy at target two greater movement adjustments were made during movement execution when vision was available. Interestingly, the adjustments to movements were not influenced by the perturbation of the second target. These results are likely due to participants in the vision condition using visual information to make similar online movement corrections to all targets, whereby participants in the no vision conditions were unable to make more effective online corrections in any of the target conditions due to both the lack of visual information of the relatively ineffective use of proprioceptive feedback when correcting movement trajectories online.

In conclusion, the findings of the current experiment indicate that the integration of movements in multiple target responses involving a perturbation in location of the second target is easier when visual feedback is available throughout the entire movement compared to when it is occluded at target one. This lends further support that visual information is used to mediate the transition between segments and continues to be used in order to ensure the accuracy of the second movement. However, when visual information is occluded at the first target participants can still plan and execute movements within an independent fashion but rely more heavily on the accurate movement planning of the second movement (as evident by increased reaction times) in order to ensure that both the timing of the implementation and, importantly, the accuracy of the second movement.

CHAPTER 7

GENERAL DISCUSION

Researchers have adopted numerous approaches to understanding how multiple segment movements are prepared and executed. While an initial surge of research was devoted to understanding the relation between reaction time (RT) and the number of response segments (or elements) (e.g., Henry & Rogers, 1960; Klapp et al., 1974, Sternberg et al., 1978), more recent efforts have been focused on the time it takes to execute movements (e.g., Adam et al., 2000).Generally, it can be accepted, that the theoretical framework behind examining this interrelation resolves around these two programming (RT) and execution (MT1) factors. The costs to RT and MT1 when a single movements is required to be extended to move to a second target are explained by Adams et al., (2000) movement integration hypothesis (MIH). Essentially, the MIH proposes that participants adopt movement planning and control strategies order to ensure a smooth transition between segments of multiple target actions. These strategies result in the planning of both movements during the RT interval. Whilst the movement commands of the first segment are triggered at movement onset, those of the second movement are held in a buffer and implemented at a time deemed optimal. This implementation occurs prior to the end of the first movement so that the transition from movement 1 to movement 2 results in a continuous smooth integrated movement. In addition, to the MIH, Fischman and Reeves' (1992) movement constraint hypothesis (MCH) proposes that the movement of the first segment is constrained such that the endpoint is highly predictable; having a predictable endpoint results in minimal need to adjust the pre-programmed commands of the second movement. Specifically, since the endpoint of the first movement is the start point of the second, participants slow down movement to the first target in order to reduce variability.

The processes involved in the MIH and MCH attempt to explain the costs associated in the control of the first movement (movement time) when a target directed movement has to be executed to multiple versus a single targets (OTA). As mentioned previously throughout this thesis, the investigation of target directed movement is not a new phenomenon. Indeed, as early as the 19th Century, Woodworth suggested that, the control of goal directed movement involves central planning before movement initiation and processing of feedback to correct errors during movement execution. The current research programme of this thesis aimed to investigate the utilisation of visual information in both the planning and execution strategies of multiple target directed movements i.e., the role vision plays in the integration processes outlined in the MIH and MCH. Consequently, amongst others, the thesis provides answers to the following pertinent questions: What role vision plays in the integration between the different segments of movement? What extent vision can be used to correct for planning errors in the first and second movement of actions whilst also ensuring segments are integrated? The extent to which the thesis provides answers to these questions together with the theoretical implications these hold are discussed in the following sections.

Spatial Variability and performance.

As previously showed, with regard to the time that takes to execute movements, the typical finding is that movement times (MT) to the first target in two target movements are shorter in single target than the same distance that followed by another target. This OTA phenomenon emerges regardless of performers hand preference and hand used (Helsen et al., 2001; Lavrysen et al., 2003) and is resistant to practice (Lavrysen et al., 2003). In the first experimental chapter , we were interested in the implications of multiple action segments on the movement accuracy under movement time constraints (typically, research has investigated movement time differences between single and dual task movements when actions are free of movement time constraints). Hence accuracy rather than movement time became our primary measure of interest. Many investigators have used time constrained movements to minimize tradeoffs between speed and accuracy (see Carlton (1994) for a discussion of time minimization versus time constrained movements). Also, constraining movement times minimized the possibility of strategically redistributing planning and control processes when movement times are free to vary under manipulations of visual feedback. Hence, examining movement accuracy and limb trajectory kinematics with and without vision under time constrained conditions offered a more direct test of the role of visual feedback in sequential aiming and the underlying assumptions of both the movement constraint and movement integration hypotheses. We found the accuracy equivalent of the OTA, that is, the locations of movement endpoints at the first target were more variable in the two compared to single target conditions. Hence, consistent with other studies that have shown that movement time to a target is influenced by the presence of a second target movement, our results indicate that components of sequential aiming movements are not controlled independently. Along the lines of the movement integration hypothesis, it seems that under the time constraint conditions of the present study, the cognitive processes associated with implementation of the second element caused interference and hence a deterioration in movement accuracy at the first target.

Variability in human movement behaviour over number of trials provides a good measure of both movement planning and execution (Elliott & Khan, 2010; Khan et al., 2006; Scholz & Schoner, 1999, Sidaway et al., 1995), and by recording and analysing the data from limb trajectories, chapter 3 indicated that when movement times to the first target are not allowed to vary, there was indeed an increase in variability at the second target compared to the first target. Hence, consistent with the movement constraint hypothesis (Fischman &Reeve, 1992), the performer has to be more precise and accurate in hitting the first target when this is preceded by a second movement. In the condition that involved only a single target, the use of time constrained movements has provided important insights in the formulation of speed accuracy trade- offs (Schmidt et al., 1979). As we mentioned previously, there is a need to reduce variability at the first target in order to meet high accuracy demands at the second target e.g., the MCH. Thus, our results indicated that constraining spatial variability is a critical component in the control of both single target and two target aiming movements.

Compatible with other research that have shown that movement time to a target is influenced by the presence of a second target movement (e.g., Adam et al., 2000; Helsen et al., 2001), our results indicate that components of sequential aiming movements are not controlled independently. In order to calculate the role of visual information within a movement segment we compared variability (i.e., area of ellipses in x–y plane) in stylus position at peak velocity and at the end of the movement at each target. In this aspect, we have shown that in visual conditions variability decreases from peak velocity to the end of the movement, while theses observations do not appear in no vision conditions. Moreover, there was a significant increase in ellipse areas from the first to the second segment in the no vision but not the vision condition and, by calculating the kinematics profile, we observed that variability was significantly greater at both peak velocity and movement end of the second segment in the no vision compared to vision condition. In addition, our results from that same experiment revealed that, variability of movement endpoints was greater at the second compared to the first target when vision was occluded whilst, in the full vision condition, there was no difference in variability at the first and second targets. Consequently, it seems that vision compensated for the natural increase in variability that occurs as movement progresses. When movement times are constrained but long enough to utilize visual feedback as in the first experiment (the MT was 450 ms), adjustments to the limb trajectory were made to combat increases in variability as movement progresses. The results from the first study also suggested that, the role of visual feedback in modifying spatial parameters both within and between segments, involves strategies of constraining movement endpoints and accurately timing the implementation of the second segment. That is, when visual feedback is available, participants are able to compensate for the interference caused by overlapping control processes under movement times of 450 ms and hence reduce variability at the first target compared to when vision was occluded (this will be discussed further under the ‘visual information and goal directed behaviour’ subheading).

Similarly to the first Experimental chapter, chapters 4, 5 and 6 revealed that the variability of movement endpoints at the first target was greatest when vision was not available over the second segment. In addition, variability at target 2 was longest in the no vision conditions compared to the full vision conditions when both target 1 (Chapter 5) and target 2 (Chapter 6) were unexpectedly perturbed in either a backward or forward direction at movement initiation. We conclude that these reductions in variability indicate strategies of movement integration. That is, movements to the first target are constrained in order to ensure the accuracy of the second target is met and, when participants are aware that visual information is unavailable during the second segment they adopt strategies associated with movement integration that ensure the second segment is programmed as accurately as possible. This increase in movement integration concern results in increased cognitive control of the first movement which we propose leads to an overloading of central processing capacity resulting in an increase in variability at the first target.

Visual information and goal-directed movement

When aiming movements are performed with vision they result in greater accuracy than movements performed without vision. In has been reported that these accuracy benefits are due to the utilisation of vision both during movement execution (i.e. online) (Khan et al., 2003, 2004) and 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 (for a review see Khan et al., 2006). As reported by Woodworth (1899) more than a century ago, 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 error correction phases 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 processing and control may be continuous in nature (Elliott et al., 1991, 1995, 1999, 2010). Thus, the online regulation of movements will not be reflected in discrete corrections to the kinematic profiles. With this in mind, researchers have adopted a methodology in which the variability in limb trajectories at different stages of movement are analysed (see Khan et al., 2006 for a review). The online utilisation of visual feedback is inferred if there is a significant difference in the variability profiles between visual conditions. The current thesis adopted this approach when investigating the role of visual feedback within each movement segment to correct errors in the limb trajectory as the limb approaches the targets (Chapter 3). Then, in order to investigate the role that vision might play in the transition between segments (i.e., visually monitoring the endpoint location at the first target in order to adjust the parameters for the second movement; Khan, Lawrence, Buckolz & Franks, 2006), we adopted the correlation analysis used by Elliott et al (1999) in single target movements to two target movements. Specifically, in all experimental chapters we correlated the distance travelled on the first segment and the distance travelled on the second segment. Rationale being, if vision is used to adjust and implement the parameters for the second movement, one can expect a negative correlation between the distances travelled on both elements. For instance, in order to compensate for a longer distance travelled on the first movement, the amplitude of the second movement would have to be shortened, and vice versa.

Ricker et al. (1999) and Lavrysen et al., (2002) have revealed that during two target aiming removing vision of the first and second movement, respectively, result in increases in the time required to execute the first movement. Furthermore, whilst removing vision of the first segment results in increases in pause times, the removal of vision during the second segment does not. These findings imply that the transition between the first and second elements might be mediated by vision i.e., when vision was removed from the first segment (Ricker et al., 1999), there was less overlap between control processes and hence the implementation of the second element occurred during the dwell time at the first target rather than during execution of the first segment. In addition, since the removal of vision following contact with the first target did not affect the time spent on the first target there is an indication that the two movements were planned interdependently and thus organised prior to the end of movement one. The results of the current thesis support and extend these proposals.

It was observed that vision played a dual role in the mediation of movement integration; First, within each movement element, and as the limb approaches the target, vision is used to correct errors in the limb trajectory. The second role played by vision is in the integration between response elements. Regardless of reductions in variability at the first target due to online corrections, the amplitude of the second segment must be adjusted depending on the location of the movement endpoint at the first target. A longer distance travelled on the first target must be compensated by a shorter distance travelled on the second segment and vice versa. By correlating the distance travelled on the first and second segments, the results revealed a negative relation for both vision and no vision conditions. However, a stronger negative correlation emerged under the vision condition. These findings suggest that vision is used to make online movement corrections during the first movement such that the variability at that target has a minimal impact of the accuracy of the second and to allow continuous monitoring of the first movement such that the implementation of the second movement is produced at a time that allows optimal integration between the two movements. This dual role of vision supports the proposed processes of both the movement constraint hypothesis, where there is a need to reduce variability at the first target in order to meet the accuracy demands at the second target, and the movement integration hypothesis (Adam et al., 2000) whereby the careful monitoring of the first movement allows for increased accuracy leading to optimal integration and a reduction in the interference associated with the implementation to the second movement during the execution of the first.

As detailed above, the availability of visual feedback during both the execution of the first and second movement influences movement integration.. In addition, separate research has revealed that target size at both target one and target two also changes movement integration (Rand & Stelmach, 2000; Ricker et al., 1999) via increasing the accuracy demands and thus the use of vision to reduce movement variability. However, the effect of movement distance to the first target under differing visual conditions had not been explicitly investigated within the OTA literature. As such, the second experiment of the thesis investigated the preparation and integration of multiple target actions when varying the location of first target location under both full vision conditions and when vision was occluded following impact at the first target. A longer distance travelled on the first target was compensated for by a shorter distance travelled on the second segment and vice versa. Specifically, the correlation of the distance travelled on the first and second segments revealed negative values for both the vision and no vision conditions. However, as in experiment 1, a stronger negative correlation emerged under the vision condition indicating that visual feedback was used to make online movement adjustments to the second segment to more effect than the afferent information available under the no vision conditions. Furthermore, MT1 and 2 were longer, variability less, and pause times shorter in the in the full vision compared to conditions were vision was removed at target 1. These findings offer further support that the availability of visual feedback throughout the entire action ensured greater transition between elements. That is, vision of both movement one and two facilitates integration of these movements by reducing endpoint variability (supporting the MCH, Fischman & Reeve, 1992) and monitoring the first segment in order to the accurately time the implementation of the second movement (MIH, Adam et al., 2000).

Experiments 1 and 2 extended empirical evidence that vision plays a role in movement integration. Specifically, by indicating that vision of movement one is used to reduce variability and target 1 and to accurately time the implementation of movement 2, and that these processes are enhanced when participants are aware that visual information is not available to make trajectory adjustments during the second movement. These novel findings were extended further in experiments 3 and 4 by indicating that trajectory adjustment to unexpected perturbations at target 1and 2 (experiment 3 and 4, respectively) were compensated for during the first rather than second movement. The findings imply that multiple targets are planned and executed in an interdependent fashion, that this interdependent programme can be adjusted online following a perturbation and that both the planning of multiple target movements together with the online adjustments are more efficient when vision is available over the whole action compared to when it is removed at the first target. In light of the finding that the availability of visual information during the second movement together with a perturbation at target 2 influences movement integration strategies, it would be interesting to explore if the integration between movements is limited to 2 segments i.e., conduct similar experiments to those of the present thesis with the addition of a third movement segment.

Conclusion

The explanations for the OTA combine the notion of advanced planning and online adjustment processes. That is, both movement within a two target response are programmed in advance of movement initiation and then either the first segment is constrained in order to ensure the commands of the second segment are accurate (i.e., MCH; Fischman & Reeve, 1992) or the second segment is implemented during the execution of the first (i.e., MIH; Adam et al., 2000). The processes involved in these proposals result in a cost in the movement time to the first target. The present experiment supported the robust nature of the OTA phenomenon by revealing the accuracy equivalent of it, together with its appearance in conditions where unexpected target perturbations are presented at movement onset. Importantly, from a theoretical viewpoint, these findings were mediated by vision availability. That is, the integration processes proposed in the MCH and MIH are enhanced when vision is available, through adjusting movement trajectories to reduce variability at target 1 together with monitoring movement 1 to accurately time the implementation of the second movement. Furthermore, the meditative role of vision in segment integration to make error corrections in order to reduce spatial variability occurs even under conditions where unexpected perturbations in target location are introduced at movement initiation. In addition, when vision is unavailable during the second movement participants still integrate movements but are more careful with both the planning and integration processes. Thus, despite receiving visual information that we have revealed mediates integration, they adopt different movement control strategies to those individuals that are afforded visual information through both movement 1 and 2. Specifically, under these conditions, the processes involved in the MCH and MIH are enhanced via our reported visual mediation effects. It therefore appears that the processes of planning the movement prior to movement initiation and both adjusting and monitoring movement trajectories to enhance movement integration have the same level of importance. The contribution of each phase depends on the visual information during execution of sequence movements.

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