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The interdependency between motor programming and movement integration in multiple target aiming

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The Interdependency between Motor Programming and Movement Integration in Multiple Target Aiming

Thomas Mottram

Ph.D. Thesis

Thesis submitted to Bangor University in fulfilment of the requirements for the degree of Doctor of Philosophy



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Publications and Conferences

Publications

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Khan, M. A., Sarteep, S., Mottram, T. M., Lawrence, G. P., & Adam, J.J. (2011). The dual role of vision in sequential aiming movements. *Acta Psychologica*, 136, 425-431.

Conferences

Mottram, T. M., Mourton, S. J., & Khan, M. A. (2007). Disrupting Movement Integration in Sequential Aiming Movements. Poster presented at SCAPPS conference in Windsor, ON, Canada on 8th November 2007.

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Abstract

Rapid aimed hand movements have been shown to be executed faster when the hand stops on a target than when it must proceed and hit a second target. This is known as the one-target advantage (OTA). This phenomenon has been shown to occur regardless of vision, practice, hand preference and hand use. Two hypotheses put forward to explain the OTA phenomenon have been the movement constraint hypothesis and movement integration hypothesis. Whilst previous research has focused on movements made with a single-limb, this thesis examined whether performing a twotarget movement with two limbs had any effect on the OTA (chapters 2 and 3). The OTA materialised in both single-limb, and two-limb two target movements suggesting similar processes were used. By using kinematic analysis, this thesis has also shown that in movements performed using a single-limb and two-limbs, ellipse areas at the end of the first movement were typically smaller, showing support for the movement constraint hypothesis. Chapter 4 examined the interdependency between movements to target 1 and target 2. What role does movement amplitude, proximity of target 1 and 2, and target size have on movement times and spatial variability? Is there an optimal position of target 1 to optimise performance? Results indicated that when two targets are situated closer to each other, an advantage in terms of quicker total movement times is shown and the difference in total movement times was shown to be due to an advantage in the shorter movements compared to the long movements or in the pause times. A smaller second target also constrained variability at the first target, even though the first target size remained constant. This provides further support for the movement constraint hypothesis.

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Chapter 1

General Introduction

1.1 Background

In everyday life, people will perform tasks that vary in complexity. For example ,some actions consist of one segment (e.g. turning on a light-switch), while other actions have multiple segments (e.g. opening a door immediately followed by switching on a light). Therefore if we are able to understand the basic principles behind these actions then it will not just have theoretical implications, but also practical importances such as designing practice protocols.

It has become well known that the processes associated with preparing and performing a required response increase as a function of response complexity (Henry & Rogers, 1960; Klapp, 1995). These processes have generally been observed through response latencies (i.e. reaction time [RT]). More complex movements will require a greater time to program a response resulting in slower RTs. However, increases in response complexity not only affect the processes prior to movement initiation (RT), but the processes during movement execution (Smiley-Oyen & Worringham, 1996; van Donkelaar & Franks, 1991). While some researchers have focused on response complexity and RT, others have investigated the effects on the time it takes to execute a response (i.e. movement time [MT]) (e.g. Adam et al., 2000). Similar to RT, the effects of response complexity on MT are not straightforward and understanding the relationship has remained a challenge to researchers. This thesis aims to examine the interrelationship between two movements using RT and MT paradigms.

1.2 The effects of response complexity on Reaction Time

In the classic study by Henry and Rogers (1960), they showed that RTs for a simple response (i.e., lifting a finger off a key) were shorter than more complex movements (i.e., lifting a finger off a key and grasping a ball). This lengthening of RT was attributed to the longer time needed to program more complex movements. Henry and Rogers suggested that for more complex movements, 'a larger amount of stored information will be needed, and thus, the neural impulses will require more time for co-ordination and direction into the eventual motor neurons and muscles' (p. 450).

The study by Henry and Rogers (1960) demonstrated that RT increased as a function of response complexity. However, this study did not distinguish what aspect of response complexity is responsible for increases in RT. Hence, following from the work off Henry and Rogers, researchers have examined how factors such as the number of elements (Fischman, 1984; Sternberg, Monsell, Knoll & Wright, 1978), response duration (Klapp & Erwin, 1976) and movement accuracy (Lajoie & Franks, 1997; Sidaway, 1991) influence RT.

A second issue that has also been investigated is the varying effects of response complexity on simple versus choice RT (Henry, 1980). In simple RT tasks, participants know which response to produce prior to stimulus presentation. In choice RT tasks, participants do not know until stimulus presentation which response to produce. Hence, RTs in choice RT tasks are longer than in simple RT tasks due to the increased decision making processes. In choice RT tasks, participants must identify the stimulus that is presented and then select an appropriate response. In simple RT tasks, because the stimulus is known prior to stimulus presentation, participants are able to pre-program the response in

advance. In choice RT tasks, since the response is unknown prior to stimulus presentation, participants are unable to pre-program the relevant response.

1.21 Two process model of response programming

Using morse code responses, Klapp (1995) was able to examine the effect of number of elements and duration of elements in both simple and choice RT tasks. Klapp showed that the duration of a single element (dit v dah) influenced choice but not simple RT. Conversely, whilst simple RT increased as the number of elements increased (1 v 4 elements), there was no effect on Choice RT. Klapp interpreted these results in a twoprocess model of response programming where INT was referred to as the programming of internal features of individual elements (e.g. duration) and SEQ as the ordering of elements. In simple RT tasks, INT takes place prior to stimulus presentation whilst SEQ occurs during RT. The time taken to complete SEQ depends on the number of elements. Since simple RT includes the time for SEQ, it depends on the number of segments in the response. In choice RT, participants do not know the stimulus until it is presented (preprogramming is not possible) so both INT and SEQ must take place during RT in parallel with each other. Klapp stated that the INT process takes longer than SEQ. Therefore, it is the duration of the individual elements that influences choice RT and not the number of elements in a response.

Klapp followed up his morse code study by examining speech articulation within simple and choice RT tasks (Klapp, 2003). He showed for syllables that could be easily integrated into a chunk, choice RT increased as a function of the number of syllables. For syllables that were not easily integrated into a chunk, simple RT increased as the number of

syllables increased, whereas this did not occur in choice RT. These findings were consistent with Klapp's (1995) study using morse code responses. Klapp (2003) also showed that when the number of syllables (but not the actual syllables) was known prior to stimulus presentation, RT increased as the number of syllables (elements) increased. Here we have the case of RT being influenced by the number of elements when the entire response was not known in advance of the stimulus (i.e. choice RT task). In this case, since the actual content of the syllables was not known in advance of stimulus presentation, both INT and SEQ would have occurred during the RT interval. Therefore, Klapp modified his original assumption that INT and SEQ occur in parallel and it was INT that determined RT because it took longer to implement than SEQ. He suggested that SEQ involved scanning an abstract time frame rather than specific sequences of chunks. This time frame can be established prior to stimulus presentation in simple RT tasks because the number of chunks is specified by the precue. During the RT interval, the time frame is activated and the time required for this activation is dependent upon the number of chunks. Therefore, simple RT increases for responses involving more elements. However, in choice RT conditions when the number of elements is not precued, the time frame is retrieved just prior to responding and so does not need to be scanned. As a consequence, choice RT is not affected by the number of elements in a sequence.

In a subsequent study, Khan, Mourton, Buckolz and Franks (2007) extended the results previously shown by Klapp (2003) using sequential aiming tasks. They showed that RT increased as a function of number of targets when the number of targets was specified in advance regardless of whether other features of the movement were known. Prior to the stimulus, advance information was given to participants either about both the required

number of targets and amplitude of the movement, the number of targets but not the amplitude, the amplitude but not the number of targets or a neutral precue in which no information was given about the required number of targets or amplitude. RT increased as a function of the number of targets in the conditions where the entire response (number of targets and movement amplitude) was precued in advance of the stimulus and when the number of targets but not movement amplitude was precued. There was no effect on RT in conditions where the number of targets was not precued. Therefore, it seems as though there is a direct relationship between the number of targets and RT when the number of targets is known in advance. There is no influence on RT when the number of targets is not known prior to stimulus presentation.

A study by Immink and Wright (2001) used a self-select paradigm that allowed the duration of INT and SEQ to be assessed collectively within a single experimental design. In the case of a self-select paradigm, the performer is allowed to study the stimulus information that identifies an upcoming response for as long as they require. The latency associated with this interval is referred to as *study time* (ST). With respect to Klapp's (1995) model, it is assumed that ST captures the demands of the INT process and should therefore be influenced by response duration. SEQ on the other hand should be affected by the processes involved during RT. However, one of Immink and Wright's (2001) unexpected findings was the influence of sequence length on ST. The interpretation for this effect was that the multiple element sequences used by Immink and Wright involved preparation of short and long duration elements as opposed to multiple elements of the same duration.

Magnuson, Robin and Wright (2008) followed up Immink and Wright's (2001) study by examining whether movement length and sequence has any impact on mean study time. Experiment 1 involved responses consisting of either a single or 4 consecutive key presses with short (150ms) or long (450ms) key press durations. Results revealed an increase in ST for single duration, multiple element tasks, indicating that the INT process involves some preparation of each element in a sequence, even when the elements being processed are of the same duration. Therefore, it appears as though for items of an upcoming sequence, it is the INT process that is involved in their preparation. There is another possible alternative explanation for the impact that sequence length has on ST and the INT process. Rather than participants processing individual elements independently during INT as Magnuson et al. (2008) previously described, another possible explanation could be that there is a separate process for handling multiple responses of the same duration within a planned sequence. Magnuson et al. (2008) described this as a 'multiplier' effect, where a count is maintained as to how many responses are required. Experiment 2 addressed whether the INT process described in Klapp's (1995) two-process model of motor programming involved this additional multiplier process or the independent planning of duration for each element. To assess which account was more plausible, responses consisted of movements of one, two or three elements of the same movement duration (150ms). Results from the second experiment revealed shorter ST when two-elements of the same duration were readied than when three elements had to be prepared. Thus, mean ST increased as a function of number of elements. This supports the notion that each element is independently handled by the INT process, and not the addition of a multiplier process.

1.22 The influence of online programming on simple and choice RT

For choice RT tasks, both INT and SEQ are present during RT, however it is INT that takes longer to initiate than SEQ so it is the duration of the individual elements that influences choice RT. An alternative explanation for the null effect of number of elements on Choice RT is the online programming hypothersis. Although RT has been used as an index of response programming time, researchers have suggested that RT may not fully capture the processes involved in response preparation and that programming can be performed during movement execution (on-line) (Glencross, 1980; Smiley-Oyen & Worringham, 1996). In simple RT tasks, the response is known prior to the presentation of a stimulus, therefore pre-programming of the movement response can occur before movement initiation. Therefore, more complex responses will result in increased RTs if the movement commands can not be sent to the neuromotor centres until stimulus presentation (Henry, 1980). However, in choice RT tasks, pre-programming is not possible, so participants may adopt a strategy to reduce RT by programming fewer elements during the RT interval (Chamberlin & Magill, 1989; Klapp et al, 1979). The other movement segments would be programmed during movement execution. Hence, choice RT would be less affected by the number of elements in a response compared to simple RT.

Ketelaars, Khan and Franks (1999) used dual-task interference as an indicator of online programming during the production of simple movement sequences. They investigated the processing demands of an elbow extension and two extension-flexion movements (one with a short pause time [50-100msec] and one with a long pause time [250-300msec]) using the probe reaction time paradigm. The probe consisted of a bite response to an auditory signal. Their results revealed that depending on the temporal location of the probe relative

to the initiation of the flexion phase, participants either initiated the masseter and biceps muscles successively or grouped them together as one response. From these findings, they proposed that responses are grouped under a common INT (programming of individual chunks) process that sets a common trigger point for the initiation of the bite and flexion response.

Khan, Lawrence, Buckolz and Franks (2006) also tested the on-line programming hypothesis by analyzing movement durations of single- and two-target reversal movements under simple and choice RT conditions. Specifically, they wanted to examine whether the influence of response complexity on RT depended on the extent to which movements are programmed in advance of movement initiation or on-line. It was expected that if on-line programming was occurring in choice RT, movement time to the first target would be longer in choice than simple RT responses. However, in contrast to their expectations, movement times to the first target were longer in simple RT conditions rather than choice, with the largest difference occurring between two-target compared to single target responses. Therefore, it appeared that the extent to which aiming movements were controlled on-line was greater in simple RT compared to choice RT tasks (Khan et al., 2006).

In order to further investigate the possibility that on-line programming was having an influence on RT, Khan et al. (2006) performed a second experiment which required participants to perform a secondary (probe) task. This probe task was a keypress in response to an auditory tone, and was to be made in conjunction with the primary aiming task. Whilst participants were performing the primary aiming task, a probe (auditory tone) would be presented at either movement initiation (MI), MI+50msec, at peak velocity (PkV)

and PkV+50msec. Probe RTs for single element movements were shorter than twoelement movements in both simple and choice RT tasks, regardless of probe location. This suggests that on-line processes were present in both simple and choice RT conditions. Of further interest from the study was that the introduction of a secondary task produced greater errors in aiming accuracy in simple compared to choice RT tasks. In simple RT tasks, target hit rates in two-element responses significantly decreased when the probe task was presented at MI+50msec. Whilst earlier results suggested that on-line programming occurred during RT in both simple and choice RT conditions, the decrease in accuracy in simple RT tasks implied that there may be additional processes occurring in simple RT tasks. Khan et al. (2006) suggested that in choice RT tasks, participants may minimize RT by only preparing the first element during RT and then program the second element online. In simple RT tasks, participants know prior to the stimulus when a two-element response was required and therefore programmed responses so that the integration between the twoelements was enhanced during movement execution. Khan et al., proposed that the execution of the first element was visually guided to enhance the integration between the first and second elements. In the following section the notion of movement integration is discussed in further detail.

1.3 The One-Target Movement Time Advantage (OTA)

As previously mentioned, increases in response complexity do not solely affect RT. Response complexity also has an effect on movement execution (Smiley-Oyen & Worringham, 2001; van Donkelaar & Franks, 1991). Similar to RT, understanding the effects of movement time in multiple target movements is important as it allows us to

distinguish whether movements are performed independently of each other, or grouped together (chunked) as one movement.

Rapid aimed hand movements have been shown to be executed faster when the hand stops on a target than when it must proceed and hit a second target (Glencross, 1980; Adam et al., 2000; Chamberlin & Magill, 1989; Elliott, Helsen, & Chua, 2001; Lavrysen, Helsen, Elliott, & Adam, 2002). This phenomenon is known as the 'one-target advantage' (OTA), and has been shown to be stable regardless of manipulations of vision, hand preference and hand used (Adam, Helsen, Elliott & Buekers, 2001; Lavrysen et al., 2002). The OTA has been interpreted in different ways.

One interpretation centres around the idea that the first movement is performed in a controlled manner to provide an ideal starting position for the start of the second movement (Fischman & Reeve, 1992). Based on the idea that spatial variability increases as a movement progresses (see Khan et al., 2006 for a review), researchers have proposed that movements to the first target in a sequence must be more constrained to provide an ideal starting position in order to be accurate at subsequent targets. Sidaway, Sekiya and Fairweather (1995) showed support for the movement times to the first target increased and spatial variability at the first target was decreased even though the size of the first target constant.

The movement integration hypothesis (MIH) (Adam et al., 2000; Elliott et al., 2001) is another concept that combines advance planning and on-line control explanations. As mentioned previously, the online programming hypothesis proposes that movement

sequences are not entirely prepared prior to response initiation. When responses are relatively complex, participants may program the initial elements of the response during RT, but then delay the programming of later elements until during MT, providing there is sufficient time. The MIH states that there is a motor control strategy whereby the neuromuscular organisation of the second movement is partially implemented during execution of the first movement. Hence, movements to targets are not organised in a serial manner and it is this overlap in processing that causes interference which leads to the OTA. Along these lines, Adam et al. (2000) have distinguished between the on-line programming hypothesis and the MIH. Whereas on-line programming consists of both the construction and implementation of a motor program during movement execution, the MIH is based on the assumption that the motor program is constructed prior to response initiation, but the implementation of the second element is performed on-line in conjunction with the execution of the first movement. This interference then leads to the OTA.

1.31 Factors that influence movement integration

Direction of second segment: A notable exception to the OTA is when a second movement involves a change (reversal) in direction. For movements including a reversal in direction, MTs to the first target are quicker for two-element responses compared to single element responses (Adam, van der Bruggen & Bekkering, 1993; Khan et al., 2006) (i.e., two-target advantage). Researchers have accounted for this advantage in terms of the underlying muscle activity patterns. In single element movements, muscle activity patterns are characterized by a triphasic EMG pattern of activation. Initially, the agonist muscle accelerate to decelerate

the limb. A second agonist then acts to serve the purpose of dampening the mechanical oscillations at the end of the movement (Enoka, 1988; Hallett, Shahani, & Young, 1975; Hannaford & Stark, 1985). In two-target reversal movements there is no need for the second agonist burst since the elastic properties of the antagonist can be exploited to save energy in moving the limb in the reverse direction (Khan et al., 2006, Enoka, 1994; Guiard, 1993). In these situations, the antagonist used to decelerate the limb at the first target also acts as the agonist on the second movement. This dual purpose of activity allows for optimal integration between elements, resulting in the two-target advantage (TTA).

Khan, Tremblay, Cheng, Luis & Mourton (2008) investigated whether the TTA emerges from the implementation of processes prior to response initiation or during movement execution by perturbating the number of targets. The perturbation task included a paradigm in which the requirements of the task changed from a one- to a two-target response and vice versa. One of the aims of the study was to examine whether reversal movements are organised as a single unit of action rather than two discrete movements. Of interest was the participants' ability to change between task demands and under which conditions the two-target advantage would occur. In the first of two experiments, participants were instructed to prepare for single target movements. On some occasions however, a second target was presented at one of three time points, (i.e. stimulus onset, movement onset or at peak velocity to the first target). If the two-target advantage is the result of preparatory processes prior to movement initiation, then it was expected that the TTA would only be observed when the second target was introduced at stimulus onset. In the second experiment, participants were instructed to prepare for a two-element reversal movement. For most of the trials, two-targets were presented. On some trials, only one

target was presented, or the second target disappeared at movement onset or at peak velocity to the first target. In these trials, participants were required to move to the first target, and inhibit the response to the second target. If the TTA is again the result of preparatory processes as predicted in Experiment 1, then movement times to the first target would be longer in the task where only 1 target was presented. Results in both experiments revealed that MT to the first target was determined by the information available at stimulus presentation. In both experiments, MTs were shorter when two targets were presented than when a single target appeared at stimulus onset (i.e. two-target advantage).

It was expected that if two-target reversal movements are grouped as a single unit of action, then the ability to inhibit the movement to the second target would be difficult once the movement was initiated. Results revealed that changing the requirements of the task after stimulus onset (movement onset and peak velocity) did not influence MTs. Hence, that it was difficult for participants to switch task demands once movements were initiated. In Experiment 1, when participants were informed at movement onset or during execution of the first movement that a dual response was required, the implementation of the reversal component occurred too late for the TTA to occur. In experiment 2, participants struggled to inhibit a response when a second target disappeared at movement onset or peak velocity. In the condition where a second target disappeared at movement onset, participants still made movements towards the position of the perturbed target. In conditions where the second target disappeared at peak velocity of the first movement to the second perturbed target. This inability to inhibit a second target provides support for the hypothesis that

reversal responses are organised as a single unit of action rather than two separate movements.

Target Size: Another situation in which the OTA does not materialize is when the target sizes are relatively small. With respect to small targets, the MIH predicts that small targets should make the OTA disappear (Adam et al., 2000). Small target sizes increase the accuracy demands required to perform a task. Pause times between the two movements are relatively long thereby disrupting the transition between targets (Adam & Paas, 1996; Adam et al., 1995; Adam et al., 2000; Rand & Stelmach, 2000). Hence, movements to both targets are processed separately into individual units, where each movement has its own preparatory and control processes. Since control processes for the two segments did not overlap, the OTA did not emerge.

Similarly when the target size of the first target is relatively large, manipulating the size of the second target has an influence over the movement to the first target (Sidaway et al., 1995). However, when the size of the first target is small, there is no influence of the size of the second target on the execution to the first element (Adam et al., 1995; Rand & Stelmach, 2000). Again this shows that the two movement segments are performed independently when the accuracy demands at the first target are high.

Adam et al. (2000) examined the combined effect of target size and direction of the second movement on the OTA. Participants performed 8 two-tap conditions in addition to a one-tap condition. In the two-tap condition, the first movement was always from the start position to a central target (positioned to the left of the start position) and was then followed by a second movement to one of 8 peripheral targets (i.e. east, north-east, north,

north-west, west, south-west, south, and south-east). For the large target condition, movement time to the first target (MT1) was significantly shorter for the one-tap condition than for all but one of the two-tap conditions (second movement in the direction 'east'). For the small target condition, as predicted by the movement integration hypothesis the OTA did not emerge. Furthermore, pause times in the small target condition also increased in comparison to the large target condition. This is consistent with the notion that successive motor chunks are separated by long intervals, supporting the idea that the first and second movements in two-tap conditions were controlled independently.

Vision: In an attempt to examine the trade-off between planning and control processes in multiple responses, Lavrysen et al. (2002) manipulated visual feedback either during the first or the second part of an aiming movement task. This was done in order to vary the opportunity for on-line control during various parts of the movement. The idea was that eliminating vision during movement one or two would reduce the opportunity for on-line control and shift the timing of preparatory processes. The results indicated that, although on-line visual processing was important for accurate limb control, participants took more time to prepare the movements when they knew vision was not going to be available for on-line control. There were also differences in the way single element movements, reversal movements and extension movements were prepared. Consistent with Adam et al. (2000) and Helsen, Adam, Elliott and Beukers (2001), the absence of a OTA for movement reversal indicated that the two elements of a reversal movement were controlled as a single unit of action. Lavrysen et al. (2002) provided further evidence to suggest advance planning in two-target movements. Their kinematic data suggested that participants

performed a more constrained first movement when that movement was followed by a second extension movement. When participants knew no visual information was available for the control of the second movement, movements to the first target were more constrained. By having a more constrained first movement, this may reduce the need for on-line control during the final phase of the first movement and the implementation of the second movement (also see Elliott et al., 2001).

As mentioned earlier, the OTA is a robust phenomenon which occurs regardless of hand preference, hand use and practice. Different interpretations have been put forward to explain the OTA. One interpretation suggests that movements to the first target in a sequence must be constrained to ensure that accuracy at subsequent targets are met (MCH). The on-line programming hypothesis and movement integration hypothesis are a further two interpretations. Whereas the on-line programming hypothesis involved both the construction and implementation of a motor program during movement execution, the MIH involves construction of the motor program prior to response initiation and the implementation of the second element is performed in conjunction with the execution of the first element.

As previously mentioned, this thesis intends to examine the interrelation between two movements. This will be done using the OTA phenomenon and hypotheses mentioned whilst examining the relation between limbs, specifically looking at comparisons in RT and MT between single limb and two-limb responses. Another possible examination between the relations between two movements will be done through examining the implementation

and optimization of two element responses. This thesis intends to borrow principles from single target aiming to attempt to examine the optimal control of two segments.

1.4 Optimisation of target directed aiming

When a person is faced with a task for the first time, there will inevitably be some uncertainty as to how to approach the task. For example, if a person is told to move as fast as possible and hit a target, then he/she must work out how fast they can move whilst still hitting the target accurately. This optimal performance will not be achieved straight away and may take time to be achieved. The performer would adjust their movement to optimise the speed and accuracy, whilst conserving energy expenditure.

1.41 Speed-accuracy explanations

Over the last century, researchers have developed a number of models to try and explain the relation between speed and accuracy. Woodworth (1899) suggested that goal directed movements consist of two parts; an initial impulse phase that gets the limb towards the vicinity of the target and a current control phase where the limb comes under current feedback control to hit the target. Woodworth's ideas about limb control have provided the foundations for dual process models of speed-accuracy tradeoffs.

The iterative correction model (Crossman & Goodeve, 1983) suggests that aiming movements are composed of a series of submovements. Organisation of each submovement is such that error can be reduced on the basis of feedback from the previous submovement. The speed accuracy relationship occurs due to the total number of error

reducing corrections in the movement whereby longer movement times are associated with increased corrections and less error.

The single correction model (Beggs & Howarth, 1970, 1972; Howarth, Beggs & Bowden, 1971) is similar to Woodworth's (1899) model of limb control. Both state that an initial ballistic phase is used to bring the limb towards the vicinity of a target. Whereas Woodworth's model proposes that it is possible for multiple corrections or continuous online control during the 'homing' phase, the single correction model suggests that there is one feedback based correction before reaching the target. The precision of the correction and therefore accuracy of the movement is dependent upon the proximity of the limb to the target when the correction towards the target is being implemented.

In the 1970's, Schmidt (Schmidt, Zelaznik & Frank, 1978; Schmidt, Zelaznik, Hawkins, Frank & Quinn, 1979) and colleagues introduced a speed-accuracy model that did not include feedback based processes. Their impulse variability model was based on the idea that variability in the muscular forces used to move the limb towards the target increased proportionally with the absolute forces required for a particular movement. Greater variable error emerges in high velocity movements and movements with a greater amplitude compared to low velocity and small amplitude movements.

Arguably, the optimised submovement model (Meyer et al., 1988) is the most comprehensive explanation of speed-accuracy relations. The model proposes that goal directed aiming movements are comprised of component submovements. Movement production is characterised by an optimal compromise between the greater noise and endpoint variability associated with fast initial impulses, and the time-consuming nature of any corrective submovements. Initial impulse and optimal corrective submovements are

combined in order to minimise movement time whilst adhering to the accuracy demands imposed by the target. Over a series of aiming attempts, neuromuscular noise will result in a normal distribution of primary movement endpoints centred on the middle of the target. If a primary submovement endpoint falls outside the target boundary, a corrective submovement is required. The corrective submovements are based on visual and other feedback obtained whilst the first submovement is in progress. Optimal performance is achieved by minimising the combined duration of the initial impulse and error correction phases. For example, faster initial impulses would be accompanied by more extensive error correction phases, and vice versa. This model incorporates the best features of the impulse variability model and the iterative correction model. Due to the integration of both impulse variability and feedback based corrective processes; this model is able to account for speedaccuracy relations for short and long duration movements.

1.42 The cost of error and optimal energy expenditure

It is often assumed that movements in which movement times are minimised are often energy efficient. For example, movements that initially undershoot a target are faster than movements that overshoot a target because the limb travels less distance. Overshooting a target requires the limb to travel a greater distance and the inertia of the limb at the point of the reversal must be overcome (Elliott, Hansen, Mendoza & Tremblay, 2004). In the case of an undershoot, the limb already has a positive velocity in the direction of the corrective submovement (Elliott, Binsted & Heath, 1999). Hence, target overshooting is generally seen as more costly, both in terms of movement time and energy expenditure than target undershooting.

Khan, Franks and Goodman (1998) examined the influence of visual feedback on the initial impulse and error correction phases of the movement as a function of practice. Participants performed a wrist rotation task, with the distance between the start position and the target being 45° of wrist rotation. After extensive practice, differences between visual conditions (full vision and no vision) in the initial impulse and error correction phases were revealed. During the later stage of practice, in the full vision group, there was a tendency for participants to undershoot the target in the initial impulse phase, whereas there was no evidence for undershooting in the no vision group. Khan et al., (1998) proposed that these differences occurred because of the different control strategies adopted by the participants. Participants in the full vision group may have undershot the target initially so that on-line error corrections in the direction as the initial programmed movement could be used (Ricker et al., 1999; Meyer et al., 1988). In contrast, participants in the no vision group did not bias initial impulses to either side of the target. Presumably this is because participants were pre-programming their movement so that they were not reliant on visual feedback and error corrections. Consistent with this explanation was the finding that the percentage of movements that contained error correction phases was less in the no vision group compared to the vision group.

Over practice, participants have been shown to reduce the spatial variability associated with the primary movement endpoint while also biasing initial impulse endpoints just short of the centre of the target. This minimises the number of target overshoots whilst decreasing the percentage of movements that require a correction (decreasing number of undershoots). This strategy of "sneaking up" on the target does not

only minimise movement time over a series of trials but will also reduce the energy expenditure associated with the target movement (Elliott et al., 2004).

This strategy has also been seen in a study by Oliveira, Elliott and Goodman (2005), where they used a ballistic target aiming task. Participants were required to propel a small disk down a track to a specific target distance. Two tasks were used, an unassisted situation where greater force produced a greater distance, and an assisted condition where a surgical rubber tube was used to propel the disk down the track. In this condition, participants had to apply an assistive force against the rubber tube or the disk would travel too far. Results revealed that participants initially adopted an energy minimisation strategy whereby they undershot the target in the unassisted condition and overshot in the assisted condition. Just as Elliott et al., (2004) showed, participants in this study were also able to gradually sneak up on the target distance as their variability at the target decreased over practice.

Movement time is minimised by producing a trade-off between the initial impulse and error correction phases (Meyer et al., 1988). It is a general assumption that initially undershooting a target results in quicker movement times than overshooting. By initially overshooting a target, the limb is required to travel a greater distance and overcome the inertia of the limb at the point of reversal. Therefore, an overshoot is more costly in terms of time taken and energy expenditure. Over practice, the spatial variability associated with the movement endpoint is reduced resulting in more accurate movements with their initial impulse. This strategy of "sneaking up" minimises movement times over a series of trials and also reduces the energy expenditure associated with the target movement (Elliott et al., 2004).

1.5 Purpose of Thesis

The purpose of this thesis was two-fold. Firstly, in Chapter 2 a comparison was made between single limb sequential aiming movements and two limb movements in which the hand was switched at the first target. The OTA has been shown to be robust regardless of manipulations of vision, hand preference and hand used. However, the OTA has never been examined when two limbs are used in two target responses. Of interest was whether the OTA would emerge when there is a transfer between limbs in sequential aiming movements. Single target movements, along with two target movements using both single and two limbs were used. Testing the presence of the OTA for one- and two-limb movements has two important theoretical implications. Firstly, the presence of the OTA would be inconsistent with the movement constraint hypothesis. The MCH states that accuracy at the second target is dependent upon the location and variability of the movement endpoints at the first target. However, in two-target movements in which the limb is switched at the first target (two-limb movement), the start point for the second movement is independent to the endpoint for the first movement. Secondly, comparing between one- and two-limb movements would allow an individual to distinguish between two possible loci of interference that causes the OTA. As Adam et al. (2000) argued, the MIH makes no assumption about the locus of the interference effect. Two possible sources for interference are a central origin (retrieval of a motor program from a motor buffer) or a peripheral origin (muscular organisation of the performing limb is adjusted to produce a second movement). Support for a purely central locus would be revealed if the OTA appeared in the two-limb condition, and the size of the advantage was similar to that of a

single-limb movement. Support for a purely peripheral locus would be revealed if the size of the OTA was significantly smaller, or if the advantage disappeared completely.

Chapter 3 further examined the effects of target size on both single and dual limb sequential aiming movements. Adam et al., (2000) showed that the OTA did not emerge with small target sizes. In single limb conditions, the MIH would predict that the OTA would not emerge under small target conditions (Adam et al., 2000). Small target sizes increases the accuracy demands required to perform a task and hence pause times between movements are relatively longer, thereby disrupting the transition between movement elements (Adam et al., 1995; Adam et al., 2000; Rand & Stelmach, 2000). As a consequence, the two movements are not processed together, but independently of each other. Of interest in this chapter was to examine whether the OTA would be affected when target size is manipulated under the two limb condition. In addition to the same dependent measures used in chapter 2, kinematic data will also be collected in this study using an optotrak three dimensional movement analysis system. This enabled the variability in limb trajectories to be assessed at various stages of the movement. In two limb aiming in which the limb is switched at the first target, one might expect that an overlap of control processes even when accuracy demands are high since the implementation of the second movement does not depend on the accuracy of the first segment.

Chapter 4 examines the optimisation of movements in multiple target aiming. Whereas most research has focused on the processes involved in movement execution when varying the position of the second target in two-target aiming responses, this chapter focuses on the effect of varying the first target in sequential aiming movements. Participants performed a two-target aiming task where the first target could randomly

appear in 1 of 5 positions between the start position and target 2. If we are able to understand the basic principles behind movement optimization, then this information will be beneficial in developing and managing new practice principles.

The MCH suggests movements to the first target in a sequence must be more constrained to provide an ideal starting position in order to be accurate at subsequent targets (Fischman & Reeve, 1992). As mentioned earlier, the MIH is based on the assumption that the motor program is constructed prior to response initiation, but the implementation of the second element is performed on-line in conjunction with the first movement (Adam et al., 2000). If the results were to show that movements at the first target were more constrained than at the second target, then this would provide further support for the MCH in multiple target aiming tasks. If the amplitude of the first or second movement is long, then there may be more chance for on-line programming to occur than in shorter amplitudes. If both the first and second movements are of the same amplitude, then participants may be able to implement these movements easier as they only have to respond to the same amplitudes.

In single target responses, participants generally undershoot a target with their initial impulse. This is because overshoots are seen as more costly in terms of time taken to reach the target and energy expenditure. Overshooting a target requires the limb to travel a greater distance to the target and the inertia of the limb at the point of reversal must be overcome. Undershooting the target means that the limb already has a positive velocity in the direction of the corrective submovement. When participants perform a two-target task, it may be the case that when the first target is closest to the second target, total movement times are fastest. This could be because the initial impulse towards the targets leaves the

limb close to the second target when the first target is reached. Therefore, only a small movement (or correction) to the second target is required.

Chapter 2

Sequential aiming with two-limbs and the one-target advantage

Experiment 1 of this study has been accepted for publication in the Journal of Motor Behavior as a research article:

Khan, M. A., Mottram, T. M., Adam, J. J., & Buckolz, E. (2010). Sequential aiming with two limbs and the one-target advantage. *Journal of Motor Behavior*, **42** (5), 325-330.

2.1 Introduction

Since the work of Henry and Rogers (1960) it has been shown that reaction time (RT) is directly related to the number of response segments (or elements) in movement sequences (e.g., Franks & van Donkelaar, 1990; Khan et al., 2006; Klapp, 1995, Sternberg et al., 1978). However, the influence of the number of response segments has not been limited to the RT interval. For sequential aiming movements in which participants are required to move to a target and then continue in the same direction to a second target, movement times (MTs) to the first target are typically slower compared to when participants are required to stop at the first target (e.g., Chamberlin & Magill, 1989; Helsen, et al, 2001; Lavrysen et al., 2002).

Different interpretations have been put forward in an attempt to explain the one-target advantage (OTA) in MT. These vary in the extent to which the lengthening of MT can be attributed to planning versus on-line control processes. It has been proposed that movements to the first target in a sequence must be more constrained to ensure that the accuracy requirements at subsequent targets are met (Sidaway et al., 1995). This proposal is consistent with evidence that spatial variability increases as movement progresses (see Khan et al., 2006 for a review). According to the movement constraint hypothesis (MCH), movement to the first target is performed in a more controlled manner in order to provide an ideal starting position for the limb to start the second movement. This strategy could be part of the overall response program and be planned before movement initiation (Fischman & Reeve, 1992). An alternative explanation for the OTA is the online programming hypothesis (Chamberlin & Magill, 1989). According to this 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, providing there is sufficient time during movement execution. Hence, MT increases due to the additional processing requirements of programming the second movement during execution of the first movement. By contrast, according to the movement integration hypothesis (MIH) (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 concurrent with 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.

The OTA has been shown to be a very stable phenomenon. It emerges regardless of the participants' hand preference and whether the preferred or non-preferred hand is used (Helsen et al., 2001; Lavrysen et al., 2003). The OTA is resistant to the occlusion of vision (Lavrysen et al., 2002) and persists after moderate (i.e., 400 trials, Lavrysen et al., 2003) and extensive (i.e., 1200 trials, Adam et al., 2001) amounts of practice. The two cases in which the OTA does not materialize are when the second movement is in the reverse direction and when the target sizes are relatively small. In the case of reversal movements, the antagonist muscle forces used to decelerate the first element also act as the agonist for the second component and the elastic properties of a lengthening antagonist muscle can be exploited to save energy in moving the limb in the reverse direction (Guiard, 1993). This allows for optimal integration between the two movements. When the accuracy demands are high, pause times on the first target are relatively long, thereby disrupting the transition between the two movements (Adam & Paas 1996; Adam et al., 1995; Adam et al., 2000;
Rand & Stelmach, 2000). In such cases, movements to targets are organized separately and independently, and hence there is no overlap of control processes.

Although the OTA is robust, it has been exclusively demonstrated for aiming tasks in which movements were performed with a single limb. The goal in the present study was to test whether the OTA would emerge when there is a transfer between limbs during sequential aiming movements. We compared performance in single target movements with (a) two target movements using a single limb and (b) two target movements in which movement to the first target was performed with one arm and movement to the second target was performed with the other arm. Testing the presence and size of the OTA for one and two limb conditions has two important theoretical implications.

First, the presence of a OTA for two limb movements would be inconsistent with the MCH. According to the MCH, accuracy at the second target would depend on the location and variability of the movement endpoints at the first target. However, in two limb movements in which the limb is switched at the first target, the start position of the limb that moves to the second target is independent of the movement endpoints on the first target. Consequently, in the two limb condition accuracy at the second target is not contingent on the variability of movement endpoints at the first target.

Second, comparing movement times to the first target in single and two limb tasks would allow one to distinguish between two possible loci of the interference effect reflected by the OTA. As Adam et al. (2000) argued, the MIH does not make any specific assumptions about the nature or locus of the interference effect. A central origin is possible (for instance, retrieval of a motor program from a motor buffer), but also a peripheral or local origin, whereby the muscular organisation of the performing limb is adjusted and

readied to produce a new/second movement. The present two-limb movement condition would seem to reduce or even to eliminate the possibility of interference occurring at the peripheral level because the two movements are implemented by largely distinct and separate neuro-anatomical effectors, thereby reducing the effect of functional/neuroanatomical dependencies between successive movements (as might be the case for single limb actions). Hence, the absence of the OTA when two limbs are used would qualify the movement integration hypothesis by suggesting that it only holds for single limb sequential movements. Support for a purely central locus would be revealed if the OTA was present in the two-limb condition and size of the OTA was similar for the one- and two-limb movements. A significant but smaller OTA for two-limb compared to one-limb movements would provide evidence in support of the two-loci notion, suggesting a limb-independent central locus (retrieval of a motor program from a motor buffer) and a limb-dependent peripheral locus.

2.2 Experiment 1

2.21 Method

Participants

Participants were 25 volunteers (10 men, 15 women; M age = 22 years; SD = 3 years, age range = 18-32 years). Participants were self-declared right hand dominant, and reported normal or corrected to normal vision. They all signed consent forms prior to the start of 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

Six micro-switches were mounted under square keys (25mm x 25mm) on a horizontal wooden frame situated on a tabletop in front of seated participants. The keys were arranged in sets of 3 pairs along the participants' midline (see Figure 2.1). The distance between each key in a pair was 35mm (centre to centre), and the distance between each pair was 150mm (centre to centre; i.e., Index of Difficulty = 3.6 bits, [Fitts, 1954]). Participants were positioned so that they could easily press each key with their index finger. The most distal keys were the start positions. The middle keys were designated as target 1 and the most proximal keys as target 2.



Figure 2.1. Position and movement of fingers under right hand condition for (a) Single-Target (1T), (b) Two-Target, Single-Limb (2T1L), and (c) Two-Target, Two-Limbs (2T2L) aiming tasks.

Task and Procedure

The aiming tasks were performed under two hand conditions (see Figure 2.1). In the right hand condition, the right index finger was initially placed on the start position (right key) while the left index finger was placed on target 1 (left key). In the left hand condition, the left index finger was initially placed on the start position (left key) while the right index finger was placed on target 1 (right key).

Participants performed three aiming tasks under each hand condition. In the one target (1T) task, participants moved their hand from the start position to target 1 (see Figure 2.1a). The other hand remained stationary on target 1. In the two target, single limb (2T1L) task, participants moved their hand from the start position to target 1 and then to target 2, pressing both targets with the same index finger (see Figure 2.1b). The other hand remained stationary on target 1. In the two target, two limb (2T2L) task, participants moved their hand from the start position to target 1 to target 2 (see Figure 2.1c). Participants were told not to start the second movement until the first had been completed, but to make this changeover as quickly as possible.

At the beginning of each trial, participants were presented with a warning tone which was then followed by a target tone after a 2000-3000 ms variable foreperiod. Participants were instructed to react and perform the movement(s) as quickly as possible in response to the onset of the target tone.

Each participant completed 120 trials (60 in the right hand condition and 60 in the left hand condition). Half the participants performed the right hand condition first while the other half performed the left hand condition first. In each condition, 20 trials were

performed in the 1T, 2T1L and 2T2L tasks. The three tasks were blocked and counterbalanced between participants.

Statistical Methods

Dependent measures consisted of reaction time (RT), movement time to the first target (MT1), pause time at target 1 (PT) and movement time from the first target to the second target (MT2).

RT was the interval from the presentation of the stimulus (auditory tone) to the release of the keypress at the starting position. MT1 was measured from the release of the keypress at the starting position to the pressing of the target 1 key. PT was the time between the pressing of target 1 and the release of the key press to perform the second movement. Finally, MT2 was the time from the release of the key press at target 1 to the pressing of target 2.

A 2 Hand condition (left, right) x 3 Task (1T, 2T1L, 2T2L) repeated measures ANOVA was performed on RT and MT1, whilst a 2 Hand Condition (left, right) x 2 Task (2T1L, 2T2L) repeated measures ANOVA was performed on PT and MT2. Tukeys HSD post hoc tests for repeated measures designs (Stevens, 2002, p. 506) were performed on significant main effects and interactions to locate significant differences.

2.22 Results

Trials in which RT was less than 100 msec or more than 700 msec and in which participants missed at least one of the targets or initiated their second segment prior to completing the first were omitted from the analysis. This amounted to less than 2% of the trials. The means and standard deviations of all dependent measures for the left and right hand conditions are reported in Table 2.1.

	Right Hand			Left Hand		
	1T	2T1L	2T2L	1T	2T1L	2T2L
RT (ms)	243	267	281	245	266	272
	45	48	51	49	47	55
MT1 (ms)	128	149	158	143	162	162
	30	35	35	34	40	28
PT (ms)		94	178		102	94
		20	37		26	26
MT2 (ms)		153	178		163	173
		94	37		23	32

Table 2.1. Means and *standard deviations* of reaction time (RT), movement time to the first target (MT1), movement time to the second target (MT2) and pause time (PT) for the one target (1T), two-target, one limb movement (2T1L), and two-target, two limb (2T2L) tasks.

Analysis of RT revealed a significant main effect for Task ($F_{2,48} = 12.1, p < 0.05, \eta^2 = 0.22$). Reaction times were shorter in the 1T task (M = 244 ms, SD = 47 ms), compared to the 2T1L (M = 267 ms, SD = 47 ms) and 2T2L (M = 276 ms, SD = 53 ms) tasks (see Figure 2.2). There was no difference in RT between the 2T1L and 2T2L tasks. There was no main effect for Hand Condition ($F_{1,24} = 0.42, p = 0.523, \eta^2 = 0.002$) nor interaction between Hand Condition and Task ($F_{2,48} = 0.748, p = 0.479, \eta^2 = 0.007$).



Figure 2.2. Reaction times (RT) for Single Target (1T), Two-Target, Single Limb (2T1L) and Two-Target, Two-Limbs aiming tasks (data is collapsed over both hand conditions). Error bars represent standard error of the mean. * Significance at p < 0.05.

There were significant main effects for Hand Condition ($F_{1,24} = 12.9, p < 0.05, \eta^2 = 0.074$), and Task ($F_{2,48} = 27.6, p < 0.05, \eta^2 = 0.31$) on MT1. Movement times to the first target were shorter in the right hand (M = 145 ms, SD = 33 ms) compared to the left hand (M = 156 ms, SD = 34 ms) condition. MT1 was shorter when a single target movement (M = 135 ms, SD = 32 ms) was performed compared to the 2T1L (M = 156 ms, SD = 37 ms) and 2T2L (M = 160 ms, SD = 32 ms) tasks (see Figure 2.3). There was no difference in MT1 between the 2T1L and 2T2L tasks. There was no interaction between Hand Condition and Task ($F_{2,48} = 1.807, p = 0.175, \eta^2 = 0.015$).



Figure 2.3. Movement times to the first target (MT1) for Single Target (1T), Two-Target, Single Limb (2T1L) and Two-Target, Two-Limbs aiming tasks (data is collapsed over both hand conditions). Error bars represent standard error of the mean. * Significance at p < 0.05.

The analysis of MT2 revealed a significant main effect for Task ($F_{1,24} = 15.1, p < 0.01, \eta^2 = 0.17$). MT2s were shorter in the 2T1L condition (158ms) compared to the 2T2L condition (176ms). There was no main effect for Hand Condition ($F_{1,24} = 0.249, p = 0.623, \eta^2 = 0.003$) but the interaction between Hand Condition and Task approached conventional levels of significance ($F_{1,24} = 3.231, p = 0.085, \eta^2 = 0.03$). As shown in Table 1, MT2 was shortest in the 2T1L condition in which the right hand was used for both targets and slowest in the 2T2L condition in which there was a switch from the right to left hand for the second segment.

The analysis of mean pause times (PT) revealed no significant *F*-values for Hand Condition ($F_{1,24} = 3.058$, p = 0.093, $\eta^2 = 0.03$) or Task ($F_{1,24} = 1.318$, p = 0.262, $\eta^2 = 0.029$). There was no interaction between Hand Condition and Task ($F_{1,24} = 2.475$, p = 0.129, $\eta^2 = 0.017$) (overall M = 96 ms, SD = 24 ms).

2.23 Discussion

The OTA has been shown to be a robust phenomenon that emerges regardless of the participants' hand preference and whether the preferred or non-preferred hand is used (Helsen et al., 2001; Lavrysen et al., 2003). The goal in the present study was to test whether the OTA would emerge when there is a transfer between limbs during sequential aiming movements. We compared performance in single target movements with (a) two target movements using a single limb and (b) two target movements in which movement to the first target was performed with one arm and movement to the second target was performed with the other arm.

Consistent with past research (Klapp, 1995, 2003; Khan et al., 2006, 2007) RT was greater when a two-target response had to be performed compared to a single target response. This was the case when the two-target response was performed within a single limb, and when the participants switched hands at the first target. Khan et al. (2007) reported that simple RT increased as a function of the number of elements when the number of elements was specified in advance regardless of whether other features were known. Consistent with Khan et al., movements that contained two elements had slower RTs than single element responses regardless of whether single-limb or two-limb responses were required.

The influence of number of elements was not limited to RT. The one-target movement time advantage was also demonstrated (also see Adam et al., 2000; Chamberlin & Magill, 1989; Helsen et al., 2001; Lavrysen et al., 2002). Movement times to the first

target were quicker when a single target response was required compared to when participants had to hit a first target and then continue to hit a second target a two target response. Also, movement times were longer in two-target conditions regardless of whether a two-target single-limb or two-target two-limb response was required. Hence, the control processes associated with the OTA are not limited to movements performed with a single limb. Furthermore, the magnitude of the OTA was similar for both the single-limb and two-limb conditions suggesting that similar mechanisms may be responsible for the OTA in the single- and two-limb conditions.

Although the size of the OTA did not differ between the right (25 ms) and left hand (19 ms) conditions, there was an overall advantage of the right hand over the left hand for MT to the first target (and near-significant for pause time and movement time to the second target in the 2T1L condition). This is consistent with the well-documented right hand advantage in manual aiming and related tasks such as finger tapping and finger sequencing (for a review, see Elliott & Chua, 1996). This right hand superiority has been ascribed to the left hemispheric specialization in controlling limb dynamics in contrast to the right hemispheric specialization in controlling limb position (e.g., Sainburg, 2002; Haaland & Harrington, 1989).

2.3 Experiment 2

2.31 Introduction

The previous experiment revealed that the OTA occurred for both single limb and two limb aiming sequences. In the present experiment, the robustness of the OTA in two-limb sequential aiming movements was tested further by manipulating target distance. The movements involved in Experiment 1 had equal distances for both the first and second movement. In the current experiment, the distance of the second movement was manipulated while keeping the distance of the first movement constant. According to Fitt's Law, movement distance is an important determinant of movement time (MT). Adam et al. (2000: Experiment 3) manipulated the distance of the second movement so that 3 distances were included in the task (8cm, 24cm and 40cm). Their results revealed that the OTA was present in each movement amplitude condition, thus providing further support for the robustness of the OTA for single limb aiming movements.

Similar to Adam et al. (2000: Experiment 3), we manipulated the distance from the first target to the second. The aim was to determine if the OTA would emerge under two limb conditions when the distance from the first to second target is manipulated. It is possible that increasing the distance travelled to the second target may reduce the magnitude of the OTA. This is because the control processes associated with the execution of the second movement can be completed during movement to the second target (on-line programming) rather than during execution of the first movement. Another possible hypothesis would be that longer movements are more complex, and thus would require more on-line control processes, increasing the magnitude of the OTA. If the OTA was to

remain or increase when varying the distance of the second movement, this would provide further evidence of the robustness for both single and two-limb movements.

2.32 Method

Participants

Participants were 24 volunteers (9 men, 15 women; M age = 20 years; SD = 1 years, age range = 18-22 years). All participants were self-declared right hand dominant, and had reported normal or corrected to normal vision. Consent forms were signed 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 apparatus was similar to Experiment 1 except for the distance of the second movement (see Figure 2.4). Short second target movements were 70mm between target 1 and target 2 (centre to centre; i.e., Index of Difficulty = 2.5 bits, Fitts, 1954), and long second target movements were 260mm between target 1 and target 2 (centre to centre; i.e., Index of Difficulty = 4.4 bits, Fitts, 1954).



Figure 2.4. Starting position of fingers, and the 2 conditions used in the study. a) Short second movement (70mm); b) Long second movement (260mm)

Task and Procedure

Since the Hand condition did not have any effect in Experiment 1, the aiming tasks were performed in the right hand condition only. Similar to Experiment 1, participants performed one target (1T), two target single limb (2T1L), and two target two limb (2T2L) aiming tasks.

Each participant completed 120 trials. For 60 trials, the distance from the first to second targets was 70mm (centre to centre). For the other 60 trials, the distance from the first and second targets was 260mm (centre to centre). Half the participants performed the short amplitude movement condition first, while the other half performed the long amplitude movement condition first. For each movement amplitude, 20 trials were performed in each of the 1T, 2T1L and 2T2L tasks. The tasks were blocked with the order of the 3 tasks counterbalanced between participants.

Statistical Methods

The same dependent variables were used as in Experiment 1. A 2 Movement Amplitude (short, long) x 3 Aiming tasks (1T, 2T1L, 2T2L) repeated measures ANOVA was performed on RT and MT1. A 2 Movement Amplitude (short, long) x 2 Task (2T1L, 2T2L) repeated measures ANOVA was performed on PT and MT2. Tukeys HSD post hoc tests for repeated measures designs (Stevens, 2002, p. 506) were performed on significant main effects and interactions to locate significant differences.

2.33 Results

Trials in which RT was less than 100 msec or more than 700 msec and in which participants missed at least one of the targets were omitted from the analysis. This amounted to less than 2% of the trials. The means and standard deviations of all reported dependent measures are reported in Table 2.2.

	Short 2 nd movement amplitude			Long 2 nd movement amplitude		
	1T	2T1L	2T2L	1T	2T1L	2T2L
RT (ms)	252	273	282	256	272	289
	37	39	43	40	40	53
MT1 (ms)	179	191	199	177	198	194
	47	37	46	49	47	43
PT (ms)		106	91		106	100
		27	25		27	36
MT2 (ms)		123	163		232	252
		26	50		42	61

Table 2.2. Means and *standard deviations* of reaction time (RT), movement time to the first target (MT1), pause time (PT) and movement time to the second target (MT2). 1T = one target movement, 2T1L = two-target, one limb movement, 2T2L = two-target, two limb movement.

Analysis of reaction time data revealed a significant main effect for Task ($F_{2,38} = 13.948, p < 0.05, \eta^2 = 0.25$). Reaction times were shorter in the 1T task (M = 254 ms, SD = 39 ms), compared to the 2T1L (M = 272 ms, SD = 40 ms) and the 2T2L (M = 285ms, SD = 48 ms) tasks (see Figure 2.5). There was no difference in RT between the 2T1L and 2T2L tasks. There was no main effect for Movement Amplitude ($F_{1,19} = 0.415, p = 0.527, \eta^2 = 0.004$) nor an interaction between Movement Amplitude and Task ($F_{2,38} = 0.427, p = .656, \eta^2 = 0.005$).



Figure 2.5. Reaction times (RT) for Single Target (1T), Two-Target, Single Limb (2T1L) and Two-Target, Two-Limbs aiming tasks (data is collapsed over both movement amplitude conditions). Error bars represent standard error of the mean. * Significance at p < 0.05.

The analysis of movement time to the first target (MT1) revealed a significant main effect for Task ($F_{2,38} = 7.491$, p < 0.05, $\eta^2 = 0.16$). MT1 was shorter in the 1T condition (M= 178 ms, SD = 42 ms) compared to the 2T1L (M = 194 ms, SD = 42 ms) and 2T2L (M =196 ms, SD = 45 ms) conditions (see Figure 2.6). There was no difference in MT1 between the 2T1L and 2T2L tasks. There was no main effect for Movement Amplitude ($F_{1,19} =$ 0.001, p < 0.971, $\eta^2 = 0.00001$) nor a Movement Amplitude by Task interaction ($F_{2,38} =$ 1.265, p < 0.294, $\eta^2 = 0.02$).



Figure 2.6. Movement times to the first target (MT1) for Single Target (1T), Two-Target, Single Limb (2T1L) and Two-Target, Two-Limbs aiming tasks (data is collapsed over both movement amplitude conditions). Error bars represent standard error of the mean. * Significance at p < 0.05.

Analysis of movement time to the second target (MT2) revealed a significant main effect for Movement Amplitude ($F_{1,19} = 337.439$, p < 0.05, $\eta^2 = 0.76$). MT2s were quicker in short amplitude movements (M = 143 ms, SD = 44 ms) than long amplitude movements (M = 242 ms, SD = 52 ms). A significant main effect was also revealed for Task ($F_{1,19} =$ 14.321, p < 0.05, $\eta^2 = 0.07$). MT2s were shorter in the 2T1L task (M = 178 ms, SD = 65ms) compared to the 2T2L task (M = 207ms, SD = 71 ms). A Movement Amplitude by Task interaction was also revealed ($F_{1,19} = 5.574$, p < 0.05, $\eta^2 = 0.008$). It looks as though movement amplitude had a larger effect in the single-limb (109ms difference) compared to the two-limb condition (89ms difference). The analysis of mean pause times (PT) revealed no significant F-values for

Movement Amplitude ($F_{1,24} = 0.964$, p = 0.338, $\eta^2 = 0.01$) or Task ($F_{1,24} = 1.559$, p = 0.227, $\eta^2 = 0.05$). There was no interaction between Movement Amplitude and Task ($F_{1,24} = 1.363$, p = 0.258, $\eta^2 = 0.008$) (overall M = 101 ms, SD = 29 ms).

2.34 Discussion

In single-limb sequential aiming movements, the OTA has also been shown to emerge regardless of the distance of the second movement (Adam et al., 2000, experiment 3). The present experiment examined whether manipulating the distance of the second movement (similar to Adam et al., 2000) has an influence on the magnitude of the OTA in two-limb movements.

Consistent with past research (Klapp, 1995, 2003; Khan et al., 2006, 2007) and Experiment 1, RT was greater when a two-target response was performed compared to a single target response, regardless of the distance of the second movement. This was the case when the two-target response was performed with a single limb and when the participants switched hands at the first target. Hence, increasing the number of elements in a response where the distance of the second movement was manipulated increased RT.

Similar to Experiment 1, the influence of number of elements was not limited to RT. The one-target movement time advantage was also demonstrated (also see Adam et al., 2000; Chamberlin & Magill, 1989; Helsen et al., 2001; Lavrysen et al., 2002). Movement times to the first target were quicker when a single target response was required compared to when participants had to aim to a first target and then continue to their movement to a second target. Similar to the RT results, movement times to the first target were longer in both the single-limb and two-limb tasks compared to a single target task. Hence, the OTA remained present in the single-limb and two-limb tasks as in Experiment 1.

The current experiment also revealed that the OTA remained regardless of whether the second movement involved a short or long distance. It was possible that longer second amplitudes could result in more time for on-line programming during the execution of the second element resulting in a reduction in the OTA. However, this was not the case and the OTA was shown to be robust regardless of the distance of the second movement.

2.4 Experiment 3

2.41 Introduction

The previous experiment supported previous findings by Adam et al. (2000) that the OTA emerges regardless of the distance of the second movement. The magnitude of the OTA was not influenced by the amplitude of the second movement, and this was the case in both single-limb and two-limb tasks.

Experiment 3 aimed at further testing the robustness of the OTA in sequential aiming movements performed with two limbs. The movements involved in Experiment 2 had a constant distance for the first segment, where as the distance of the second movement varied. In the current experiment, the distance of the first movement was manipulated, whereas the distance of the second movement remained constant. Previous work by Adam et al. (2000: Experiment 4) showed that the OTA emerged in single limb movements when the first segment amplitude was manipulated while keeping the segment amplitude fixed.

Similar to Adam et al. (2000: Experiment 4), we manipulated the distance between the start position and the first target. It may be expected that reducing the distance travelled to the first target will reduce the magnitude of the OTA. This may be because the movement time is too short for the cognitive processes involved in implementing the second movement to take place. This may encourage more on-line programming during the second movement or longer PTs. In contrast, when the distance between the start position and the first target is relatively large, movement times should be sufficiently long to enable online processes to operate during the first segment. Hence, one would expect the OTA to

emerge from the implementation of the second segment during execution of the first segment.

2.42 Method

Participants

Participants were 14 volunteers (6 men, 8 women; M age = 22 years; SD = 3 years, age range = 19-32 years). All participants were self-declared right hand dominant, and had reported normal or corrected to normal vision. Consent forms were signed 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 apparatus was similar to Experiment 1 except that the distance of the first segment was manipulated (see figure 2.7). Short first target movements were 70mm between target 1 and target 2 (centre to centre) (i.e., Index of Difficulty = 2.5 bits, Fitts, 1954), and long first target movements were 260mm between target 1 and target 2 (centre to centre) (i.e., Index of Difficulty = 4.4 bits, Fitts, 1954).



Figure 2.7. Starting position of fingers, and the 2 conditions used in the study. a) Short first movement; b) Long first movement

Task and Procedure

Each participant completed 120 trials. For 60 trials, the distance from the start to first targets was 70mm (centre to centre). For the other 60 trials, the distance from the start and first targets was 260mm (centre to centre). Half the participants performed the short amplitude movement condition first, while the other half performed the long amplitude movement condition first. Similar to Experiment 2, participants performed one target (1T), two target single limb (2T1L), and two target two limb (2T2L) aiming tasks. For each movement amplitude, 20 trials were performed in each of the 1T, 2T1L and 2T2L tasks. The tasks were blocked with the order of the 3 tasks counterbalanced between participants.

Statistical Methods

The same dependent variables measured in Experiment 1 were also measured in Experiment 2. A 2 Movement Amplitude (short, long) x 3 Aiming Tasks (1T, 2T1L, 2T2L) repeated measures ANOVA was performed on RT and MT1. A 2 Movement Amplitude (short, long) x 2 Task (2T1L, 2T2L) repeated measures ANOVA was performed on PT and MT2. Tukeys HSD post hoc tests (Stevens, 2002, p.506) were performed on significant main effects and interactions.

2.43 Results

Trials in which RT was less than 100 msec or more than 700 msec and in which participants missed at least one of the targets were omitted from the analysis. This amounted to less than 2% of the trials. The means and standard deviations of all reported dependent measures are reported in Table 2.3.

	Short 1 st movement amplitude			Long 1 st movement amplitude		
	1T	2T1L	2T2L	1T	2T1L	2T2L
RT (ms)	241	265	273	259	277	282
	50	58	54	45	60	56
MT1 (ms)	127	155	155	241	265	254
	41	51	61	67	77	67
PT (ms)		111	99		112	105
		30	35		27	35
MT2 (ms)		188	229		180	199
		44	61		42	48

Table 2.3. Means and *standard deviations* of reaction time (RT), movement time to the first target (MT1), pause time (PT) and movement time to the second target (MT2). 1T = one target movement, 2T1L = two-target, one limb movement, 2T2L = two-target, two limb movement.

The main effect of Movement Amplitude approached conventional levels of significance ($F_{2,38} = 4.243$, p = 0.053, $\eta^2 = 0.06$). Reaction times were shorter for short movement amplitudes to the first target (M = 260 ms, SD = 55 ms) compared to long movement amplitudes to the first target (M = 272 ms, SD = 54 ms). Analysis of reaction time data revealed a significant main effect for Task ($F_{2,38} = 13.401$, p < 0.05, $\eta^2 = 0.21$). Reaction times were shorter in the 1T task (M = 250 ms, SD = 47 ms), compared to the 2T1L (M = 271 ms, SD = 47 ms) and the 2T2L (M = 277 ms, SD = 55 ms) tasks (see figure 2.8). There was no difference in RT between the 2T1L and 2T2L tasks. There was no interaction between Movement Amplitude and Task ($F_{2,38} = 0.630$, p = 0.538, $\eta^2 = 0.006$).



Figure 2.8. Reaction times to the first target (MT1) for Single Target (1T), Two-Target, Single Limb (2T1L) and Two-Target, Two-Limbs aiming tasks (data is collapsed over both movement amplitude conditions). Error bars represent standard error of the mean. * Significance at p < 0.05.

As expected analysis of movement time to the first target (MT1) revealed a significant main effect for Movement Amplitude ($F_{2,38} = 364.258$, p < 0.05, $\eta^2 = 0.84$). Movement times were shorter when amplitude to the first target was short (M = 146 ms, SD = 52 ms) compared to when amplitude to first target was long (M = 253 ms, SD = 70 ms). The analysis also revealed a significant main effect for Task ($F_{2,38} = 15.130$, p < 0.05 $\eta^2 = 0.036$). Tukeys post hoc test revealed that MT1 for single target movements (M = 184 ms, SD = 54 ms) were significantly shorter than the 2T2L (M = 204 ms, SD = 64 ms) and 2T1L (M = 210 ms, SD = 64 ms) tasks (see figure 2.9). There was no difference in MT between the 2T1L and 2T2L tasks. There was no Movement Amplitude by Task interaction ($F_{2,38} = 1.978$, p = 0.152, $\eta^2 = 0.003$).



Figure 2.9 Movement times to the first target (MT1) for Single Target (1T), Two-Target, Single Limb (2T1L) and Two-Target, Two-Limbs aiming tasks (data is collapsed over both movement amplitude conditions). Error bars represent standard error of the mean. * Significance at p < 0.05.

Analysis of movement time to the second target (MT2) revealed a significant main effect for Movement Amplitude ($F_{1,19} = 8.319, p < 0.05, \eta^2 = 0.099$). Movement times to the second target were longer when the movement amplitude to the first target was short (M= 208 ms, SD = 56 ms) compared to long (M = 190 ms, SD = 45 ms). A main effect for Task ($F_{1,19} = 18.177, p < 0.05, \eta^2 = 0.26$) was also revealed. Movement times were shortest in the 2T1L condition (M = 184 ms, SD = 43 ms) compared to 2T2L (M = 214 ms, SD = 56ms). A Movement Amplitude x Task interaction was also revealed ($F_{1,19} = 7.052, p < 0.05,$ $\eta^2 = 0.037$). Post hoc tests revealed that in both short and long first movement amplitudes, movement times to the second target were significantly faster in the 2T1L tasks compared to 2T2L. The differences between the 2T1L and 2T2L tasks were significantly greater when the first movement amplitude was short (41ms difference) compared to long (19ms difference). The analysis of mean pause times (PT) revealed no significant *F*-values for Movement Amplitude ($F_{1,24} = 0.543$, p = 0.470, $\eta^2 = 0.009$) or Task ($F_{1,24} = 3.464$, p = 0.078, $\eta^2 = 0.059$). There was no interaction between Hand Condition and Task ($F_{1,24} = 0.257$, p = 0.618, $\eta^2 = 0.003$) (overall M = 107 ms, SD = 32 ms). The present experiment examined whether the influence of manipulating the distance of the first movement had any effect on the magnitude of the OTA in two-limb movements.

Consistent with past research (Klapp, 1995, 2003; Khan et al., 2006, 2007) and Experiment 1, RT was greater when a two-target response had to be performed compared to a single target response. This was the case when the two-target response was performed with a single limb and when the participants switched hands at the first target. Hence, increasing the number of elements in a response where the distance of the second movement was manipulated increased RT. Also, RTs were longer for two segment movements compared to single target movements regardless of the amplitude of the first movement.

Similar to the RT results, the one-target movement time advantage was also demonstrated with movement times to the first target. Movement times were longer in conditions where participants had to perform a movement to two-targets compared to a single target response. Similar to Experiment 1 and 2, the OTA was present whether participants performed a two-target movement with a single-limb or with two-limbs. The experiment also revealed that the OTA remained regardless of whether the first movement involved a short or long distance.

The results from the present experiment suggest that the OTA was not influenced by movement distance of the first target. It may have been that reducing the distance travelled to the first target would have reduced the magnitude of the OTA since insufficient time may have been available for the cognitive processes involved in implementing the second movement to take place. However, this was the not the case and the OTA was shown to be a robust phenomenon regardless of the distance of the first movement.

2.5 General Discussion

Increasing the number of response segments from one to two has been shown to increase the time taken to initiate and execute the first segment in the sequence. This finding implies that individual elements in a response are not functionally independent. There has been considerable debate about the nature of the interdependency that may exist between response segments. In the present study, we addressed this issue by comparing response times in single and dual limb sequential aiming movements in which the limb was switched at the first target.

Consistent with previous studies, reaction time was longer in the two-target condition than it was in the one target condition. This was the case when aiming movements to the first and second targets were performed with the same limb and when participants switched hands at the first target. Hence, the planning processes that underlie the increase in reaction time for multiple segment responses were not restricted to the use of one limb. Using speech articulation, Klapp (2003) has shown that RT increased as a function of the number of syllables when the number of syllables was known in advance of the stimulus but not the actual syllables themselves. Similarly, Khan et al. (2007) have shown that RT was longer for two than for single target movements when the amplitude of both movements was not known until stimulus presentation. Hence, it seems that RT increases as a function of the number of segments when the number of segments is known in advance but not other specifics of the response. Klapp (2003) proposed that when the number of segments is known in advance, an abstract time frame that specifies the order and timing of individual segments but does not contain information on the specific action is loaded in short term memory (STM). Upon presentation of the stimulus, the

implementation or reading out from STM of this time frame takes longer as the number of segments increases thereby leading to a lengthening of RT. Although participants in the present study had prior knowledge of whether a single or two limb response was required, our results are consistent with past findings that have revealed a direct relation between RT and the number of response segments regardless of the specific action that was required.

The influence of the number of response segments was not limited to the RT interval. Movement times to the first target were greater when participants were required to move to a second target compared to when they were required to stop on the first target (i.e., the OTA). Similar to the RT results, there was an increase in movement time to the first target for both the single and dual limb two-target conditions. Hence, the processes underlying the OTA are not limited to movements performed with one limb. Similar to single limb movements, sequential aiming movements that involve more than one limb require longer preparation intervals prior to movement execution and more time during movement execution.

The presence of the OTA for the present two limb movement task cannot be explained by the movement constraint hypothesis (MCH). The MCH assumes that the all programming operations are completed before the start of the first movement and, moreover, that spatial variability increases as movement progresses (Fischman & Reeve, 1992). Hence, accuracy at the second target depends on the variability of the movement endpoints at the first target. In the two limb condition of the present study, however, the limb was switched at the first target and hence the starting point for the movement to the second target was fixed. In other words, the start position of the movement to the second target did not depend on where the first movement ended. Since endpoint variability at the

first target was not relevant to the production of the second movement, there was no need to constrain or reduce variability of movement endpoints at the first target. Hence, the presence of a robust OTA in the dual limb condition that was of similar size to the single limb condition does not accord with the movement constraint hypothesis of the OTA. It should be noted however that a movement constraint explanation cannot be ruled out for single limb movements where controlling spatial variability might be more critical under higher accuracy demands.

According to the movement integration hypothesis (MIH) (Adam et al., 2000), the processes associated with the production of a second movement are implemented during the execution of the first movement to enhance the transition between response elements. This overlap between processes underlying the first and second movements leads to interference and hence the OTA. As suggested by Adam et al., there are two possible loci for the interference effect. At a central level, interference may be associated with the retrieval of motor programs from a motor buffer. At a more peripheral or local level, interference may stem from the implementation (translation) of these motor commands into muscle activity to execute the movements. These results reveal the recruitment of extra and even new agonist activity during the execution of the first movement for the benefit of the second movement.

This difference in muscle recruitment pattern for one- and two-element movements is consistent with a peripheral account of the OTA (peripheral alterations in muscle recruitment pattern may influence movement time). However, it does not support it unequivocally because it is also fully compatible with a central account. This is because differences in muscle recruitment pattern also indicate differences in underlying central

motor programs. Hence, for the single limb aiming task employed in the present study, it is possible that both central and peripheral sources are contributing to the OTA. However, for the dual limb aiming task, which introduces a switch between hands at the first target, peripheral factors play a very minor role. Our results showed that the OTA emerged for both single and two limb movements and the magnitude of the OTA was similar for both conditions. Hence, the processes that led to interference during execution of movement towards the first target were effector-independent and thus appear to originate at a more central rather than peripheral level.

Movement times to the second target were generally greater in the dual-limb twotarget condition compared to the single limb two-target condition. One possible explanation for this could be that in the two-limb condition, the second target movement is initiated from a rest position while in the single limb condition; the limb is already active prior to the start of the second target movement. Alternatively, it could be that performing the second movement with the non-dominant hand (left hand) in the two-target two-limb task produces slower movement times. It has been suggested that the dominant right hand is usually superior at movement execution (see Elliott & Chua, 1996, for a review), specifically in accuracy and movement time (Roy, 1983; Roy & Elliott, 1986; 1989; Roy, Kalbfleisch & Elliott, 1994); whilst the non-dominant left hand usually enjoys a reaction time advantage in goal directed aiming (Mieschke et al., 2001). This may be a consequence of the right hand superiority in making smaller adjustments to the movement trajectory as the limb approaches the target area (see Carson, 1996, for a review). It is also suggested that the right hand/left hemisphere system is able to process visual feedback information faster and more efficiently than the left hand/right hemisphere system (Flowers, 1975; Roy,

1983; Roy & Elliott, 1986). Hence, one would expect movement times to be quicker in the 1T1L condition since the right hand performs the second target movement while the left hand performs the second target movement in the 2T2L condition.

This chapter has shown that the OTA emerged regardless of movement amplitude to the first or second segment, hence further showing the robustness of the OTA. By showing that movement amplitude did not affect the OTA, the results from this chapter suggest that the OTA was not influenced by the potential for more online programming. Perhaps there is some central level mechanism that leads to the OTA such as the timing of the implementation of the second movement. As mentioned previously, in the two limb sequential aiming task, the start position of the second movement was fixed at the beginning of each trial. Hence, in contrast to the single limb condition, the amplitude of the second movement was not dependent on where the first ended. However, for both single and two-limb movements, the timing of the implementation of the second movement remained crucial to ensure a fast transition between response elements. Using a dual-task procedure, Ketelaars et al. (1999) have demonstrated that the onset of agonist activity for the second segment was influenced by when the secondary task stimulus was presented. Based on the re-organization of muscle activity underlying the primary and secondary task into one conjoint response, they suggested that timing the implementation of the second element may have been the cause of interference in the dual task procedure. Integrating this finding with the role of vision, Khan et al. (2006) have proposed that when participants know in advance that a two-target response is required, MT to the first target is lengthened so that the execution of the first segment is visually monitored to decide when the second movement should be implemented. Of course, it is also possible that proprioceptive

information is used to perform this control function (e.g., Abbs & Winstein, 1990). Hence, in the two-limb aiming movements of the present study, it is perhaps the central processes associated with the timing of the implementation of the second element that are responsible for the interference that leads to the OTA. This conclusion indicates that execution of a simple series of two fast movements is not controlled in an "automatic", interference-free, manner, but instead may suffer a cost due to online implementation operations. This suggests that pre-planned and online processes may work in tandem to produce rapid movement sequences.
Chapter 3

Sequential aiming with two-limbs: the effect of target size

3.1 Introduction

Consistent with previous research on single limb sequential aiming movements, the previous chapter revealed that the OTA emerged for two-limb sequential aiming regardless of changes in movement amplitude for the first and second movement. In the current chapter the influence of target size on two limb sequential aiming movements was examined.

For single limb aiming, the movement integration hypothesis (MIH) predicts that the OTA would disappear under high accuracy demands (Adam et al., 2000) because increased pause times at the end of the first segment would disrupt the transition between movements (Adam & Paas, 1996; Adam et al., 1995; Adam et al., 2000; Rand & Stelmach, 2000). Consistent with this prediction, Adam et al. (2000) showed that when target size was reduced movement times to the first target were similar for single and two target aiming movements. This was accompanied by increased pause times suggesting that the two segments were performed independently.

The goal in the present research was to test whether the OTA would emerge when there is a transfer between limbs during sequential aiming movements in both small (1cm) and large (3cm) target conditions. An optotrak motion analysis recording system was used to record kinematic data. In tasks when participants are performing movements to large targets it could be hypothesised that the OTA would remain in both single-limb and twolimb movements. However, when performing movements to small targets it may be expected that the OTA would not emerge in the single-limb condition. This could be due to

the additional accuracy demands required at the first target. As mentioned earlier, pause times between the two movements would be relatively long, disrupting the transition between movements. In the task where participants are performing a movement to small targets using two-limbs, you may expect the OTA to remain. This may be due to the end location of the first movement not being relevant to the starting position of the second movement. Therefore, it is possible that the two-movements may be processed together which may cause this extra interference and lead to the OTA.

Variability has been shown to increase as the movement progresses, hence movements are constrained at the first target in order to be accurate at subsequent targets. This is known as the movement constraint hypothesis (MCH) (Fischman & Reeve, 1992). According to the MCH, variability at the first target should be highest in tasks where participants perform a two-target task with the same limb. Whether the task is a single target task or a two-target task using two limbs, the end position of the first movement does not matter for future movements, unlike in the two-target single-limb task. Hence, in the two-target single-limb task, smaller variability should be present at target 1.

3.2 Method

Participants

Participants were 24 volunteers (12 men, 12 women; M age = 21 years; SD = 3 years, age range = 18-25 years). Participants were self-declared right hand dominant, and reported normal or corrected to normal vision. Consent forms were signed prior to the start of 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. A sheet of plexi-glass 5 mm thick covered the monitor surface and was flush with the table top. Targets were presented on the monitor. Two small infrared-emitting diodes (IREDs) were positioned on the end of two thimbles which participants placed on their index fingers. Positions of these markers were measured using an Optotrak (Northern Digital Inc) three-dimensional movement analysis system at a sampling rate of 500Hz.

Circular targets were arranged in sets of 3 pairs along the participants' midline (see Figure 3.1). Target sizes were either 1cm or 3cm in diameter. The distance between each target in a pair was 40mm (centre to centre), and the distance between each pair was 100mm (centre to centre; i.e., Small Targets Index of Difficulty = 4.3 bits, Large Targets Index of Difficulty = 2.7 bits [Fitts, 1954]). Participants were positioned so that they could easily contact each target with their index fingers. The most distal targets were the start

positions. The middle targets were designated as target 1 and the most proximal targets as target 2.



Figure 3.1. Starting position of fingers for right hand dominant movements, and the 3 conditions used in the study. a) Single target (1T); b) Two-target, single limb (2T1L); c) Two-target, two limbs (2T2L).

Procedure

The aiming tasks were performed in right hand conditions. In the right hand condition, participants' placed their right index finger on the start position (top right target) and their left index finger on target 1 (left middle target) (see figure 3.1).

Participants performed 3 aiming tasks under each target size condition. In the one target (1T) task, participants moved their hand from the start position and moved to target 1 (see figure 3.1a). The other hand remained stationary on target 1. In the two target, single limb (2T1L) task, participants moved their hand from the start position to target 1 and then to target 2, contacting both targets with their index finger (see figure 3.1b). The other hand remained stationary on target 1. In the two target 1 and then aremained stationary on target 1. In the two target, two limb (2T2L) task, participants moved their hand from the start position to target 1 and then to target 1 hand from the start position to target 1 and then moved their hand from the start position to target 1 and then moved their other hand from its position on target 1 to target 2 (see figure 3.1c). Participants were told not to start the second movement until the first had been completed, but to make this changeover as quick as possible.

The aiming tasks were performed under two target size conditions. In the small target condition targets had a 1cm diameter, whilst in the large target condition targets had a 3cm diameter.

At the beginning of each trial, participants were presented with a warning tone which was then followed by a stimulus tone after a 2000-3000 ms variable foreperiod. Participants were instructed to react and perform the movement(s) as quickly as possible.

Each participant completed 120 trials (60 in the small target condition and 60 in the large target condition). Half the participants performed the small target condition first while the other half performed the large target condition first. In each condition, 20 trials were performed in the 1T, 2T1L and 2T2L tasks. The 3 tasks were blocked and counterbalanced between participants.

Data Reduction

The 3D position data from the Optotrak were filtered using a second order, dualpass Butterworth filter with a low pass cut-off frequency of 16Hz. Position data were then filtered to obtain velocity information. Peak resultant velocity was identified for movements to each target. The start of the 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 than 15mm/s. The end of the first movement was the point in which velocity in the vertical velocity fell below 15mm/s.¹ This process was repeated for the start and end locations of the second movement. At the end of each movement segment and at peak resultant velocity for each segment, position coordinates were

¹ The velocity in the vertical direction was used to locate the start and end of movements since sliding of the thimbles on the table top made it difficult to locate velocity zero line crossings in the horizontal plane.

recorded in the primary direction of the movement (i.e., x-axis) and perpendicular to the primary movement (i.e., y-axis)

Statistical Methods

Dependent measures consisted of reaction time (RT), movement time to the first target (MT1), movement time from the first target to the second target (MT2), pause time at target 1 (PT), ellipse area at peak velocity of the first movement (PkV1 EA), ellipse area at the end of the first movement (End1 EA), ellipse area at peak velocity of the second movement (PkV2 EA), ellipse area at the end of the second movement (End2 EA). Ellipse areas were calculated at peak velocity and at the end of movements for each segment using the within-participant standard deviations of position along the y and x axes as the radii (π x SDx x SDy) (Hansen, Elliott and Khan, 2008).

A 2 Target size condition (small, large) x 3 Task (1T, 2T1L, 2T2L) repeated measures ANOVA was performed on RT, MT1 and EA1, whilst a 2 Target size condition (small, large) x 2 Task (2T1L, 2T2L) repeated measures ANOVA was performed on PT, MT2 and EA2. Tukeys HSD post hoc tests were performed on significant main effects and interactions.

3.3 Results

Trials in which RT was less than 100 msec or more than 700 msec and in which participants missed at least one of the targets or initiated their second segment prior to completing the first were omitted from the analysis. This amounted to less than 5% of the trials. The means and standard deviations of all dependent measures for the left and right hand conditions are reported in Table 3.1.

	S	Small Targets		Large Targets			
	1 T	2T1L	2T2L	1T	2T1L	2T2L	
RT	290	307	304	271	297	290	
	66	55	58	54	60	60	
MT1	306	319	321	226	267	265	
	67	56	74	35	51	48	
MT2		285	311		238	276	
		73	69		66	61	
PT		144	91		87	70	
		80	57		58	44	
PkV1 EA	124	108	100	110	126	112	
	84	72	93	73	86	125	
End1 EA	35	27	34	56	47	39	
	11	11	16	24	29	15	
PkV2 EA		107	166		142	220	
		58	169		172	282	
End2 EA		30	42		46	48	
		11	22		24	19	

Table 3.1. Means and *standard deviations* of reaction time (RT), movement time to the first target (MT1), movement time to the second target (MT2), pause time (PT), ellipse area at peak velocity of movement 1 (PkV1 EA), ellipse area at the end of movement 1 (End1 EA), ellipse area at peak velocity of movement 2 (PkV2 EA) and ellipse area at the end of movement 2 (End2 EA) for the one target (1T), two-target, one limb movement (2T1L), and two-target, two limb (2T2L) tasks.

Analysis of reaction time revealed a significant main effect for Target size ($F_{1,23} = 5.293, p < 0.05, \eta^2 = 0.19$) and a main effect for Task ($F_{2,46} = 8.002, p < 0.05, \eta^2 = 0.26$). Further analysis showed that RTs were quicker when the target sizes were large (286ms) compared to small (301ms). Tukeys post hoc test also revealed that RTs were quicker in the 1T condition (281ms) compared to both 2T1L (302ms) and 2T2L (296ms) conditions. There was no Target size by Task interaction ($F_{2,46} = 0.388$, p = 0.68, $\eta^2 = 0.017$).

Analysis of movement time to the first target (MT1) revealed a main effect for Target size ($F_{1,23} = 74.997$, p < 0.05, $\eta^2 = 0.77$) and Task ($F_{2,46} = 15.774$, p < 0.05, $\eta^2 = 0.41$). Further analysis revealed that MT1s to small targets (316ms) were slower than those to large targets (253ms). Tukeys post hoc test revealed that MT1s for responses where two movements were required (i.e. 2T1L, 294ms; 2T2L, 293 ms) were slower than responses which only required a single target movement (i.e. 1T, 266ms). A Target size by Task interaction was also revealed ($F_{2,46} = 3.264$, p < 0.05, $\eta^2 = 0.12$). Follow up tests revealed that in the large target condition, the 1T task had quicker MT1s than both the 2T1L and 2T2L tasks. In the small target condition, there were no significant differences between the 3 tasks (see figure 3.2).



Figure 3.2. Movement Times to the first target (MT1) in each of the 3 tasks, in both the small and large target conditions. Error bars represent standard error of the mean.

Analysis of movement time to the second target (MT2) revealed a main effect for Target size ($F_{1,23} = 41.388$, p < 0.05, $\eta^2 = 0.64$). MT2s were quicker in the large target condition (257ms) compared to the small target condition (298ms). A main effect for Task was also revealed ($F_{1,23} = 10.707$, p < 0.05, $\eta^2 = 0.32$). MT2s were slower when participants had to switch limb at the first target (2T2L) (293ms) compared to when the same limb performed both the first and second movements (2T1L) (262ms). No Target size by Task interaction was revealed ($F_{1,23} = 1.341$, p = 0.259, $\eta^2 = 0.06$).

Analysis of pause times (PT) revealed a significant main effect for Target size ($F_{1,23}$ = 22.343, p < 0.05, $\eta^2 = 0.49$). Quicker PTs were present in the large target (78ms) compared to the small target condition (117ms). A main effect for Task was also revealed ($F_{1,23} = 8.252$, p < 0.05, $\eta^2 = 0.26$). PTs were quicker when participants switched limb at the first target (2T2L) (81ms) compared to when participants used the same limb for performing both the first and second movements (2T1L) (115ms). Analysis also revealed a Target size by Task interaction ($F_{1,23} = 8.806$, p < 0.05, $\eta^2 = 0.28$). Tukeys HSD post hoc test revealed no significant difference between PTs in the large target condition, but in the small target condition PTs were significantly longer in the 2T1L task (144ms) than the 2T2L (91ms).

Analysis of the ellipse areas at the end of movement 1 (End1 EA) revealed a main effect for Target Size ($F_{1,23}$ = 25.622, p < 0.05, $\eta^2 = 0.53$). Smaller targets (32mm²) had smaller ellipse areas at the first target than large targets (47mm²). A main effect was also revealed for Task ($F_{2,46}$ = 4.548, p < 0.05, $\eta^2 = 0.17$). The single target response (1T)

(45mm²) had a larger ellipse area at the first target than both the 2T1L (37mm²) and 2T2L (36mm²) conditions. Finally, a Target size by Task interaction was also present ($F_{2,46}$ = 4.183, p < 0.05, $\eta^2 = 0.15$). Post hoc analysis revealed no difference between the 3 tasks in the small target condition, whereas there was a significant decrease in the large target condition between the 1T and 2T2L tasks. There were also significant differences between the large and small target condition in the 1T and 2T1L tasks, however no difference between target sizes in the 2T2L task (see figure 3.3).



Figure 3.3. Ellipse areas at target 1 in all 3 task conditions for a) small targets and b) large targets. Error bars represent standard error of the mean.

Analysis of ellipse areas at the end of the second movement revealed a main effect for Target size ($F_{1,23}$ = 7.907, p < 0.05, $\eta^2 = 0.26$). Similar to the first segment, ellipse areas were smaller in the small target condition (36mm²) compared to the large target condition (47mm²). A main effect for Task was also present ($F_{2,46}$ = 4.745, p < 0.05, $\eta^2 = 0.17$). Ellipse areas were smaller at the end of the second movement when participants performed the 2T1L task (38mm²) compared to the 2T2L task (45mm²). However, there was no Target size by Task interaction ($F_{2,46}$ = 2.741, p = 0.11, $\eta^2 = 0.11$).

3.4 Discussion

Increasing the number of targets in a sequence has been shown to increase the time taken to initiate (Klapp, 1995, 2003; Khan et al., 2007) and execute (Glencross, 1980; Adam et al., 2000) the first segment in the sequence. This finding implies that the two movements are not functionally independent of each other. The OTA has been revealed for both single limb responses and tasks in which two limbs are used. When target sizes are small in single limb responses, the OTA does not emerge. Under high accuracy demands pause times between the two movements are relatively long thereby disrupting the transition between movements (Adam & Paas, 1996; Adam et al., 1995; Adam et al., 2000; Rand & Stelmach, 2000). This implies that the two movements are processed separately into individual units, where each movement has its own preparatory and control processes. Hence, there is neither integration between units nor the OTA. In the current study, the influence of target size in tasks using two-limbs was investigated.

Reaction times were longer in the two-target condition than in the single-target condition. This was the case regardless of whether the two-target condition was performed with a single-limb or when the participants switched hands at the first target. Hence, as shown by Khan et al. (2010), the planning processes involved with the increase in reaction time were not restricted to one-limb. The results from the present study are consistent with past findings in which there is a direct relationship between reaction time and the number of elements in a response, regardless of the specific action that was required (Klapp, 2003; Khan et al., 2007).

The influence of the number of response segments was not limited to reaction times. Movement times to the first target were shorter when participants were instructed to stop on the first target compared to when they were instructed to hit the first target and then proceed and hit a second target (i.e. one-target advantage). Regardless of whether the two-target movement consisted of a single-limb response or a two-limb response, the OTA was present. However, when the results were separated according to the size of the targets, the OTA only remained in the large target condition (41ms OTA in the two-target single limb task [2T1L], 39ms OTA in the two-target task where participants switched limbs at the first target [2T2L]). Similar to Adam et al. (2000), when the size of the targets were small, the OTA failed to materialise. Hence, it seems as though the small targets caused the two movement segments in both the 2T1L and 2T2L tasks to be decomposed into separate units. Therefore the integration between the segments was minimal.

The movement integration hypothesis (MIH) (Adam et al., 2000) states that the processes associated with the production of a second movement are implemented during the execution of the first so that the transition between the response segments is enhanced. The overlap of processes involved in the movement to the first target caused by the influence of a second target leads to interference and the OTA. With respect to the size of the targets, the MIH predicts that small targets should make the OTA disappear. This is because small targets are characterised by long pause times on the first target which reduce the overlap of control processes underlying the first and second movements. The two movements are composed into separate units, with each movement having independent preparatory and control processes.

In the present study, pause times for the two-target responses with a small target were longer than the large target. This supports the MIH which predicted that small targets are characterised by longer pause times. This implies that the two segments were performed independently and hence the OTA did not emerge. Pause times were also shown to be quicker for responses which involved a two-limb compared to a single-limb response.

The movement constraint hypothesis (MCH) (Fischman & Reeve, 1992) claims that the requirements of performing a second movement constrain the execution of the first movement to ensure accuracy at subsequent targets are met (Sidaway et al., 1995). Specifically, Fischman and Reeve (1992) state that participants might adopt a strategy of constraining the limb as it approaches the first target in order to smoothly and quickly execute the second movement. By constraining the limb at the first target, it can also provide an ideal starting position for the limb to start the second movement.

In Chapter 2 participants performed a single-target task, and two two-target tasks where participants performed both movements with the same limb, or switched limbs when they reached the first target. In the two-target single limb task, implementation of the second movement was dependent upon two factors. The first factor was the endpoint location of the first movement. If an undershoot occurred at the first target, the distance required to reach the second target would increase, and vice versa. Endpoint location at the first target also affects variability at the second target. This is based on the premise that variability increases as the movement progresses. A second additional factor that is important for efficient transition between elements is the timing of the implementation between elements. In the two-target two-limb task, the start position of the second

movement was always fixed and not dependent upon the end location of the first movement. Hence, the presence of the OTA in the two-target two-limb task in Chapter 2 does not accord with the MCH. However, variability was not measured so the MCH cannot be ruled out.

The present study used kinematic data to analyse ellipse area variability at the end of both movements. As expected, in the small target condition there were no significant differences in ellipse areas at the first target between the three tasks. As target sizes were small, it is likely that movements were constrained and controlled in order to produce an accurate movement. In the large target condition ellipse areas at the first target had a tendency to be smaller in the two-target single-limb task compared to the single-target task. This may suggest that movements in the 2T1L task were constrained in order to maintain accuracy at subsequent targets. However, in the two-target two-limb task, ellipse areas at the end of the first movement decreased even further, suggesting that more constraining was taking place compared to the two-target single-limb task. This was surprising since movement to target 1 and target 2 were performed with different limbs. This result provides evidence for the MCH in the 2T2L task, and is further supported when the ellipse area at the first target in the 2T2L task in the large target condition had a similar ellipse area to the 2T2L task in the small target condition. It may be possible that participants use the position of the second hand as an extra target to assist in the quick transition between target movements. By concentrating on the location of the second hand, the final end position of the first movement may be positioned closer to the start position of the second movement. This may give more control in changing limbs between movements. Although a difference

in pause times was not seen in the large targets condition, there was a slight tendency for quicker pause times in the two-target two-limb task, suggesting that a quicker transition was taking place between movements.

This chapter shows once again, the OTA materialising in both single-limb, and twolimb two target movements (Khan et al., 2010), but only in the large target condition. As shown by Adam et al., (2000), the present study also shows that the OTA failed to materialise in the small target condition in both single-limb, and two-limb tasks. By using kinematic analysis, the study also showed that in the large target condition, the two-target single-limb and two-limb tasks shared similar ellipse areas at the end of the first movement. This shows support for the MCH (Fischman & Reeve, 1992) in both the two-target singlelimb, and more interestingly in the two-target two-limb tasks.

Chapter 4

Interdependency of movements in multiple target aiming

4.1 Introduction

In both everyday life and in sporting situations, people are required to perform skills quickly and accurately. Whether this involves catching a falling cup from a table or shooting targets in a 25 metre rapid fire pistol competition, the need to be fast whilst maintaining a high degree of accuracy is very important. The following chapter aims to examine the optimisation of multiple target movements.

Meyer et al. (1988) introduced the optimized submovement model, which holds that movement time is minimised by establishing a trade off between the initial impulse and error correction phases. According to this model, over a series of attempts the performer will produce a normal distribution of movement endpoints centred on the middle of the target. If the initial impulse falls outside of the target boundaries then a corrective submovement is required. However, the central tendency principle of the optimized submovement model is not consistent with a lot of research that suggests that performers are more likely to undershoot a target rather than overshoot (Elliott et al., 2001; Elliott et al., 2004; Engelbrecht, Berthier & O'Sullivan, 2003). This has been suggested because under normal circumstances, there is a greater cost of time and energy associated with reversing direction following a target overshoot. In conditions where an undershoot occurs, the limb already has a positive velocity in the direction of the corrective submovement (Elliott et al., 1999). A study by Oliveira et al. (2005) created a situation where using less energy would result in a target overshoot and using more energy resulting in a target undershoot. Their study involved 2 tasks; the first involved propelling a slider along a track with the intention of having the slider stop at or as close as possible to the target. The

second task was the similar to the first task, however, in the second task participants had to apply a force against an assistive force (rubber tube). It is important to note that in this task, if participants simply let go of the slider from the start position, then the slider would overshoot the target. Their results showed an undershoot bias in the unassisted condition and an overshoot bias in the assisted condition. This suggested that the undershoot bias might be the result of a general energy minimisation bias.

Lyons, Hansen, Hurding & Elliott (2006) examined the degree to which primary movement endpoint distributions depended on the direction of the movement with respect to gravity. Participants performed a single target aiming task both towards and away from the body on a horizontal orientation, and both an upward and downward movement on a vertical orientation. Results revealed that undershoots were more pronounced in the task where participants performed a downward movement on the vertical orientation, and that the primary movement in the upward movement took the participants closer to the target than in any other condition. This was the case as the cost of overshooting in this particular condition is greater due to overcoming the inertia of zero velocity at the point of reversal and performing the reversal against gravity. These results are consistent with energy minimisation strategies that suggest that movements are organised to minimise energy expenditure and movement time, whilst maximising mechanical advantages just as shown by Oliveira et al. (2005).

Sidaway, Sekiya and Fairweather (1995) examined the effect of varying the accuracy demands of a second target on the variability of movements to the first target of a constant size. Performers performed a two-target movement to a large first target (8cm), followed by a second movement to a smaller second target which varied in size (1.5cm and

6cm). Results from the study revealed that reaction times and movement times to the first target were slower when the second target was small (1.5cm) compared to the larger target (6cm). Also, a smaller last target constrained movement variability on the first target more than the larger last target did, even though the size of the first target was constant between conditions.

In the present study, the principles of movement optimization in single target aiming were extended to two-target sequential aiming movements. The present study aims to investigate the optimal position of a varying first target location in a two-target aiming task. The effect of varying target sizes of target 1 and 2 on movement optimisation was also investigated. The study examined whether having the first target close to the second target produced faster movement times, and the role the size of the second target had on the error variability at the first target. As Elliott et al., (2004) showed when "sneaking up" occurs in single target movements, movement times and energy expenditure is decreased. Of interest was whether this strategy can carry across into multiple target aiming

The study comprised of 4 experiments. Experiment 1 examined movements involving small targets. Experiment 2 examined at movements going to a large target followed by a movement to a second smaller target. Experiment 3 involved movements to a small first target followed by a second movement to a larger target. Both targets in experiment 4 were large targets. Of specific interest in the study was the effect of reducing the size of the second target when the first target size remained constant. Previous research has suggested that variability in distance travelled increases as the movement distance increases. This is because any errors that occur early in the movement would be magnified

at latter stages of the movement (Khan et al., 2003a; Khan, Lawrence, Franks & Elliott, 2003b). According to the statement above, movement variability should increase as the distance of the targets increases. However, the movement constraint hypothesis (MCH) states that the first movement in a two-element movement is performed in a controlled manner to provide an ideal starting position for the start of the second movement (Fischman & Reeve, 1992). Does the extra demand of a smaller second target further constrain movements at the first target, even if the size of the first target remains constant? The movement integration hypothesis (MIH) suggests that smaller targets will disrupt the integration between elements due to the increased accuracy demands at the targets. This will result in longer movement times and pause times. With large targets, transition is easier as the accuracy demands are reduced, allowing quicker movement times. It may also be possible that when two targets in a movement have the same distance, it may be easier to integrate the segments since the parameters for both movements are the same. Hence total movement times may be shorter when the first target is halfway between the start and second target compared to when the first target is closer to the second target.

4.2 Method

Participants

Participants were 80 volunteers (47 men, 33 women, M age = 20.9 years; SD = 2.3 years, age range = 18-30 years) (20 participants in each of the 4 experiments). 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 75cm 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. A sheet of plexi-glass 5mm thick covered the monitor surface and was flush with the table top. Participants wore a thimble on their right index finger. The position of the thimble was recorded by a small infrared-emitting diode (IRED) that was secured at the end of the thimble. The IRED was monitored using an Optotrak (Northern Digital Inc) three-dimensional movement analysis recording system at a sampling rate of 500 Hz (resolution 0.01mm).

Procedure

The task consisted of a two target sequential aiming movement. Participants were seated so that they were positioned in line with the second target, with the start position 300mm to the right of target 2. These targets remained in the same position for each trial. The position of the target 1 varied from trial to trial. Target 1 could appear at 1 of 5 locations (50, 100, 150, 200 and 250mm) to the left of the start position (see figure 4.1).



Fig.4.1. Diagram illustrating position of start, target 2, and 5 locations of target 1.

At the beginning of each trial, participants positioned their right index finger on the start position. A warning tone was presented and then following a variable foreperiod (1500-2500ms), the two targets appeared. Participants were informed that as soon as the targets appeared, to react and move as quickly as possible to the two targets in sequence. Key emphasis was made on being accurate at both targets. The only difference between experiments was the size of the targets (Large targets = 30mm diameter, Small targets = 10mm diameter). Combinations of target sizes resulted in four experimental conditions (L-L, L-S, S-L, S-S). In Experiment 1, participants performed the L-L target size condition. In Experiment 2, participants performed the S-S target size condition. In Experiment 3, participants performed the L-S target size condition. In Experiment 4, participants performed the S-L target size condition. Participants performed 1 of the 4 experiments (between groups design). Participants performed 100 trials (20 trials for each of the 5 target 1 locations).

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 16Hz. Position data were then filtered to obtain velocity information. Peak resultant velocity was identified for movements to each target. The start of the 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 than 15mm/s. The end of the first movement was the point in which velocity in the vertical velocity fell below 15mm/s.² This process was repeated for the start and end locations of the second movement. At the end of each movement segment and at peak resultant velocity for each segment, position coordinates were recorded in the primary direction of the movement (i.e., y-axis) and perpendicular to the primary movement (i.e., x-axis)

Statistical Methods

A 4 Target size (L-L, L-S, S-L, S-S) x 5 Target 1 distance (T1(50), T1(100), T1(150), T1(200), T1(250)) ANOVA with repeated measures on the Target 1 distance was performed on reaction time (RT), total movement time (total MT), movement time to the first target (MT1), movement time to the second target (MT2), pause times (PT), ellipse areas at the first target (EA1) and ellipse areas at the second target (EA2). Ellipse areas were calculated by multiplying the x error, y error and pi (π) together. In the case of total ellipse area (Total EA), the ellipse area of target 1 (EA1) was added to the ellipse area of target 2 (EA2). The primary analyses of interest are TMT and EA1as these will be

 $^{^{2}}$ The velocity in the vertical direction was used to locate the start and end of movements since sliding of the thimbles on the table top made it difficult to locate velocity zero line crossings in the horizontal plane.

analysed to see if the accuracy demands of the second target have any effect on the variability at the first target, and provide a measure of optimal performance in terms of movement time. Additional dependent variables are analysed to examine whether they follow expected patterns.

One-way ANOVA's for the individual conditions were performed if any interactions were revealed in the main analyses. Bonferroni's post hoc test was performed to identify any significant differences in main effects of Target size, and Target 1 distance, and in interactions of between Target size and Target 1 distance.

It has been hypothesised that TMT's will be quicker when the first target is closest to the second target. In order to examine whether this may be due to a benefit occurring at the second movement, the speed of MT2 from each target position will be computed relative to the speed of MT1 for the equivalent trajectory length. For example, the shortest second movement, MT2 $_{T1(250)}$ (i.e. MT2 when target 1 is at 250cm) will be divided by the shortest first movement, MT $_{T1(50)}$ (i.e. MT1 when target 1 is at 50cm; see figure 4.2). In this way the MT2 values can be compared for the various target positions to determine whether there is a movement time benefit for shorter MT2 trajectories. This will be done separately for the short MT2 trajectories (MT2 from positions T1(250), T1(200), and T1(150)) and for the long MT2 trajectories (MT2 from positions T1(150), T1(100), and T1(50)).

For Short Movements



Figure 4.2. Proportions for short movements. Proportion 1 (red lines): MT2 T1(250) / MT1 T1(50); Proportion 2 (black lines): MT2 T1(200) / MT1 T1(100); Proportion 3 (blue lines): MT2 T1(150) / MT1 T1(150).

Therefore, proportions between MT2 and MT1 for short movements (see figure 4.2) were calculated as follows:

Proportion1	Proportion 2	Proportion 3
MT2 _{T1(250)}	MT2 _{T1(200)}	MT2 T1(150)
MT1 T1(50)	MT1 T1(100)	MT1 T1(150)

For Long Movements



Figure 4.3. Proportions for long movements. Proportion 1 (red lines): MT2 T1(50) / MT1 T1(250); Proportion 2 (black lines): MT2 T1(100) / MT1 T1(200); Proportion 3 (blue lines): MT2 T1(150) / MT1 T1(150).

Proportions between MT2 and MT1 for long movements (see figure 4.3) were calculated as follows:

Proportion1	Proportion 2	Proportion 3		
MT2 T1(50)	MT2 T1(100)	MT2 T1(150)		
MT1 _{T1(250)}	MT1 _{T1(200)}	MT1 T1(150)		

For both short and long movements a 4 Target size (L-L, L-S, S-L, S-S) x 3 Proportions ANOVA with repeated measures on Proportions was also performed on the proportions between MT2 and MT1.

4.3 Results

Trials in which RT was less than 100 msec or more than 700 msec and in which participants missed at least one of the targets were omitted from the analysis. This amounted to less than 5% of the trials. The means and standard deviations of all dependent measures for the 4 different task conditions are reported in Table 4.1.

RT L-L 267 (42) 261 (48) 264 (44) 269 (45) 276	(46)
TURNER REPORT	
(ms) L-S 268 (37) 264 (41) 256 (36) 256 (36) 261	(32)
S-L 272 (34) 260 (30) 258 (28) 263 (32) 268	(32)
S-S 297 (53) 287 (52) 280 (52) 283 (57) 290	(55)
Total MT L-L 598 (91) 614 (99) 609 (98) 608 (101) 571	(97)
(ms) L-S 745 (112) 761 (116) 757 (134) 733 (126) 691 (130)
S-L 820 (126) 841 (139) 838 (139) 826 (133) 787 (125)
S-S 880 (182) 906 (177) 920 (184) 908 (193) 837 (183)
MT1 I J 195 (27) 237 (30) 267 (44) 301 (53) 331	57)
(ms) $I_{-}S$ 228 (36) 282 (46) 324 (53) 360 (60) 397	60)
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	(09)
S-S = 275(51) = 324(52) = 384(71) = 416(68) = 442	(77)
3-3 273 (37) 334 (33) 364 (77) 410 (06) 447	(1)
MT2 L-L 367 (61) 342 (54) 305 (47) 268 (45) 209	(41)
(ms) L-S 469 (66) 435 (61) 390 (65) 332 (56) 256	(50)
S-L 412 (60) 380 (57) 343 (55) 294 (44) 230	(36)
S-S 457 (77) 430 (67) 398 (63) 345 (60) 257	(50)
PT L-L 35 (37) 35 (34) 36 (39) 39 (41) 32	(36)
(ms) L-S 49 (35) 44 (36) 43 (36) 41 (32) 38	(32)
S-L 135 (83) 131 (81) 126 (76) 126 (75) 115	(69)
S-S 148 (112) 141 (109) 137 (105) 147 (123) 133 (108)
	(22)
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	(22)
(mm^{-}) L-S 26 (8) 29 (11) 30 (12) 31 (14) 30	(12)
S-L 13 (5) 15 (7) 15 (7) 16 (7) 14	(5)
S-S 16 (9) 20 (12) 24 (20) 24 (14) 21	(15)
EA2 L-L 55 (18) 60 (21) 55 (21) 53 (28) 41	(20)
(mm^2) L-S 17 (7) 19 (7) 18 (9) 17 (7) 14	(5)
S-L 24 (11) 25 (12) 25 (15) 24 (12) 23	(9)
S-S 20 (12) 19 (12) 16 (8) 17 (11) 16	(7)

Target 1 distance from Start Position (mm)

the second se		at the second				Paulin Long Construction 111	a set of the set of the set of the	11	contraction of the state	1744 V 100 10	
	S-S	36	(20)	39	(21)	40	(26)	41	(23)	37	(21)
	S-L	37	(13)	40	(17)	40	(19)	40	(15)	37	(12)
(mm ²)	L-S	43	(12)	49	(16)	48	(18)	48	(18)	44	(15)
Total EA	L-L	90	(26)	109	9 (41)	103	3 (35)	108	3 (47)	95	(37)

Table 4.1. Means and *standard deviations* of Reaction Time (RT), Total Movement Time (Total MT), Movement Time to the First target (MT1), Movement Time to the Second Target (MT2), Pause Time (PT), Ellipse Area at the First Target (EA1), Ellipse Area at the Second Target (EA2) and the combined Ellipse Areas at both Target 1 and Target 2 (Total EA) for the conditions where target 1 and 2 were both large (L-L), target 1 was large and target 2 was small (L-S), target 1 was small and target 2 was large (S-L), and when target 1 and 2 were both small (S-S).

Reaction Time (RT)

Analysis of RT revealed no main effect for Target size ($F_{3,74} = 1.677$, p = 0.179, η^2 = 0.06). A main effect for T1 distance (F_{4, 304} = 14.728, p < 0.05, $\eta^2 = 0.15$) as well as a T1 distance by Target size interaction (F_{12, 304} = 2.329, p < 0.05, $\eta^2 = 0.09$) was revealed. In the L-L condition, a main effect for T1 distance was revealed (F_{4, 76} = 4.532, p < 0.05, $\eta^2 =$ 0.19). Post hoc analysis revealed that RTs were shortest for the T1(100) condition and longest for the T1(250)condition. In the L-S condition, a main effect for T1 distance was revealed (F_{4, 76} = 3.581, p < 0.05, $\eta^2 = 0.16$). Post hoc analysis revealed shortest RTs for the T1(150) and T1 (200) conditions and longest RTs for the T1(50) condition. In the S-L condition, a main effect for T1 distance was revealed (F_{4, 76} = 8.291, p < 0.05, $\eta^2 = 0.30$). Post hoc tests revealed RTs were significantly longer for the T1(50) condition compared to the T1(100), T1(150) and T1(200) conditions. Also, RTs for the T1(250) condition were similar to the compared to the T1(150) condition. In the S-S condition, a main effect for T1 distance was revealed (F_{4, 76} = 6.521, p < 0.05, $\eta^2 = 0.26$. Post hoc tests revealed longer RTs for the T1(50) condition compared to the T1(150) and T1(200) conditions. Also, RTs for the T1(150) condition were longer compared to the T1(250) condition.

Total Movement Time

Analysis for Total MT revealed a main effect for Target size ($F_{3, 76} =$ 16.840, p < 0.05, $\eta^2 = 0.40$). MTs for the L-L condition (600ms) were shorter compared to all of the other three target size conditions (L-S, S-L, S-S). Also, MTs for the S-S condition (890 ms) were longer than the L-S condition (737 ms). There was also a main effect for T1 distance (F_{4, 304} = 86.486, p < 0.05, $\eta^2 = 0.50$) and a T1 distance by Target size interaction (F_{12, 304} = 3.276, p < 0.05, $\eta^2 = 0.06$). Break down of this interaction using one way ANOVAs revealed a main effect for T1 distance in the L-L condition ($F_{4, 76} = 13.501$, p < 0.05, $\eta^2 = 0.42$). Post hoc analysis revealed quicker total MTs for the T1(250) condition compared to all other target 1 locations (see figure 4.4). No other differences were revealed. For the L-S condition, a main effect for T1 distance was revealed ($F_{4, 76} =$ 27.441, p < 0.05, $\eta^2 = 0.59$). Total MTs were quickest for the T1(250) condition compared to all other target 1 locations (see figure 4.4). Total MTs were also significantly longer in the T1(100) condition compared to the T1(150) and T1(200) conditions. For the S-L condition, a main effect for T1 distance was revealed (F_{4, 76} = 16.299, p < 0.05, $\eta^2 = 0.46$). Total MTs were quickest for the T1(250) condition compared to all other target 1 locations (see figure 4.4). No other differences were revealed. For the S-S condition, a main effect for T1 distance was revealed (F_{4, 76} = 35.408, p < 0.05, $\eta^2 = 0.65$). Total MTs were quicker in the T1(50) and T1(250) conditions compared to all other target 1 locations. Also, Total MT was significantly quicker for the T1(250) condition compared to the T1(50) condition.



Figure 4.4. Total MT (MT1+PT+MT2) for each of the 4 different task conditions. Error bars are represented as standard error of the mean.

Movement Time to the First Target (MT1)

Analysis of MT1 revealed a main effect for Target size ($F_{3,76} = 52.460, p < 0.05, \eta^2 = 0.41$). Bonferroni's post hoc test revealed MT1s in the L-L condition (266 ms) were significantly quicker than in all other target size conditions. There were also quicker MT1s in the L-S condition (318 ms) compared to the S-L (364 ms) and S-S (371 ms) conditions. Analysis also revealed a main effect for T1 distance ($F_{4,304} = 916.447, p < 0.05, \eta^2 = 0.91$) and a T1 distance by Target size interaction ($F_{12,304} = 3.196, p < 0.05, \eta^2 = 0.01$). As would be expected, post hoc analysis of the T1 distance by Target size

interaction revealed that MT1 increased as the distance of target 1 increased in all target size conditions (see figure 4.5).



Figure 4.5. Total MT spent during movement time to the first target (MT1), pause time (PT) and movement time to the second target (MT2) for a) Large-Large, b)Large-Small, c)Small-Large and d)Small-Small target size conditions.

Movement Time to the Second Target (MT2)

Analysis of MT2 revealed a main effect for Target size ($F_{3, 76} = 10.130$, p < 0.05, $\eta^2 = 0.29$). Post hoc tests revealed quicker MT2s in the L-L condition (298 ms) compared to the S-S (377 ms) and L-S (376 ms) conditions. There was also a tendency for the S-L condition to have quicker MT2s compared to the S-S (p = 0.055) and L-S (p = 0.066) conditions. There was also a main effect for T1 distance ($F_{4, 304} = 1150.217$, p < 0.05, $\eta^2 = 0.93$) and a T1 distance by Target size interaction ($F_{4, 304} = 5.515$, p < 0.05, $\eta^2 = 0.01$). Post hoc analysis of the interaction revealed that MT2 decreased as the distance of target 1 increased in all target size conditions (see figure 4.5).

Proportion of Movement Times

Examination of figure 4.5 reveals that there was a steady increase in MT1 as target 1 distance increased. On the other hand, there was a more dramatic decrease in MT2 between T1(200) and T1(250).

Proportions of movement times were analysed to compare movement times between the first and second segment of equal distance. Three proportions were compared for both short and long movements (see table 4.2).

		Proportions (MT2/MT1)				
		T1(250)/T1(50)	T1(200)/T1(100)	T1(150)/T1(150)		
MT Proportions	L-L	1.07 (0.16)	1.14 (0.17)	1.15 (0.17)		
(short movements)	L-S	1.12 (0.13)	1.18 (0.12)	1.21 (0.13)		
	S-L	0.85 (0.12)	0.90 (0.11)	0.93 (0.10)		
	S-S	0.94 (0.12)	1.04 (0.11)	1.05 (0.12)		
MT Proportions	L-L	1.12 (0.15)	1.14 (0.16)	1.15 (0.16)		
(long movements)	L-S	1.19 (0.11)	1.22 (0.11)	1.21 (0.13)		
	S-L	0.94 (0.09)	0.94 (0.10)	0.93 (0.10)		
	S-S	1.03 (0.09)	1.04 (0.09)	1.05 (0.12)		

Table 4.2. Means and *standard deviations* of proportions of movement time (for short and long movements) for the conditions where target 1 and 2 were both large (L-L), target 1 was large and target 2 was small (L-S), target 1 was small and target 2 was large (S-L), and when target 1 and 2 were both small (S-S).

Analysis of proportions of movement time for short movements revealed a between subjects main effect for Target size ($F_{3, 76} = 21.703$, p < 0.05, $\eta^2 = 0.46$). The S-L group had the smallest ratio, whilst the L-L and L-S had the largest ratios. Analysis also revealed a main effect for Proportions ($F_{2, 152} = 42.553$, p < 0.05, $\eta^2 = 0.35$). Post-hoc analysis revealed that proportion 1 (MT2 T1(250) / MT1 T1(50)) had the smallest ratio and proportion 3 (MT2 T1(150) / MT1 T1(150)) had the largest ratio. All three calculated proportions were significantly different from each other. No Proportions by Target size interaction was revealed ($F_{6, 152} = 0.544$, p = 0.751, $\eta^2 = 0.01$).

Analysis of proportions of movement time for long movements revealed a between subjects main effect for Target size ($F_{3, 76} = 23.126$, p < 0.05, $\eta^2 = 0.48$). The S-L group had the smallest ratio, whilst the L-L and L-S had the largest ratios. There was no main effect for Proportions ($F_{2, 152} = 2.254$, p = 0.109, $\eta^2 = 0.03$) nor a Proportions by Target size interaction ($F_{3, 76} = 0.572$, p = 0.752, $\eta^2 = 0.02$).

Pause Time (PT)

Analysis of PT revealed a main effect for Target size ($F_{3,76} = 11.826$, p < 0.05, $\eta^2 = 0.32$). Post hoc analysis revealed that PTs were significantly shorter in the L-L and L-S conditions compared to the S-L and S-S conditions. There were no differences between the L-L and L-S conditions, or between the S-L and S-S conditions. There was also a main effect for T1 distance ($F_{4,304} = 11.289$, p < 0.05, $\eta^2 = 0.12$), and an interaction between T1 distance and Target size approached conventional levels of significance ($F_{12,304} = 1.827$, p

= 0.053, η^2 = 0.06). There was a trend for PTs to decrease as the distance of target 1 increased.

Ellipse Areas at Target 1(EA1)

Analysis for EA1 revealed a main effect for Target size ($F_{3, 76} = 31.311, p < 0.05, \eta^2 = 0.55$). Bonferroni's post hoc test revealed that the greatest EA1 was in the large-large condition (48mm²) and the smallest was in the small-large condition (15mm²). Analysis of EA1 also revealed a main effect for T1 distance ($F_{4, 304} = 12.149, p < 0.05, \eta^2 = 0.13$) and a T1 distance by Target size interaction ($F_{12, 304} = 2.696, p < 0.05, \eta^2 = 0.08$) were revealed. Post hoc analysis revealed a significant increase in EA1 between T1(50) and T1(250), indicating that EA1 increased as the distance to reach target 1 increased (see figure 4.6). This trend was greater in the L-L and L-S conditions compared to the S-L and S-S conditions.

Ellipse Areas at Target 2(EA2)

Analysis for EA2 revealed a main effect for Target size ($F_{3,76} = 42.338$, p < 0.05, $\eta^2 = 0.63$). Post hoc tests revealed the L-L condition had a significantly greater EA2 compared to the other target size conditions. Analysis of EA2 also revealed a main effect for T1 distance ($F_{4,304} = 7.931$, p < 0.05, $\eta^2 = 0.09$) and a T1 distance by Target size interaction ($F_{12,304} = 2.414$, p < 0.05, $\eta^2 = 0.08$) were revealed. For the L-L condition, a main effect for T1 distance ($F_{4,76} = 4.931$, p < 0.05, $\eta^2 = 0.20$) indicated that EA2 decreased as the distance of target 1 increased (see figure 4.6).



Figure 4.6. Total EA at the end of the first movement (EA1) and end of the second movement (EA2) for a) Large-Large, b)Large-Small, c)Small-Large and d)Small-Small target size conditions.

Total Ellipse Areas (Total EA: - EA1 + EA2)

Analysis revealed a main effect for Target Size ($F_{3, 76} = 37.728, p < 0.05, \eta^2 = 0.59$). Post-hoc tests revealed significantly greater Total EAs in the L-L condition compared to the
other target size conditions (see figure 4.6). A main effect for T1 distance ($F_{4, 304} = 6.758, p$ < 0.05, $\eta^2 = 0.08$) was also revealed. Total EA was lowest for the T1(50) and T1(250) conditions compared to the other three target size conditions. There was no difference between T1(50) and T1(250). No T1 distance by Target size interaction was revealed (F_{12} , $_{304} = 1.273, p = 0.233, \eta^2 = 0.04$).

4.4 Discussion

In single target aiming movements, participants typically undershoot the target in the initial impulse phase. This control strategy enables corrections to be made in the same direction as the initial impulse and minimizes energy expenditure that would be associated with reversing direction in the event of a target overshoot. The present study extended the concept of movement optimization to two-target aiming movements. The primary purpose was to find the optimal position of the first target in two-target aiming movements with different target sizes.

Total movement time was significantly quicker when the first target was positioned closest to the end target. A proportional benefit in MT was also revealed when the first target was positioned closest to the second target. A possible explanation for this could be that when these 2 end targets were presented together, participants found it easier to produce an initial impulse in the vicinity of the first target and then to produce a shorter movement in order to move to the second target. Although eye movements were not measured in this study, it may be that the proximity of the first target to the end target simplified eye movements. These simplified eye movements could then in turn provide benefits in movement time.

When pause times were analysed, no differences were seen indicating that any differences seen in total movement time occur during the actual movement time to one of the two targets. The analysis of proportions of movement times of segment of equal distances revealed that having the first target situated closest to the end target produced

proportionally quicker movement times to the second target than any of the other proportions. These results could provide evidence to indicate that participants are able to use this close proximity of the two targets at the end of the movement to produce a response which allows a strategy similar to the 'sneaking up' strategy (Elliott et al., 2004; Oliveira et al., 2005) seen in single target responses.

In single target movements, variability has been shown to increase as the movement distance to the target increases (Khan et al., 2003a; Khan et al., 2003b; Khan et al., 2006; Schmidt et al., 1979). In conditions where vision is occluded or where movement times are very fast, movement trajectories tend to be pre-programmed before movement initiation. Therefore, any errors that occur early in the movement would be magnified at later stages in the movement (Khan et al., 2003b).

The present study examined whether ellipse area variability increased as the movement distance to the first target increased. Also of interest was whether the size of the second target had any effect on the variability at the first target. This comparison was made by comparing ellipse areas at target 1 when the size of the second target was either small or large and the size of the first target remained constant.

Based on the idea that spatial variability increases as the movement progresses (see Khan et al., 2006 for a review), researchers have proposed that movements to the first target are constrained in order to provide an ideal starting position in order to be accurate at the second target. If participants do not constrain their movements at the first target, the

increase in variability as the movement progresses would result in reduced accuracy at the second target.

When total ellipse areas (ellipse area of target 1 + ellipse area of target 2) were analysed, ellipse areas did not significantly change as the movement progressed from target 1 to target 2. This is unsurprising as vision was always available throughout the movement allowing for error corrections as participants approached each target. The present study examined whether the size of the second target had any effect on the ellipse area variability at the first target when the size of the first target remained constant. In the large-large task condition variability increased as the distance of the first target also increased. In the largesmall task condition, variability was significantly smaller at all target 1 locations and increased as the distance of the first target increased. These results indicate that by having a smaller second target, participants constrained their movements at the first target. The findings from this study support previous findings by Sidaway et al. (1995). In their study they had participants perform movements to two targets in a simple reaction time paradigm. The size of the first target always remained constant whereas the size of the second target was varied and always smaller than the first. Just like in this present study, when the size of the second target was reduced, the variability at the first target was constrained even though the first target in both conditions was the same.

To conclude, it seems as though when the two targets in a sequence are situated closer to each other, there is an advantage in terms of quicker total movement times. The advantage in total movement times was due to the relatively short movement time from the first to the second target. This finding is similar to that observed in single target aiming

where participants tend to undershoot the target in the initial impulse phase and error correct in the primary direction of the movement. Finally, this study replicated the finding by Sidaway et al., (1995) which revealed that a smaller second target constrains variability at the first target, even though the first target size remained constant. This provides further support for the movement constraint hypothesis (MCH) which states that movements to the first target are performed in a more controlled manner in order to provide an ideal starting position for the limb to start the second movement.

Chapter 5

General Discussion

5.1 General Discussion

Previous research has revealed that movements in a sequence are not prepared and controlled separately. The chapters contained within this thesis were aimed at examining the interrelation between two movements. The theoretical framework behind examining this interrelation resolves around RT and MT paradigms. It is widely accepted that the processes associated with specifying and organising a response increase as a function of the number of elements in a response. These preparatory processes have typically been observed through examining reaction time. Henry and Rogers (1960) demonstrated that an increase in RT was related to the number of elements in a response. They showed that lifting a finger off a key was faster than lifting a finger followed by subsequent tasks. The lengthening of RT was attributed to more time needed to program the more complex movements. As stated by Henry and Rogers, a more comprehensive program needs "a larger amount of stored information.....and the neural impulses will require more time for coordination and direction into the eventual motor neurons and muscles" (p.450).

It is generally accepted the time taken to program a response increases as the complexity of the task increases, but what aspect of response complexity is responsible for the increase in RT has investigated in many ways. Researchers have investigated the effects of the number of response elements (Fischman, 1984; Sternberg et al., 1978), the response duration (Klapp & Erwin, 1976), and movement accuracy (Lajoie & Franks, 1997; Sidaway, 1991) on RT. Klapp (1995) further examined RT by comparing the effects of response complexity in simple and choice RT tasks. Participants performing simple RT tasks know what the required response is prior to stimulus presentation, whereas in a choice

RT task participants do not know what the required response is until the stimulus is presented. In Klapp's (1995) morse code experiments, the duration of a single element response (e.g. dit v dah) influenced choice RT but not simple RT. Alternatively, the number of elements in a response (e.g. dit v dit, dah, dah, dit) influenced simple RT but not choice RT. This pattern of RT results has also been identified in multiple target aiming tasks (Khan et al., 2006). In this study, participants performed a series of experiments in which participants performed single or two-target aiming responses. Similarly to Klapp (1995, 2003), Khan et al. revealed that RT was greater for the two-target responses compared to the single target responses in a simple RT task. This thesis has shown similar results to further support previous RT literature. In both chapters 2 and 3, regardless of hand use, distances to the first and second target, or target size, RTs were shown to increase as the number of elements in the response increased. This thesis also revealed that in a simple RT task, RT was longer in two-target conditions regardless of whether the movement was performed with a single limb or with two limbs (when participants switched hands at the first target). Hence, the planning processes that underlie the increase in RT for multiple element responses are not restricted to the use of one limb. These results indicate that when the number of elements in a response is known prior to stimulus presentation, RT increases as the number of elements increase. This supports previous research from Khan et al. (2007) who showed that RT increased as a function of the number of response elements when the number of elements but not other features of the response were precued in advance. They suggested that there appears to be a necessary condition for the number of elements to be known prior to stimulus presentation in order for RT to increase as the number of element increases.

The influence of the number of elements in a response is not limited to the RT interval. Movement times to the first target (MT1) were greater when participants are required to continue and hit a second target compared to when they are required to stop on the first target (Glencross, 1980; Adam et al., 2000; Chamberlin & Magill, 1989). This one-target advantage (OTA) phenomenon has been shown to be robust regardless of manipulations of vision, hand preference and hand use (Adam et al., 2001; Lavrysen et al., 2002). The requirement of continuing a movement to hit a second target increases movement time to the first target suggesting that the two movement elements may not be controlled separately but there is an interrelation between the first and second movements. Different interpretations have been put forward to explain this phenomenon.

One interpretation centres on the premise that variability increases as a movement progresses (see Khan et al., 2006, for a review) and suggests that movements to the first target in a sequence must be more constrained to provide an ideal starting position in order to be accurate at subsequent targets (Fischman & Reeve, 1992). The movement constraint hypothesis (MCH) suggests that MT1 lengthens when a second response is required because of the movement constraints placed on the participant who must adopt a strategy of restraining the limb as it approaches the first target. The movement integration hypothesis (MIH) (Adam et al., 2000; Elliott et al., 2001) is a concept that combines advance planning and on-line control explanations. The MIH states that the second movement in a response is prepared in advance but there is also a cost associated with implementing the second movement is implemented during movement execution to the first target in order to facilitate a smooth

and efficient transition from the first movement into the second; hence the two movements are not controlled separately. The overlap of processes during the movement to the first target causes interference, and it is this interference that leads to an increase in MT1 and the OTA. Adam et al. (2000) distinguished between the on-line programming hypothesis and MIH by stating that on-line programming involves both the construction and implementation of a motor program during movement execution to the first target. By contrast, according to the MIH, construction of a motor program is performed before response initiation, but the implementation of a second movement is performed online as the first movement is being executed. This implementation process causes interference and the OTA.

Firstly, by comparing MT1s in single and two limb sequential aiming tasks this would allow one to distinguish between two possible loci of the interference effect reflected by the OTA. As Adam et al. (2000) stated, the MIH does not make any specific assumptions about the nature or locus of the interference effect. Two loci of interference are possible: a central and peripheral origin. At a central origin, interference is associated with the retrieval of a motor program from a motor buffer, whereas at a peripheral origin, interference stems from the implementation of these motor commands into muscle activity to execute the movements. The present 2T2L condition would seem to reduce or even to eliminate the possibility of interference occurring at the peripheral level because the two movements are largely anatomically distinct. In the 2T1L task, it is possible that both central and peripheral sources are contributing to the OTA. However, for the dual limb aiming task, which introduces a switch between hands at the first target, peripheral factors

play a very minor role. Hence it seems that the processes that lead to interference during movement execution to the first target were effector-independent and therefore originate at a central level. MT1 results from both Chapters 2 and 3 reveal that the OTA was present in both 2T1L and 2T2L movements, and the magnitude of the OTA was similar for both conditions. This suggests that the loci of interference occurs more at a central level rather than a peripheral level.

A second theoretical implication of using a two-limb paradigm would be that the presence of a OTA in the 2T2L task would be inconsistent with the MCH. According to the MCH, accuracy at the second target would depend on the location and variability of the movement endpoints at the first target. However, in two limb movements in which the limb is switched at the first target, the start position of the limb that moves to the second target is independent of the movement endpoints on the first target. Consequently, in the two-target two limb conditions accuracy at the second target is not contingent on the variability of movement endpoints at the first target.

The MIH can explain the OTA in the 2T2L task as processes associated with production of a second movement are implemented during execution to the first target. Regardless of which limb is performing the second movement, there is still a cost of implementing a second movement during execution of the first movement. This is also the case regardless of whether the first or second movement consisted of a short or long movement. For shorter movements to the first target it was suggested that the magnitude of the OTA would reduce because the movement time is too short for the cognitive processes

proposed by the MIH to be involved in implementing the second movement. When the distance to the second target was manipulated, it was expected that a longer distance to the second target would result in more time for on-line programming, possibly resulting in a reduction in the OTA. The rationale here being that participants adopt a strategy whereby the entire movement response is not pre-programmed and thus the second movement is implemented fully before the completion of the first movement (as suggested by the MIH). However this was not the case when manipulating the distance of the first or second movements suggesting that neither a short first movement nor the potential for online programming during the second movement influences this phenomenon further adding to the robustness of the OTA.

The OTA has been shown to be a robust phenomenon; however there is a notable exception when target sizes are small. Chapter 3 further examined the OTA phenomenon by examining the effect of target size on two-limb sequential aiming movements. According to the MIH, small targets will eliminate the OTA (Adam et al., 2000). Small targets increase the accuracy demands required to perform a task. Pause times (PTs) are typically longer when a target sizes are small, thereby disrupting the transition between targets (Adam & Paas, 1996; Adam et al., 1995; Adam et al., 2000; Rand & Stelmach, 2000). Hence, movements to both targets are processed separately into individual units, where each has its own preparatory and control processes. Therefore, you would also expect the OTA to be eliminated in the two-target two-limb task. Since the MIH suggests that each movement has its own preparatory and control processes the two segments will not overlap, hence no OTA. According to the MCH, the accuracy at the second target

depends on the location and movement endpoints of the first movement. Since, in the 2T2L task where there is a switch in limbs at the first target, the start position for the movement to the second target does not depend upon where the first movement ended. According to the MCH in a small target condition, the first movement in the 2T2L task may be similar to the first movement in the 1T task as the only accuracy demand in both tasks is the target size. In the 2T1L task however, according to the MCH there is an additional demand of having to constrain the first movement in order to be accurate at the second as well as the accuracy demands of performing a task to small targets. Therefore, it is possible that MT1 in the 2T1L task would increase resulting in the OTA being present. Data from Chapter 3 of this thesis revealed that when target sizes were large the OTA materialized in both the 2T1L and 2T2L tasks (with similar OTA magnitudes), supporting the original findings in Chapter 2 and suggesting that there may be similar processes involved in the programming and execution of two target single limb and dual limb movements. Small targets were shown to eliminate the OTA in both the 2T1L and 2T2L tasks. Results from Chapter 3 provide support for the MIH in small targets as there was no difference in MT1s between the 3 tasks (1T, 2T1L and 2T2L) and PTs were longer in the small target condition compared to the large target condition. This suggests that movements, whether performed within a single limb or across two limbs, are processed separately with each movement having its own preparatory and control processes as stated by the MIH (Adam et al., 2000). As expected, the increase in accuracy demands of smaller targets reduced variability at the first target in comparison to large targets, with no difference between the three tasks. In the large target condition, there was a tendency for variability to be smaller at the first target in the 2T1L task compared to the 1T task.

Although not significant, this result suggests that some form of constraining at the first target is occurring, possibly due to the added demands of aiming for a second target as stated by the MCH (Fischman & Reeve, 1992). In the 2T2L task however, a significant decrease was seen in variability at the first target, suggesting that constraining was occurring at the first target even though the end position of the first movement is not relevant to the start position of the second movement. One particular finding of interest was the variability at the first target in the 2T2L was similar in both small and large target conditions. This shows support for the MCH, which would contradict the initial suggestions put forward by Khan et al. (2010) who suggested that the MCH should have no impact on the OTA in two-limb movements. Since the OTA occurred in both single-limb and two-limb tasks, and variability at the first target movement, there is an argument to suggest that the MIH and MCH are both involved in some capacity with the presence of the OTA.

A second way in which we examined the interrelation between two movements was by examining how two elements in a sequence are optimally integrated. This thesis borrowed principles from single target aiming tasks. The optimized submovement model (Meyer et al., 1988) is arguably the most comprehensive explanation of speed-accuracy relations. It states that rapid aimed movements contain submovements whose durations are optimized to cope with a noisy neuromotor system. Over a series of attempts a normal distribution around the centre of the target is created. If movements then fall outside of this distribution a correction is required. MTs are minimized by producing a trade-off between the initial impulse and error correction phases. However, more recent research has

suggested that movements whose MTs are minimized are often associated with being more energy efficient. Movements that initially undershoot a target are faster than movements that overshoot a target. Target overshoots are associated with the limb travelling a greater distance and the inertia of the limb at the point of the reversal having to be overcome (Elliott et al., 2004). In target undershoots the limb already has a positive velocity in the direction of the corrective submovement (Elliott et al., 1999), and are therefore seen as more efficient in terms of MT and energy expenditure. The final experimental chapter of the thesis had performers perform a two-target aiming task, where the position of the first target could occur in 1 of 5 locations between the start position and the second target. One question this chapter wanted to examine was whether having the first target close to the second target produced more efficient movements (in terms of MT). Elliott et al. (2004) have shown that participants in a single target aiming task employ a strategy whereby they initially undershoot a target. Over time, they are able to 'sneak up' on the target with their primary submovement in order to maximise MT without increasing the number of overshoots. This might suggest that total movement time (TMT) will be optimal when the first target is closest to the second target as participants might be able to adopt a strategy similar to that in single target aiming tasks for a two element response. There are two movement distances in this experimental chapter, the movement from the start position to the first target, and the movement from the first target to the second target. With TMT being used as a measure of performance, and as the position of the first target changes between trials, it is possible to start to examine the optimum trade off in these competing control factors. According to the MIH, TMTs may be quicker when the first target is located directly between the start position and the second target (i.e. the distance of the first

and second movements are of an equal distance). As the MIH states that the implementation of the second movement is performed during execution of the first movement, it may be easier to implement the second movement if the two movements share a similar property (i.e. movement distance). The MCH might suggest that having the first target closest to the start position may result in a more optimal performance. When a movement has a large distance between targets, it may encourage more on-line programming of subsequent movements, increasing MTs to the target and an increase in TMT. Conversely, optimal performance may be achieved when the first target is closest to the second target. Similar to when the first target is closest to the start position, when the first movement is long; more time is available for on-line programming. As the MCH is based on the premise that variability increases as a movement increases, it is logical to assume that as the first target moves further away from the start position, variability at the first target is likely to increase. Therefore in order to be accurate at the first target and at subsequent targets, movements at the first target must be constrained. If variability increases as the movement progresses, variability at the first target closest to the start position would need less constraining than when the first target is closest to the second target. The MCH may suggest that the increased demand of constraining a movement at the first target as the location moves further away from the start position could increase MT1s.

Target sizes were also manipulated in the final experimental chapter. As the MIH states and as previously shown in this thesis, small targets disrupt the transition between movement elements and as a result increase MT1s and PTs. Instead of participants always

performing aiming tasks to targets of the same size, participants performed 1 of 4 possible target size combinations (Large-Large, Large-Small, Small-Large and Small-Small). The MCH states that participants reduce variability at the first target in order to be accurate at the second target. The present study wanted to examine what would happen to variability at the first target when the size of the second target was either large or small. Sidaway et al., (1995) have examined the effect of varying the accuracy demands of the second target on the variability of movements to the first target. Participants performed a two-target movement to a large first target (8cm) followed by a second movement to a target that varied in size (1.5cm or 6cm). Their results revealed that when the second target was small, variability at the first target was significantly smaller than when the second target was larger. This finding supports the MCH as variability has to be constrained at the first target in order to be accurate at subsequent targets.

When the first target was positioned closest to the second target, TMT were quicker across all target size conditions than at any other location for the first target. There was also a proportional benefit in MT when the first target was positioned closest to the second target. One potential reason for this could be a result of participants being able to identify targets more quickly because eye movements were simplified. By identifying the close proximity of the two-targets and by having a long first movement, participants were able to achieve higher peak velocities as they approached target 1. Although no data was reported in chapter 4 on the kinematics of the movement, participants were able to achieve higher peak velocities proportionally earlier in the movement when the two-targets were situated close together, similar to results shown in studies where vision was manipulated (Elliott,

Chua, Pollock & Lyons, 1995; Elliott, Lyons & Dyson, 1997; Khan & Franks, 2000). By achieving a higher peak velocity earlier in the movement, this has the effect of bringing the limb to the target area more quickly. This thesis chapter also examined the effect of changing target sizes in a two element response. When the first target was small, TMT was longer than when the first target was large. This result is consistent with what would be expected with Fitt's Law (1954) and previous research findings (Aivar, Brenner & Smeets (2005). Consistent with previous research, when the second target was small MT1s increased (Adam et al., 1995; Rand, Alberts, Stelmach & Bloedel, 1997; Rand & Stelmach, 2000) and suggests that when movements in a sequence involve a small target, the movement elements are planned separately as the MIH states. Variability at the first target was also influenced by the size of the second target. In support of the MCH and previous research by Sidaway et al. (1995), variability at the first target was smaller when subsequent movements were to a small second target. This thesis has shown that movements to the first target are constrained when a second target is required to be performed and when the accuracy demands of the second target are increased.

The results from this thesis suggest that the requirement of producing a movement to a second target has an influence on the execution of movements to the first target. The OTA has been shown to be a robust phenomenon and occur regardless of whether movements are performed within a single limb or using two limbs. Whist the MIH has been widely accepted to explain the increase in MT1; this thesis has shown that movement constraining is prevalent in two element movements using a single limb and two limbs, providing some support for the MCH. This thesis has shown evidence for both the MIH

and MCH, therefore it can be argued that both theories are involved in multiple target aiming and the prevalence of the OTA. To try and ascertain which theory may best explain the OTA phenomenon, future studies should examine the OTA in single limb and two limb tasks with the added presence of a probe task presented at various times during the movement to the first target, similar to the probe task experiment by Khan et al. (2006). The MIH states that the implementation of the second movement occurs during the execution of the first movement. If the MIH holds true, then by adding a probe task at various points during the first movement it would be possible to recognise when the implementation of the second element occurs, and whether this differs between single limb and two limb responses. It may be that the implementation of the second movement and the response to the probe task are grouped together as one response, as reported by Ketelaars et al. (1999). Their results revealed that depending on the temporal location of the probe relative to the initiation of the flexion phase, participants either initiated the masseter and biceps muscles successively or grouped them together as one response. The possible increase in interference during the first movement due to the implementation of a second movement and a probe task could also lead to an increase of the OTA. If the MCH is individually responsible, then since the constraining of the first movement is responsible for the OTA, a probe stimulus later in the execution of the first movement may have more of an effect as participants constrain the movement as they reach the target.

This thesis aimed to examine the interrelation between two movements in two ways; by comparing two movements between limbs and the examining the interrelation between movement elements. Chapter 2 and 3 have shown that the OTA still remains

whether a movement is performed with a single limb or with two limbs, whilst Chapter 4 has shown that the second target in a movement sequence can affect variability and movement times to the first target. Further investigations should examine the effect of varying the sizes of the first and second targets in single limb and two limb tasks. A key question to address would be what happens to the OTA when target sizes for the first and second target were of a different size. More specifically, does the size of the second target influence movement time to the first target in both two-target single-limb and dual-limb tasks? The data from a study such as this would be able to examine whether the OTA would remain when the size of the second target varies and the first target remains constant in both single-limb and dual-limb movements. Secondly, it would also further examine the MCH and whether it plays a role if there is the OTA present in both single and dual limb tasks.

This thesis has shown the OTA to be a robust phenomenon regardless of whether a single limb or two limbs are used to perform a movement. Within every experimental chapter, one factor that remained the same was the direction in which movements were performed. The OTA has been shown to disappear when a reversal in direction is required. For movements that involve a reversal in direction, MTs to the first target are quicker for a two element response compared to a single element response (Adam et al., 1993; Khan et al., 2006) (i.e., two-target advantage). This has been accounted for in terms of muscle activity patterns. In a single element response, muscle activity patterns are characterised by a triphasic EMG pattern of activation. Initially, the agonist muscle accelerates the limb towards the target followed by an antagonist muscle burst to decelerate the limb. A second

agonist then acts to serve the purpose of dampening the mechanical oscillations at the end of the movement (Enoka, 1988). In two-target reversal movements there is no need for the second agonist burst since the elastic properties of the antagonist can be exploited to save energy in moving the limb in the reverse direction (Khan et al., 2006). In these situations, the antagonist used to decelerate the limb at the first target also acts as the agonist on the second movement. This dual purpose of activity allows for optimal integration between elements, resulting in the two-target advantage (TTA). These two target reversal movements have all been performed using a single limb condition, but not in the two limb condition as used in this thesis. As the limb used to produce the second movement is different to the limb used to produce the first movement in the two limb condition, the muscle activation pattern as seen in a two target reversal movement with a single limb is not possible. Therefore, will the OTA be present in a two target movement with a reversal in direction when two limbs are used to perform the movement. Presence of the OTA in this condition would support the MIH, as the MCH is unable to explain why the OTA would be present in the two limb conditions. The MIH however would explain the presence of the OTA as the second movement is implemented during execution of the first movement causing interference. Conversely, would the presence of performing a reversal movement still eliminate the OTA even if the second movement is performed by a different limb?

This thesis has shown that optimisation of control processes and minimization of TMT is greatest when the first target in a sequence is positioned closest to the second (end) target. One possible reason given was that the proximity of the first target to the end target

simplified eye movements. These simplified eye movements could then in turn provide benefits in movement time. However, since eye movements were not measured during the present study, future studies measuring eye movements using the same experimental paradigm are required to investigate this hypothesis.

In conclusion, this thesis has examined the interrelation between two movements. The experimental chapters in this thesis have shown the OTA to be a robust phenomenon and to remain present regardless of whether a movement is performed with a single limb or with two-limbs. Support for both the MIH and MCH (Fischman & Reeve, 1992) have been shown which could suggest that a combination of both hypotheses might be required to explain the effects of multiple target aiming and the OTA. Furthermore, both hypotheses are shown to be relevant in the optimisation of control processes and the minimization of overall MT in sequential aiming movements.

Chapter 6

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