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The integration of sequential aiming movements: Switching hand and direction at the first target.

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Abstract

Movement times to a single target are typically shorter compared to when movement to a second target is required. This one target movement time advantage has been shown to emerge when participants use a single hand throughout the target sequence and when there is a switch between hands at the first target. Our goal was to investigate the lacuna in the movement integration literature surrounding the interactive effects between switching hands and changing movement direction at the first target. Participants performed rapid hand movements in five conditions; movements to a single target; two target movements with a single hand in which the second target required an extension or reversal in direction; and movements to two targets where the hands were switched at the first target and the second target required an extension or reversal in direction. The significance of including these latter two (multiple hand-multiple direction) movements meant that for the first time research could differentiate between peripheral and central processes within movement integration strategies. Reaction times were significantly shorter in the single task compared to the two target tasks. More importantly, movement times to the first target were significantly shorter in the single target task compared to all two target tasks (reflecting the so-called one target advantage), except when the second movement was a reversal movement with the same hand. These findings demonstrate for the first time the contrasting effects of movement integration at central and peripheral levels.

Key words: One-target advantage; Sequential aiming; Movement integration; Peripheral processes; Central processes

The integration of sequential aiming movements: Switching hand and direction at the first target.

In two target aiming sequences, researchers have revealed that reaction times and movement times to the first target are typically longer compared to single target responses (Adam et al., 2000; Chamberlin & Magill, 1989; Fischman & Reeve, 1992). This one target advantage in reaction and movement time implies that individual segments in a targeted sequence are not prepared and executed independently (Khan, Helsen, & Franks, 2010). Understanding the factors that influence the nature of the interdependency between segments has been of considerable interest to researchers (Adam et al., 2000; Cullen et al., 2001; Khan, Mottram, Adam, & Buckolz, 2010; Khan, Sarteep, Mottram, Lawrence, & Adam, 2011; Helsen, Adam, Elliott & Buekers, 2001; Lavrysen, Helsen, Elliott, & Adam, 2002; Lavrysen et al., 2003; Lawrence, Reilly, Khan, Mottram, & Elliott, 2013; Mottram, Khan, Lawrence, Adam, & Buckolz, 2014). The aim of the present study was to differentiate between the processes underlying the integration between movement segments at central cognitive and peripheral neuromuscular levels by examining the interactive effects of switching hands and movement direction at the first target.

The interdependency between movement segments in a two target aiming sequence has generally been explained via two central or cognitively based hypotheses. The movement constraint hypothesis is based on the assumption that the variability of movement endpoints accumulates from one target to the next. Hence, in order to be accurate at a second target, movement to the first target must be constrained so that the accuracy demands at the second target are met (Sidaway, Sekiya, & Fairweather, 1995). The constraining of movement

endpoints at the first target is achieved through more precise movement planning and/or feedback processing during movement execution (Khan et al., 2010).

The movement integration hypothesis (Adam et al., 2000) poses that response segments are programmed and stored in a buffer prior to movement initiation. In order to facilitate a smooth and efficient transition between segments, the implementation of the second segment is performed concurrently with the execution of the first. This online implementation results in increased cognitive control during the production of the first segment which leads to (dual-task) interference. Although the transition between segments is facilitated via the implementation of the second segment online, the resultant increased cognitive processing load during response execution leads to a lengthening of movement time to the first target.

The one target movement time advantage has typically been investigated using single limb movements (Adam, Helsen, Elliott, & Buekers, 2001; Lavrysen et al., 2002). More recently, the robustness of the one target movement time advantage was extended to include movements involving two limbs. In a study by Khan et al. (2010), participants performed single target movements, two target extension movements with one hand, and two target extension movements in which hands were switched at the first target (i.e., one hand was used to perform the first segment and the other hand for the second segment). The results revealed a robust and similar one-target movement time advantage for the single and two hand conditions. This finding had two important theoretical implications. Firstly, the presence of the one target movement time advantage for two hand movements would seem to be inconsistent with the central processes proposed within movement constraint hypothesis. This is because the start position of the hand responsible for the second movement was fixed and hence did not depend on the variability of endpoints of the first movement. Hence, accuracy of the second segment should not have depended on the accuracy of the first

segment. Secondly, the finding that the magnitude of the one target movement time advantage was similar for both the single and two hand conditions implied a central locus of interference as the underlying cause of the one target movement time advantage (i.e., the online retrieval and implementation of a motor program from a motor buffer). If the one target movement time advantage was due to peripheral factors (i.e., muscular organisation of the limb being adjusted and readied for a second movement), one would not expect the effect to emerge in the two hand condition because the first and second movement segments were performed by separate effector systems.

The one notable exception to the one target movement time advantage is when the second movement segment involves a reversal in direction. For reversal movements, the one target movement time advantage either does not emerge (e.g., when movements involve tapping target areas) (Adam et al., 2000), or a two-target movement time advantage arises where movement times to the first target are shorter for two compared to single segment responses (e.g., when movements involve sliding in a single dimension between target areas) (Khan, Lawrence, Buckolz, & Franks, 2006; Khan, Mourton, Buckolz, & Franks, 2007). Researchers have accounted for the two-target movement time advantage in terms of peripheral processes (i.e., the patterns of muscle activity) underlying rapid aiming movements. Single target movements are typically characterized by a triphasic, agonist-antagonist-agonist, pattern of muscle activity (Adam, Savelberg, & Bakker, 2005; Britton, Thompson, Day, Rothwell, Findley, & Marsden, 1994; Gottlieb, 1998; Hallett, Shahani, & Young, 1975; Savelberg, Adam, Verhaegh, & Helsen, 2002). The initial agonist activity accelerates the limb towards the target while the burst of antagonist activity serves to decelerate the limb upon nearing the target. The final burst of agonist activity is responsible for dampening mechanical oscillations at the end of the movement. More specifically, this final agonist muscle activity counteracts any tendency of the limb reversing direction due to

the storage of elastic energy from a rapidly lengthening antagonist muscle. In two target reversal movements, there is no need for the second burst of agonist activity since the elastic properties of the muscle can be exploited to save energy in moving the limb in the reverse direction. Moreover, the antagonist muscle forces used to decelerate the first element also act as the agonist for the second component. This dual purpose of antagonist activity allows ‘the possibility to establish an intimate, synergetic coupling between the two movement elements’ (Adam et al., 2005, pp.249) leading to optimal integration between elements and the two-target movement time advantage (Adam et al., 2000). Direct support for the contrasting neuromechanical activation patterns proposed between extension and reversal movements has been offered by both Adam et al., (2005) and Savelberg et al., (2002). Specifically, only tri-phasic patterns of muscle activity emerged for extension movements and comparison of muscle activity levels between the two movement tasks revealed that agonist activity was greater at the end of the first movement in the extension compared to reversal movements, whereas the antagonistic muscle activity was greater in the reversal compared to extension movements.

It is important to distinguish between the mechanisms underlying integration between segments in two target extension and reversal movements (see Khan, Helsen, & Franks, 2010). For both single and two limb extension movements, the Movement Integration Hypothesis accounts for the one target movement time advantage by proposing that executive processes control the implementation of the second segment during execution of the first. This explanation implies that interference arises from cognitive processes operating online, that is, when the pre programmed movement commands of the second segment are retrieved from the central buffer and implemented during the execution of the first movement. While the one target movement time advantage is due to interference at a cognitive level, the two target advantage in reversal movements emerges from the integration of muscular forces

associated with the mechanical characteristics of changing direction. Hence, while the integration between segments in two target extension movements is at the cognitive level, segments involving a reversal in direction are integrated at a more peripheral neuromuscular level as a single unit of action (Khan, Tremblay, Cheng, Luis, & Mourton, 2008).

The aim of the present experiment was to examine single and two hand extension and reversal movements in order to directly investigate the contributions of the central processes (proposed within the movement integration hypothesis) and the peripheral neuromechanical processes (proposed to account for the two target advantage) when integrating two target movements. To achieve this, we extended the two hand sequential aiming paradigm employed by Khan et al. (2010) to include movements with a reversal in direction. Hence, participants performed movements to a single target, two target movements with a single hand in which the second segment was either in the same or opposite direction to the first segment, and two target movements in which the hand was switched at the first target with the direction of the second segment either in the same or opposite direction to that of the first. Consistent with past research, we expected that the one target movement time advantage would emerge for single hand and two hand movements in which the second segment is in the same direction as the first. This finding would imply a cognitive locus of interference giving rise to the one target advantage. For single hand movements in which the second segment involves a reversal in direction, the one target movement time advantage should not emerge. This is because of the integration of muscular forces between the two segments whereby the antagonist of the first segment also serves as the agonist for the second segment. However, for reversal movements where the second segment is performed with a different hand than that used to move to the first, we expected the one target movement time advantage to be reinstated because of the lack of muscular integration at the peripheral level. That is, because the neuromechanical advantage of the bi-phasic muscle activation pattern is removed

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within two target two hand reversal movements, it was expected that the integration between the first and second elements would be governed by the processes within the movement integration hypothesis i.e., the implementation of the second segment would be performed concurrently with the execution of the first, resulting in increased cognitive processing load during response execution and a lengthening of movement time to the first target (compared to single target tasks).

Method

Participants

25 participants (14 men & 11 women; age = 22.5 years, $SD = 4.1$ years, age range = 18-33 years) volunteered to participate. All were self-declared right hand dominant and reported normal or corrected to normal vision. Participants signed consent forms before taking part in the experiment and the study was carried out according to the ethical guidelines stated by the Institutions Ethics Committee 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 table top in front of seated participants. The six keys were arranged in sets of 3 pairs along the participants' midline (see Figure 1a). The distance between each key in a pair was 35mm (centre to centre), and the distance between each pair was 150mm (centre to centre) resulting in an Index of Difficulty of 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. The apparatus was built as a circuit using a microcontroller (Microchip Technology; PIC18f452 running at 8Hz) that was designed to read the micro-switch status'. An auditory stimulus was connected to the same micro-circuit

and a Windows PC running a custom written Visual Basic 6 programme was used to send a command to the microcontroller via serial link. The microcontroller would then trigger the auditory stimulus, scan the micro-switch outputs, and measure the times of the presses and releases (the scan time of all switches was better than 1KHz and thus error was < 1msec). A short period (250 msec) after the last switch had been released, timing data was sent back to the PC. The Visual Basic 6 Programme wrote/read all data to the serial port, provided the experimenter interface, and output all data to an excel file.

Insert Figure 1 here

Task and Procedure

Participants performed 5 aiming tasks (see Figure 1 b). At the start of each trial, participants were required to place the index figure of their right hand on the right start position and the index finger of their left hand on the left target 1 key (see Figure 1b, left panel). In the one target (1T) task, participants moved their right hand from the start position to target 1. The left hand remained stationary on target 1. In the two target single hand extension (2T1He) task, participants moved their right hand from the start position to target 1 and then to target 2, pressing both targets with the same index finger. The left hand remained stationary on target 1. In the two target single hand with a reversal (2T1Hr) task, participants moved their right hand from the start position to target 1, and then moved the same hand back to the original start position. The left hand remained stationary on target 1. In the two target two hand extension (2T2He) task, participants moved their right hand from the start position to target 1 and then moved their left hand from its position on target 1 to target 2. In the two target two hand with a reversal (2T2Hr) task, participants moved their right hand from the

start position to target 1, and then moved their left hand from its position on target 1 to the left key of the start position. In both of the two hand tasks (2T2He and 2T2Hr), participants were told not to start the second movement until the first had been completed, but to make this changeover as quickly as possible¹.

At the beginning of each trial, participants were presented with a warning tone which was then followed by a stimulus tone after a 1500-2500 ms variable foreperiod. Participants were instructed to react and perform the movement(s) as quickly as possible in response to the onset of the stimulus tone.

Each participant was first given 20 practice trials in each task. They then completed 100 test trials (20 trials in each task). The 5 tasks were presented in blocks and counterbalanced between participants using a Latin Square design.

Statistical Methods

Dependent measures consisted of reaction time (RT), movement time to target 1 (MT1), pause time at target 1 (PT), and movement time from target 1 to target 2 (MT2).

RT was the interval from the presentation of the stimulus (auditory tone) to the release of the key press at the starting position. MT1 was measured from the release of the key press 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.

¹ Whilst we did not explicitly measure (count) anticipatory segment 2 starts (i.e., situations in which the second segment commenced prior to the end of first segment), if cases occurred data were saved as 'bad', omitted from the analysis, and the trial was repeated.

Separate 5 Task (1T; 2T1He; 2T1Hr; 2T2He; 2T2Hr) repeated measures ANOVAs were performed on RT and MT1 data, whilst separate 4 Task (2T1He; 2T1Hr; 2T2He; 2T2Hr) repeated measures ANOVAs were performed on PT and MT2 data. Assumptions surrounding ANOVA use were ensured and any violations to sphericity were addressed using Greenhouse-Geisser correction methods. Tukeys HSD post-hoc tests ($p < .05$) were performed on all significant main effects to locate significant differences.

Results

Trials in which RT was less than 100 ms or more than 700 ms were omitted from the analysis. This amounted to less than 4% of the trials. The means and *SDs* for all dependent variables are reported in Table 1.

Insert Table 1 here

Reaction Time (RT)

The analysis revealed a main effect for Task ($F_{(4,96)} = 3.90, p < .01, \eta^2 = .14$) with reaction times being significantly faster in the 1T task compared to all the two target tasks (see Figure 2).

Insert Figure 2 here

Movement Time 1 (MT1)

As shown in Figure 3, analysis of movement time to the first target revealed a main effect for Task ($F_{(2.47,59.47)} = 5.20, p < .01, \eta^2 = .18$). Post-hoc analysis revealed that MT1 for the 1T task was significantly shorter compared to the 2T1He, 2T2He and 2T2Hr tasks whilst

there was no significant difference between the 1T and 2T1Hr tasks. Finally, the 2T1Hr task had faster movement times to the first target than the 2T2He and the 2T2Hr tasks.

Insert Figure 3 here

Pause Time

The analysis of pause times at the first target revealed a significant main effect of Task ($F_{(1.94,46.56)} = 17.08$, $p < .001$, $\eta^2 = .42$) with post-hoc analysis indicating that tasks involving a single hand (i.e., 2T1He and 2T1Hr) had significantly longer pause times compared to tasks involving two-hands (i.e., 2T2He and 2T2Hr).

Movement Time 2 (MT2)

Movement times from the first to the second target were significantly faster in the single hand (i.e., 2T1He and 2T1Hr) tasks compared to the two hand (i.e., 2T2He and 2T2Hr) tasks where the second segment was performed with the non-dominant left hand ($F_{(2.21,52.99)} = 3.12$, $p < .05$, $\eta^2 = .12$).

Discussion

Increasing the number of targets in a sequence has been shown to increase the time taken to initiate and execute the first segment in the sequence (Glencross, 1980; Adam et al., 2000; Klapp, 1995, 2003; Khan et al., 2007, 2010). Previous research has revealed that the one target movement time advantage occurs in both single hand responses and manual aiming tasks in which the hands are switched at the first target (Khan et al, 2010). This finding suggested that interference arising from the integration between segments occurs at a central

level. In contrast to movements in which the second segment is in the same direction as the first, the one target movement time advantage does not emerge when the second movement involves a reversal in direction (Adam et al., 2000; Ketelaars, Garry, & Franks, 1997; Khan et al., 2006, 2007). This is because the antagonist activity of the first movement in a reversal sequence acts to decelerate the first segment and accelerate the second segment in the opposite direction. Hence, for movements involving a reversal in direction, there is a high degree of integration between segments at a more peripheral neuromuscular level. In the present study, single target movements were compared to two target movements performed with a single hand and two target movements in which there was a switch between hands at the first target. Crucially, for the purpose of this study, the second segment was in the same (i.e., an extension) or opposite (i.e., a reversal) direction to the first. This design enabled the effects of processes at the central (i.e., processes within movement integration hypothesis or the retrieval and implementation of motor programs during movement execution) and peripheral levels (i.e., processes associated with patterns of neuromuscular activity and the possible exploitation of the elastic muscle properties of the antagonist muscles of movement one being utilised as the agonist muscle groups of movement two in the two-target one-hand reversal task) to be distinguished in terms of their impact on the integration between response segments.

Reaction times were faster in the single target compared to the two target conditions. Since target conditions were administered in blocks of trials in the present study, this finding is consistent with past research in which participants knew the number of targets in advance of stimulus presentation (Khan et al., 2006; 2007; 2010; Klapp, 1995; 2003). Also, reaction time increased as a function of the number of targets regardless of whether both segments were performed with the same or different hands and whether the second segment was in the same or opposite direction to the first. Similar to past research (Khan et al., 2007; Klapp,

1995, 2003), this finding demonstrates that the critical factor that influences reaction time is the number of segments rather than the nature of the segments.

In line with our hypothesis and similar to previous research (Adam et al., 2000; Chamberlin & Magill, 1989; Helsen et al., 2001; Lavrysen et al., 2002; Khan et al., 2010), movement times to the first target were quicker when a single target response was required compared to when the first movement was followed by a second movement in the same direction (i.e., an extension movement). This one target movement time advantage was not limited to the control of movements performed with a single hand. Movement times were longer in two target extension conditions regardless of whether a single or two hand response was required. Additionally, the magnitude of the one target movement time advantage was similar for the single and two hand extension conditions (also see Khan et al., 2010; Lawrence et al., 2013). As suggested by Khan et al. (2010), these findings cannot be explained by the movement constraint hypothesis since the start position of the second segment is independent of the endpoint of the first segment in the two hand aiming sequence. Hence, the variability of movement endpoints at the first target should have no influence on the execution of the second segment. Instead, along the lines of the movement integration hypothesis, it appears that the implementation of the second segment during the execution of first leads to interference and hence the lengthening of movement times. Khan et al. (2010, 2011) have suggested that in order to ensure an efficient transition between segments, visual feedback is regulated during the first segment in order to time the implementation of the second segment. It is the central processes associated with the timing of the second segment that leads to interference and the one target movement time advantage (also see Ketelaars, Khan, & Franks, 1999).

Whilst, the data of the two target two hand tasks are difficult to explain via the movement constraint hypothesis, it is important to note that in the single hand extension task

the lengthening of MT1 could be due to a combination of central processes. That is, one cannot rule out the possibility that the implementation of the second movement (i.e., movement integration hypothesis) is achieved via an interaction of using visual information to regulate both the timing of this implementation *and* to adjust the movement trajectory in order to ensure an accurate start point of the pre-programmed movement two (i.e., movement constraint hypothesis). Thus, it is possible that the lengthening of movement times to the first target in the single hand extension task are a result of an interaction between the processes involved in the movement integration hypothesis and the processes involved in using vision to regulate movement trajectories and ensure movement accuracy. To investigate this further, future research should explicitly measure both the variability of movement endpoints together with the variability of movement kinematics throughout the trajectory of movement (for a review see Khan et al., 2006). Whilst speculative, one might reasonably predict that in two target single hand extension movements, the endpoint variability of movement one would be significantly less than those of single target movements (see Mottram et al., 2014). In addition, processes within both the movement constraint and the movement integration hypothesis would predict that participants would likely spend significantly more time after peak velocity and that trajectory kinematics would show greater use of online adjustments in the two target single hand extension movements compared to single target movements.

While the one target movement time advantage was present for both single and two hand responses when the second segment was in the same direction as the first (i.e., extension), the phenomenon was less robust when the second movement was a reversal in direction. Consistent with previous findings, the one target movement time advantage was not present in the single hand reversal task (e.g., Adam et al., 2001; Khan et al., 2006, 2010). In a two target reversal movement the elastic properties of the antagonist muscle group used to decelerate the first movement are also utilised to accelerate the limb in the second reversal

movement and therefore there is no need to dampen the mechanical fluctuations at the end of the first movement. This bi-phasic pattern of muscle activation allows for optimal integration between movements whereby the two segments are prepared and executed as a single unit of action (Adam et al., 2000; Khan et al., 2006).

Importantly, the key finding of the present study was that, in contrast to the one hand reversal task, the one target movement time advantage *was* present in the two hand reversal task. When the hands were switched at the first target, the integration of muscular activity at the peripheral level that occurs in the single hand condition was eliminated. Therefore, similar to extension movements, it appears that central processes associated with the implementation of the second element during execution of the first (i.e., the movement integration hypothesis) leads to interference and the emergence of the one target movement time advantage (it is unlikely that the lengthening of MT1 was a result of participants constraining the variability at target one since the start location of movement two was fixed in the two target two hand reversal condition).

Interestingly, movements requiring only a single hand paused at the first target for significantly longer periods of time than movements that required a switch in hands at the first target. This supports our central and peripheral explanations of the movement time data. That is, single hand movements are proposed to be controlled and integrated at a central and peripheral level, whereas two hand movements are proposed to experience reduced amounts of interference at the peripheral level as the two movements are implemented by two largely distinct and separate neuroanatomical effectors (Khan et al., 2010). Given these proposals, it can be assumed that pause times were longer in the single hand movements because of the interactive effects involved in the central processes (i.e., the accurate retrieval and implementation of the motor program) together with the peripheral processes (i.e., those involved in the concurrent muscular organisation of movement one and two) required to

ensure optimal integration and transition between the movements of the performing arm. In contrast, in the two limb conditions a central locus for performance is dominant as there is a switch between hands at the first target and therefore peripheral factors are largely redundant meaning only executive resources associated with central processes are required for movement integration.

Aside from the combined central and peripheral process explanation for the increased PTs in the two-target single-hand tasks, it is possible that the increased PTs are a result of additional central processes associated with the movement constraint hypothesis. That is, in the single hand tasks participants adopt central control strategies that involve both the implementation of the pre-programmed motor commands of movement two (i.e., the movement integration hypothesis) together with applying online control mechanisms to ensure accurate endpoint locations of movement one (i.e., the movement constraint hypothesis) (Khan et al., 2011). The reduced PTs of the two target two hand movements relative to the two target single hand movements, might therefore be due to the removal of the processes associated with constraining the endpoint of the first movement. When the hands are switched between the first and second movement the starting location of the second movement is not governed by the endpoint of the first and thus, in comparison to the two target single hand tasks, there is no immediate benefit of constraining the first movement in the two target two hand tasks. Whilst this interpretation does not allow the current research to tease apart the processes associated with the movement integration and the movement constraint hypothesis when explaining the integration of single hand sequential aiming tasks, the finding that the OTA was still present when hands were switched at target two (i.e., when constraining the first movement does not influence the starting location of the second movement) provides evidence that leans more heavily to explanations proposed within the movement integration hypothesis.

Movement times to the second target were faster in the two target single hand tasks compared to the two target two hand tasks. This may be accounted for via an activation and momentum viewpoint; whereby the limb was already active prior to the start of the second movement in the single hand tasks, but was initiated from a static position in the two hand tasks. In addition, performing the second movement with the non-dominant hand (left hand) in the two target two hand task could produce slower movement times; right hand advantage is well documented in manual aiming studies (Elliot & Chua, 1996). Future research may wish to investigate this handedness possibility further by either counterbalancing left and right hand starts or including the hand used (right versus left) to make the first and second movements as an independent variable.

Based on both reaction time and movement time evidence, researchers have proposed that segments in a target sequence are not prepared and controlled independently. According to the movement integration hypothesis, integration processes operating at the central and/or peripheral level mediate the coupling of movement segments and underlie the one target advantage (Adam et al., 2000). The current study adds to our understanding by experimentally distinguishing between the effects of movement integration at the central and peripheral level. The one target movement time advantage emerged when the second segment was an extension in direction of the first. Since this was the case for both single and two hand movements, it appears that the processes underlying the integration of same direction movement segments reside at a central level. A different pattern of results emerged for the conditions that included a movement reversal. Here it was found that using the same hand eliminated (or substantially reduced) the one target advantage, whereas using two different hands reinstated the one target advantage. As suggested by Adam et al. (2000) and Khan et al. (2008), reversal movements may be prepared as a single unit of action in order to exploit the mechanical characteristics of reversing direction. Therefore, while integration at

the central level may enhance the transition between segments that are in the same direction, it comes with the cost of increased movement times to the first target. However, movement time benefits are realised when integration at the peripheral level can be exploited for segments involving a reversal in direction. But, when the hands are switched at the first target, the use of different effector systems prohibits this integration at the peripheral neuromuscular level. Hence, unlike single hand reversal tasks, the movement times of reversal movements involving separate hands are impacted (i.e., slow down) by central processes in a manner similar to extension movements involving one or two limbs, thereby revealing a one target advantage. This is an important finding when ascertaining the role of the separate central processes involved in the movement integration and the movement constraint hypothesis and role these play in the integration of sequential aiming tasks. That is, regardless of the direction of movement two (extension or reversal) the integration between movements when there is a switch between hands at the first target is more likely governed by processes within the movement integration hypothesis (i.e., timing the implementation of the pre-programmed motor commands of the second movement during execution of the first) since there is no immediate benefit of constraining the movements of the first target when the starting location of movement two is fixed and known in advance of movement onset (i.e., in the two target two hand task). Finally, through revealing the OTA in the two, but not single hand reversal movements the current research is able to demonstrate for the first time the separate and contrasting roles of central (i.e., the retrieval and implementation of pre-programmed motor commands) and peripheral (i.e., the patterns of neuromuscular activity and the possible exploitation of the elastic muscle properties of the antagonist and agonist muscle groups) processes within movement integration.

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| | 1T | | 2T1He | | 2T1Hr | | 2T2He | | 2T2Hr | |
|-----|-----|-----------|-------|-----------|-------|-----------|-------|-----------|-------|-----------|
| | M | <i>SD</i> | M | <i>SD</i> | M | <i>SD</i> | M | <i>SD</i> | M | <i>SD</i> |
| RT | 269 | 50 | 293 | 62 | 292 | 66 | 289 | 55 | 289 | 59 |
| MT1 | 182 | 76 | 202 | 71 | 191 | 73 | 211 | 89 | 207 | 80 |
| PT | - | - | 112 | 37 | 112 | 43 | 78 | 32 | 81 | 33 |
| MT2 | - | - | 196 | 63 | 194 | 54 | 217 | 103 | 209 | 75 |

Table 1. Means and *SDs* of reaction time (RT), movement time to the first target (MT1), pause time (PT), and movement time to the second target (MT2) for the one target (1T), two target one hand extension (2T1He), two target one hand reversal (2T1Hr), two target two hand extension (2T2He), and two target two hand reversal (2T2Hr) tasks.

Figure Captions

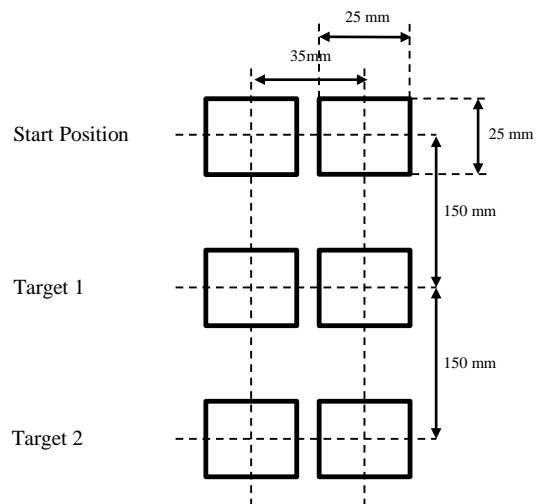
Figure 1. a) Target locations and size. b) Starting location of fingers and schematics of the 5 tasks used in the study; 1T = one target ; 2T1He = two-target single hand extension ; 2T2He = two-target two hand extension; 2T1Hr = two-target single hand with a reversal; 2T2Hr = two-target two-hand with a reversal.

Figure 2. Reaction time (and *SDs*) as a function of response task (1T = one target; 2T1He = two target one hand extension; 2T1Hr = two target one hand reversal; 2T2He = two target two hand extension; 2T2Hr = two target two hand reversal).

Figure 3. Movement times (and *SDs*) to target 1 as a function of response task (1T = one target; 2T1He = two target one hand extension; 2T1Hr = two target one hand reversal; 2T2He = two target two hand extension; 2T2Hr = two target two hand reversal).

Figure 1.

a



b

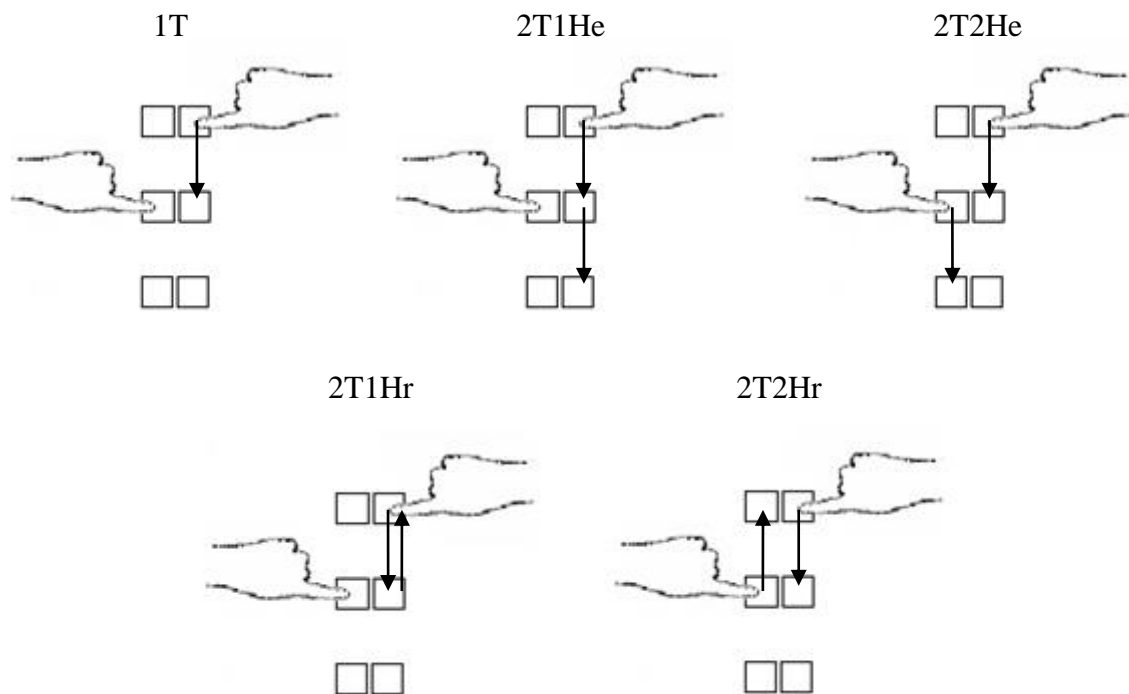


Figure 2.

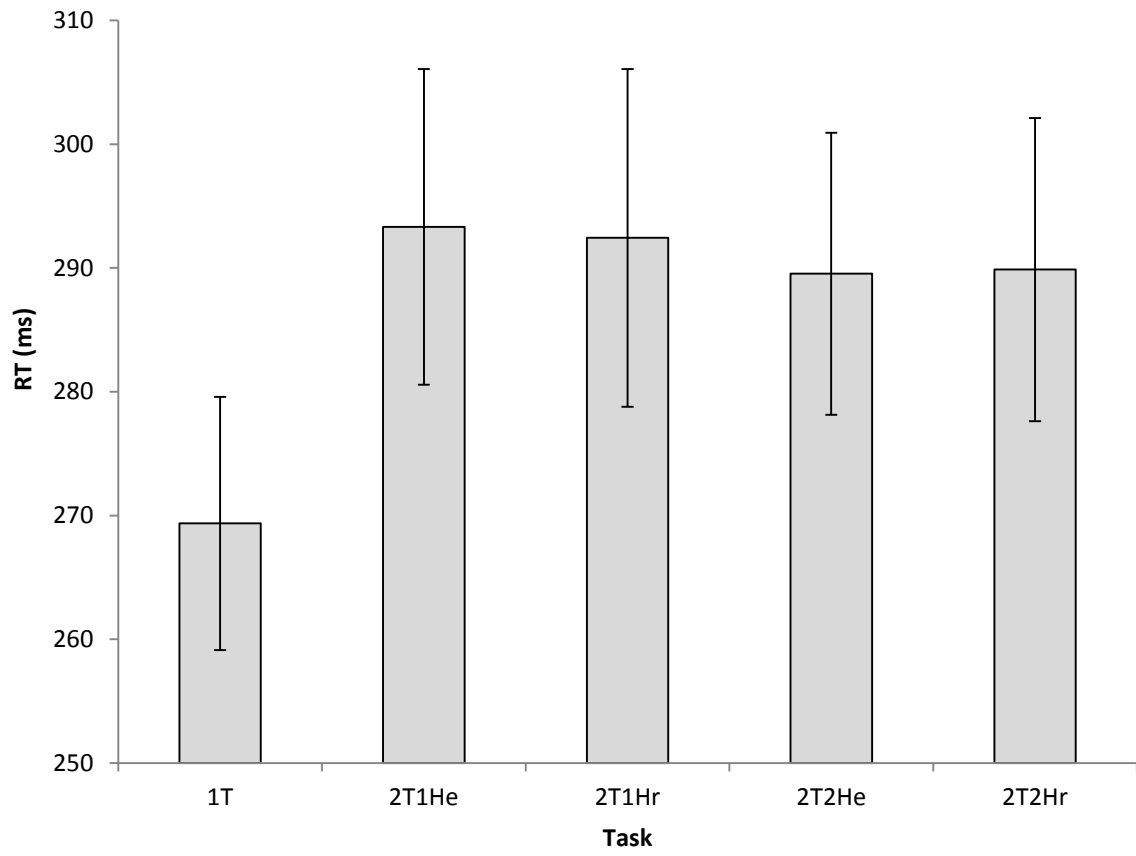


Figure 3.

