

Running head: Gunslinger effect and Müller-Lyer illusion

Title: Gunslinger effect and Müller-Lyer illusion: examining early visual information processing for late limb-
target control

James W. Roberts^a,

Jim L. Lyons^a, Daniel B. L. Garcia^a, Raquel Burgess^a, & Digby Elliott^{a,b}

^a Motor Control Laboratory, Department of Kinesiology, McMaster University,
Hamilton, L8S 4L8, Canada

^b Brain & Behaviour Laboratory, Liverpool John Moores University
Liverpool, L3 5AF, UK

Corresponding author:

James W. Roberts

Department of Kinesiology

McMaster University

Hamilton, ON, L8S 4L8, Canada

E-mail: robjames@mcmaster.ca

Accepted author manuscript version reprinted, by permission, from Motor Control, 2016,

<http://dx.doi.org/10.1123/mc.2015-0079>. © Human Kinetics, Inc.

Abstract

The multiple process model contends that there are two forms of online control for manual aiming: impulse regulation and limb-target control. This study examined the impact of visual information processing for limb-target control. We amalgamated the Gunslinger protocol (i.e., faster movements following a reaction to an external trigger compared to the spontaneous initiation of movement) and Müller-Lyer target configurations into the same aiming protocol. The results showed the Gunslinger effect was isolated at the early portions of the movement (peak acceleration and peak velocity). Reacted aims reached a longer displacement at peak deceleration, but no differences for movement termination. The target configurations manifested terminal biases consistent with the illusion. We suggest the visual information processing demands imposed by reacted aims can be adapted by integrating early feedforward information for limb-target control.

Keywords: limb-target control, visual feedback processing, feedforward

Introduction

There are many explanations as to how individuals deal with speed-accuracy relations for the control of goal-directed movement (Beggs & Howarth, 1972, Crossman & Goodeve, 1983; Keele, 1968; Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Woodworth, 1899), however the general consensus is that performers amend errors associated with the initial ballistic movement to successfully land on the target (cf. Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). Recently, Elliott and colleagues (2010) brokered the multiple process model of limb control to elucidate the uses of sensorimotor information to alleviate the stochastic properties of the motor system along with the sensory processing time delays imposed by error corrections. That is, they proposed both an early/feedforward (*impulse regulation*) and late/feedback (*limb-target*) control system. The former control process features a comparison between the predicted and actual sensory consequences, and involves early regulation of limb direction and velocity (Grierson & Elliott, 2008; Hansen, Tremblay, & Elliott, 2008). It is assumed to be a more egocentric mode of control (body-centred) as the external spatial coordinates are coded in peripersonal space with subsequent changes to the limb's trajectory resulting from the parafovea, which could then potentially cause the performer to resist any influence of an illusory target configuration (e.g., Müller-Lyer illusion; Grierson & Elliott, 2009a). Meanwhile, the latter control process depends on the relation between the limb and target location, and is typically featured toward the end of the movement (Pratt & Abrams, 1996; Woodworth, 1899; see Grafton & Desmurget, 2000). It is suggested to encompass a more allocentric mode of control (environment-centred), where the performer can more readily code spatial coordinates in extrapersonal space using central vision and be more heavily influenced by an illusory target configuration (cf. Glover, 2004).

On a separate note, recent evidence from aiming in pairs of individuals has revealed underlying temporal differences between reaction and initiation. That is, aiming in reaction to a stimulus generates faster movements than movements that are initiated (Pinto, Otten, Cohen, Wolfe, & Horowitz, 2011; Welchman,

Stanley, Schomers, Miall, & Bulthoff, 2010). This reacted movement time advantage has been attributed to dichotomous neural processes surrounding the disinhibition of internally and externally generated actions (Cunnington, Windischberger, Robinson, & Moser, 2006; Obhi, Matkovich, & Chen, 2009; Rushworth, Hadland, Paus, & Sipila, 2002). Recently, La Delfa and colleagues (2013) investigated where in the movement these temporal differences unfold. They found the reacted advantage manifested in the time to peak velocity, and referred to this as the 'Gunslinger effect'. It is noteworthy that movement time differences between reacted and initiated movements have failed to elicit a trade-off between speed and accuracy. That is, terminal errors (Welchman et al., 2010) and biases (La Delfa et al., 2013) have not reflected systematic differences between the two types of aims. However, there has yet to be an examination of the potential impact toward prior kinematic landmarks (peak acceleration, peak velocity, peak deceleration) that are associated with early feedforward processes, along with the terminal endpoint location (e.g., undershoot or overshoot of target centre) following late limb-target control. Indeed, such examination may garner further understanding of the associated control processes underlying the 'Gunslinger effect'.

Because limb-target control involves a relation between the limb and target location, and occurs near the end of the movement, it relies on visual feedback processes that take time to unfold (Elliott, Hansen, Mendoza & Tremblay, 2004). That is, there is additional time required in order to process visual feedback during the deceleration phase of the movement (Elliott et al., 2010; Meyer et al., 1988). Thus, extending the time prior to movement termination affords a longer visual feedback processing time for limb-target control. In a similar vein, one might expect a longer feedback processing time in slower initiated aims compared to reacted aims. Although movement time differences between reacted and initiated aims do not impact speed-accuracy trade-offs, it is possible that differences unfold in limb-target control near the end of the movement. That is, the temporal differences may underlie changes in terminal biases as a function of the target configuration. Indeed, it has been shown that in the absence of vision, performers engage in less online control

(Elliott et al., 2014; Khan, Franks, & Goodman, 1998). Moreover, amendments toward the perceived and/or remembered target location appear to unfold near the end of the movement (or following peak velocity) (Grierson & Elliott, 2009a, b; Roberts et al., 2013). For example, following movement onset, changes to a tails-in or tails-out Müller-Lyer figure elicit terminal biases consistent with illusory context (i.e., undershoot to perceptually shorter tails-in, overshoot to perceptually longer tails-out). These illusory target biases unfold late in the movement because the performer becomes increasingly influenced by the perceived target context once visual feedback processes begin to intervene (Mendoza, Elliott, Meegan, Lyons, & Welsh, 2006; see also Elliott et al., 2010). Taken together, we propose the shorter movement times following reacted compared to initiated aims will afford a shorter visual feedback processing time. Consequently, reacted aims will elicit terminal biases that are less consistent with the illusory target context compared to the slow initiated aims. On the other hand, the impulse regulation processes preceding limb-target control involve at least some pick-up of sensory information pertaining to the target context (Elliott et al., 2010). More precisely, the system begins to anticipate corrections with respect to the target context as early as peak acceleration. Indeed, there is evidence to suggest performers can make adjustments to the propulsive forces generated early in the movement (peak acceleration) following sudden changes to the target configuration (Grierson & Elliott, 2009b). Therein, despite being limited in-time by delayed visual feedback processes, limb-target control may be supplemented by the visual reafferent processes associated with the early phases of the movement (i.e., impulse regulation). In this situation, the performer should still be able to adapt to the shorter visual feedback processing times of reacted aims to produce terminal biases that are similar to initiated aims.

To this end, the present study sought to examine late limb-target control following reacted and initiated aims. Pairs of participants freely executed fast and accurate aims with the caveat that, following an initial response from the confederate, they themselves must react and generate a response. The targets were either a tails-in, control or tails-out configuration (see Figure 1b), thus recreating the Müller-Lyer illusion. Firstly, we

predicted there would be a shorter time following a reaction compared to an initiation. If limb-target control is underpinned by temporally-constrained visual feedback processing then we would predict a greater influence of target context on slower initiated aims as demonstrated by a terminal and/or displacement bias that is consistent with the illusory context (e.g., greater undershoot toward the tails-in and overshoot toward the tails-out) (cf. Glover & Dixon, 2002; Milner & Goodale, 1995). Alternatively, if limb-target control is able to adapt to feedback processing time differences then both reacted and initiated aims will equally reflect illusory biases consistent with the perceived target location. In addition, we extended earlier work from our lab (La Delfa et al., 2013) by examining the influences of the Gunslinger effect on the spatial, as well as the temporal, characteristics of the movement trajectory.

Methods

Participants

Sixteen participants (12 male, 4 female) agreed to take part in the study. All participants were self-declared right-handed, had normal or corrected-to-normal vision and were between 19 and 38 years old. Participants were randomly assigned to gender-matched pairs (see La Delfa et al., 2013). This matching procedure ensured there was no confounding influence of gender (Hansen & Elliott, 2009). The study was in accordance with the Declaration of Helsinki and approved by the local ethics committee.

Apparatus, Task and Procedures

Movements were recorded via an infrared sensor attached the index finger of the participant and recorded using Optotrak (Northern Digital Inc., Waterloo, ON) sampling at 200 Hz for a duration of 8 s. The experiment was controlled via a custom software designed routine on E-prime (Psychology Software Tools Inc., Sharpsburg, PA) that displayed a black-to-white image display on a LCD monitor (temporal resolution =

60 Hz; spatial resolution = 1024 x 768 pixels) positioned in the sagittal plane near the edge of the workspace. The change in the colour display was used to mark the onset of a trial. Participants performed in pairs and sat freely at a table directly opposite each other with the same target configuration displayed on the table-top directly in front of them (Figure 1a and 1b). The target was one of three possible Müller-Lyer configurations corresponding to tails-in, control or tails-out (Figure 2). The vertex of the figure was presented at the midline and 255 mm from the starting trigger. Previous evidence from similar rapid goal-directed reaching tasks featuring the presence of vision indicate terminal biases that are consistent with the perceived context of the illusion (Grierson & Elliott, 2008; 2009b; Mendoza et al., 2006).

Insert Figure 1 and Figure 2 about here

The experimental task was to execute single fast-and-accurate aiming movements along the midline of the body and toward the target placed in front (i.e., vertex of the figure) at any moment during the 8 s trial. However, in the event one member of the pair initiated a response, the other participant had to reciprocate by executing an aim toward their own target. Trial preparation was marked by a written instruction on the black monitor display instructing participants to relocate their index finger to the start position at a table-mounted trigger. Following a random foreperiod (2000-3200 ms), the monitor display would change to white to signal the option to move. Providing neither participant initiated a movement within the 8 s, the trial ended and the next trial commenced. The selection of aiming movement was determined by the participants themselves. There were a total of 180 self-selected aiming trials with each of the target conditions presented in blocks and counter-balanced between participants. The proportional range of the two types of aims was 34-66%.¹

Dependent measures and Statistical analyses

Time-series position data were processed using a dual-pass second-order Butterworth filter at a low-pass cut-off frequency of 10 Hz. The data were differentiated and double-differentiated to obtain velocity and acceleration respectively. Movement onset was determined by the moment velocity in the primary movement axis (y-axis) reached above 30mm/s for 40 ms or more. Movement offset was determined by identifying the moment that velocity in the primary movement axis fell below 30mm/s for 40ms or more. Trials that featured reaction times less than 100 ms (i.e., double-initiation) or greater than 1000 ms (14.14% of trials) and movements terminated outside of the target (≥ 30 mm; see La Delfa et al., 2013) (0.15% of trials) were removed from the analysis. Dependent measures included constant error (CE), time to, time after, and amplitude displacement at, kinematic landmarks including peak acceleration (PA), peak velocity (PV), peak deceleration (PD) and movement end (END). We also determined measures of dispersion including variable error (VE) and spatial variability at kinematic landmarks. Central tendency measures (CE, time to kinematic landmarks, displacement at kinematic landmarks) and VE were analysed using a 2 trial category (reacted, initiated) by 3 target (tails-in, control, tails-out) repeated-measures ANOVA. Finally, spatial variability was analysed using a 4 kinematic (PA, PV, PD, END) by 2 trial category (reacted, initiated) by 3 target (tails-in, control, tails-out) repeated-measures ANOVA. In the event of a violation of sphericity (as indicated by Mauchly's test of sphericity; $p < .05$), the Huynh-Feldt correction was used when ϵ was greater than or equal to .75, whereas the Greenhouse-Geisser correction was used when ϵ was less than .75. Significant effects featuring more than two means were decomposed using the Tukey HSD post hoc procedure. Significance was declared at $p < .05$.

Results

Gunslinger effect

For movement time, there were no significant effects of trial category, $F < 1$, and target, $F(2, 30) = 1.12$, $p > .05$, $partial \eta^2 = .07$, nor a trial category by target interaction, $F < 1$. However, there was a significant main effect of trial category for the time to peak acceleration, $F(1, 15) = 8.86$, $p < .05$, $partial \eta^2 = .37$, and time to peak velocity, $F(1, 15) = 4.63$, $p < .05$, $partial \eta^2 = .24$, indicating a shorter time for the reacted compared to the initiated trials (Table 1). The time to peak deceleration indicated no significant effect of trial category, $F < 1$, and target, $F < 1$, nor a trial category by target interaction, $F(2, 30) = 1.53$, $p > .05$, $partial \eta^2 = .09$. For the time after kinematic landmarks, there were no significant main effects of trial category ($Fs < 1$), and target (peak acceleration: $F(2, 30) = 1.37$, $p > .05$, $partial \eta^2 = .08$; peak velocity: $F(2, 30) = 1.39$, $p > .05$, $partial \eta^2 = .09$; peak deceleration: $F(2, 30) < 1$), nor a trial category by target interaction ($Fs < 1$). Therefore, the reacted temporal advantage ('Gunslinger effect') was localised to the time to early-mid kinematic landmarks, and appeared to dissipate at peak deceleration, and subsequently overall movement time.

Insert Table 1 about here

Reacted movements and illusory biases in terminal position and amplitude displacement

For CE, there was no significant main effect of trial category, $F < 1$, although there was a significant main effect of target, $F(2, 30) = 26.15$, $p < .05$, $partial \eta^2 = .64$, indicating a greater undershoot for tails-in ($M = -1.6$ mm, $SE = 1.0$) compared to control ($M = -.6$ mm, $SE = .9$) and tails-out ($M = 1.6$ mm, $SE = 1.0$) figures. The difference between control and tails-out figures approached conventional levels of significance ($p = .08$). There was no significant trial category by target interaction, $F < 1$. For the displacement at peak acceleration, there were no significant main effects of trial category, $F(1, 15) = 1.56$, $p > .05$, $partial \eta^2 = .09$, and target, $F < 1$, nor a trial category by target interaction, $F(2, 30) = 1.52$, $p > .05$, $partial \eta^2 = .09$. Similarly, there were no significant main effects of trial category, $F < 1$, and target, $F < 1$, nor a trial category by target interaction, $F(2,$

30) = 1.29, $p > .05$, *partial* $\eta^2 = .08$, for the displacement at peak velocity. However, the displacement at peak deceleration revealed a significant main effect of trial category, $F(1, 15) = 16.48$, $p < .05$, *partial* $\eta^2 = .52$, indicating a longer amplitude displacement for reacted compared to initiated trials (Table 2). In addition, there was no significant main effect of target, $F < 1$, nor a trial category by target interaction, $F(2, 30) = 2.28$, $p > .05$, *partial* $\eta^2 = .13$. Meanwhile, for the displacement at movement end, there was no significant main effect of trial category, $F < 1$, though there was a significant main effect of target, $F(2, 30) = 28.09$, $p < .05$, *partial* $\eta^2 = .65$, indicating a greater undershoot for tails-in compared to control and tails-out figures, whilst the difference between control and tails-out figures approached significance ($p = .08$) (Table 3; see also CE results). There was no significant trial category by target interaction, $F(2, 30) = 1.71$, $p > .05$, *partial* $\eta^2 = .10$. These results point to similar displacement biases for reacted and initiated aims despite there being differences in temporal performance. This suggests faster reacted aims were adapted by incorporating early reafferent information for limb-target control.

Insert Tables 2 and 3 about here

Spatial Dispersion

For VE, there were no significant main effects of trial category, $F(1, 15) = 2.30$, $p > .05$, *partial* $\eta^2 = .13$, and target, $F(2, 30) = 1.37$, $p > .05$, *partial* $\eta^2 = .08$, nor a trial category and target interaction, $F(2, 30) = 1.16$, $p > .05$, *partial* $\eta^2 = .07$. For spatial variability, there was a significant main effect of kinematic landmark, $F(3, 45) = 65.99$, $p < .05$, *partial* $\eta^2 = .82$, as participants incrementally increased levels of dispersion from peak acceleration to peak deceleration prior to achieving lower levels at movement end. In addition, there was a trial category by target interaction that almost reached significance, $F(2, 30) = 3.31$, $p = .05$, *partial* $\eta^2 = .18$,

indicating less dispersion for reacted ($M = 10.0$ mm, $SE = 0.6$) compared to initiated ($M = 11.4$ mm, $SE = 0.7$) trials when aiming toward the tails-in figure.

Supplementary Movement Time Bin Analysis

It could be argued that the magnitude of temporal differences showed for reacted and initiated aims, which are assumed to underlie differences in visual feedback processing (shorter visual feedback for the reacted aims), may not be substantial enough to register any changes in limb-target control. That is, the seeming adaptation of fast reacted aims toward the illusory target context may in fact result from the same procedures governing slowed initiated aims. To investigate this possibility, both reacted and initiated trials were collapsed and a median split of the movement time data was conducted in order to form both fast and slow trials. This way, there would be more salient visual feedback processing time differences. The separation of movement times resulting from such spontaneous stereotypical responses also serves the advantage of preventing performers from adapting their movements as a function of imposed temporal constraints (e.g., Carlton, 1994; Elliott, Chua, Pollack, & Lyons, 1995; Mendoza et al., 2006). Temporal (movement time, time to kinematic landmarks) and displacement (CE, amplitude displacement at kinematic landmarks) measures were then each submitted to a 2 time (fast, slow) by 3 target (tails-in, control, tails-out) repeated-measures ANOVA. Significant effects featuring more than two means were decomposed using the Tukey HSD post hoc procedure ($p < .05$). If there was no feedforward adaptation to supplement limb-target control, and corrective processes are solely underpinned by delayed feedback-based processes, then we would anticipate a greater illusory target bias for slow compared to fast movements (cf. Glover & Dixon, 2002; Milner & Goodale, 1995). On the other hand, if limb-target control is supplemented by visual reafferent processes unfolding earlier in the movement then the biases should manifest regardless of movement time.

For movement time, there was significant main effect of time, $F(1, 15) = 324.44$, $p < .05$, $partial \eta^2 = .96$, indicating a significantly shorter movement time for fast ($M = 321.3$ ms, $SE = 15.3$) compared to slow ($M = 409.7$ ms, $SE = 16.8$) trials. There was no significant main effect of target, $F > 1$, nor a time by target interaction, $F > 1$. The time to kinematic landmarks showed the effect of time was evident throughout the entire movement trajectory (including peak acceleration, peak velocity, peak deceleration) ($ps < .05$). Moreover, there was no significant effect of target, $F_s < 1$, nor a significant time by target interaction ($ps > .05$) at any of the landmarks. The comparatively large movement time differences found between each category of time (M difference = 88.4 ms $SE = 4.9$) meant we could more closely detect the influence of visual feedback processing on terminal error and displacement as originally intended.

For CE, there was no significant main effect of time, $F(1, 15) = 3.29$, $p > .05$, $partial \eta^2 = .18$, although there was a significant effect for target, $F(2, 30) = 28.34$, $p < .05$, $partial \eta^2 = .65$, indicating a greater undershoot for tails-in ($M = -1.72$ mm, $SE = 1.00$) compared to control ($M = .60$ mm, $SE = .90$) and tails-out ($M = 1.53$ mm, $SE = .1.00$) figures. There was no significant time by target interaction, $F(2, 30) = 1.39$, $p > .05$, $partial \eta^2 = .09$. The displacement at kinematic landmarks showed neither significant main effects of time, and target, nor a time by target interaction ($ps > .05$). Therefore, similar to our previous analyses on reacted and initiated aims, the illusory target bias resulting after limb-target control unfolded the same for fast and slow movements featuring differences in visual feedback processing, which would lend support to the claim that feedforward control processes accommodate limb-target control at the end of the movement.

Discussion

The multiple process model of limb control (Elliott et al., 2010) suggests there are two forms of online control: early impulse regulation, and late limb-target control. Limb-target control is suggested to involve a delayed feedback-based comparison between the limb and target location near the end of the movement. The

current study sought to examine the impact of the differential processing times elicited by reacted and initiated aims on limb-target control. Firstly, it was predicted that reacted aims would be associated with shorter movement times than initiated aims. Because limb-target control is associated with longer visual feedback processing times, we also predicted greater illusory target bias for the initiated movements (cf. Glover & Dixon, 2002). Alternatively, if the feedforward control processes of impulse regulation can also inform the feedback-based processes of limb-target control then both initiated and reacted aims should equally manifest illusory target biases.

Firstly, there was a significant Gunslinger effect shown in the early-mid kinematic landmarks as there were shorter times to peak acceleration and peak velocity in reacted compared to initiated aims. There were no such differences for the time to peak deceleration, nor in the time after kinematic landmarks. These findings are in line with evidence of the Gunslinger effect unfolding within the initial phases of aimed movements (i.e., during early impulse regulation) (La Delfa et al., 2013). Surprisingly, the initial temporal differences found in the current study failed to influence the overall movement time. Though at first glance, this appears to conflict with previous studies, it is instructive to examine the fundamental differences between experimental aiming tasks. For example, the original Gunslinger study (Welchman et al., 2010), along with recent work from our lab (La Delfa et al., 2013), adopted a sequence aiming task featuring multiple segments. The present study featured only a single aimed response. It may be that the underlying contribution of planning and control processes differed as a function of the number of movement segments (see Adam et al., 2000). In this methodological context we should also consider underlying differences in alternative classes of movement which have also demonstrated the Gunslinger effect, including karate punching (Martinez de Qual & Bennett, 2014) and keyboard button pressing (i.e., release '5' and press '4'; Pinto et al., 2011). Indeed, these movements may have limited the contribution of on-line control processes and reduced the limb degrees-of-freedom respectively. This was not the case in the present study. Instead, it may be that following a reaction there is a

greater need to engage in late feedback-based control in order to reduce the impact of the greater initial acceleration (Schmidt et al., 1979; Sidaway, Sekiya, & Fairweather, 1995). This type of compensation would reduce any overall movement time differences between reacted and initiated aims. Therefore, the Gunslinger effect may be isolated at the initial portions of the movement and/or manifest throughout the entire movement depending on the nature of the performed task.

As well as temporal differences, there was an effect of trial category for the spatial components of the task. Specifically, there was a longer amplitude displacement for reacted compared to initiated aims at peak deceleration. This evidence further emphasises the advantage served by reacting compared to initiating movements as performers travelled further without a movement time cost. In addition, there were no systematic differences between reacted and initiated aims at the end of the movement, which highlights the failure of this initial reactive advantage to impact the movement goal. At the same time, there was an effect of target configuration that was consistent with the direction of the illusion. The impact of target configuration was focused at the end of the movement with little or no impact during earlier phases. The illusory biases reflected here are in line with many other experiments from our lab (e.g., Grierson & Elliott, 2009a, b; Roberts et al., 2013), and have been attributed to the limb-target control manifesting near the end of the movement.

Of interest, there was limited influence of the Gunslinger effect on the displacement and terminal endpoint resulting from the target configuration. That is, the reacted and initiated aims elicited similar terminal biases that were consistent with the illusory context (i.e., greater undershoot for the perceptually shorter tails-in figure compared to control and tails-out figures). At first glance, it appears that the separate Gunslinger and target manipulations impacted independent limb control processes (see Sternberg, 1969; Grierson & Elliott, 2009a for additive factor logic). However, the temporal differences caused by the Gunslinger manipulation would suggest performers adapted their movements in order to accommodate any feedback processing time-lag. In a similar vein, the parsing of movement times into fast and slow for our supplementary analysis, where

more robust visual feedback processing time differences could be examined, showed illusory target biases were independent of the elapsed time. Though it is possible the illusory target biases resulted from individual differences in visual feedback processing, within the context of the multiple process model (Elliott et al., 2010), we suggest the visual reafferent processes associated with early impulse regulation supplemented the visual feedback processes underlying limb-target control toward the end of the movement. This conjecture is supported by recent evidence pertaining to the multiple process model (Elliott et al., 2010), which indicates impulse regulation and limb-target control are not as dichotomous as first thought (cf. Grierson & Elliott, 2009a). For example, it has been shown that the timing and magnitude of early peak acceleration are sensitive to unexpected changes in target configuration (Grierson & Elliott, 2008; 2009b). Moreover, the illusory target biases exhibited at the end of movement following no vision are different to those that are present when the performer is provided a brief sample of vision during the early phases of the movement (i.e., first 200ms; Roberts et al., 2013). Together, it appears that there is an amalgamation of visual inputs for the dynamic limb control associated with impulse regulation and the more discrete comparison process associated with limb-target control. The current findings elaborate on this proposed integration by indicating that performers may not so much overcome the visual feedback processing time-lag as adapt to its temporal constraints.

The fact that there were differences in the time to early kinematic landmarks associated with impulse regulation, yet there were no differences in illusory target biases resulting from limb-target control, highlights the capacity of the sensorimotor system to coordinate visual inputs for both control processes. To elucidate, the response-produced visual information allowing for early trajectory control may also supplement amendments made later toward the target location. In addition, the performer may reference pre-planned allocentric codes pertaining to the target configuration when in the early phases of the movement. These suggestions are supported by our spatial variability findings. That is, for both reacted and initiated aims there was a gradual increase in spatial dispersion until peak deceleration followed by a pronounced decrease in

variability between peak deceleration and the end of the movement. Thus, independent of the initial temporal performance, and subsequent impact on visual information processing, the reacted aims may adapt by engaging similar control processes as the initiated aims following the integration of visual information for feedforward dynamic limb control to a target-based mode of control.

With respect to spatial dispersion, we also found reacted aims generated less spatial variability toward the tails-in configuration compared to the initiated aims. This finding is somewhat counterintuitive given the greater amplitude displacement at peak deceleration associated with reacted aims. Indeed, there is a departure from typical speed-accuracy findings where greater amplitude movements are associated with an increase in spatial variability (e.g., Elliott et al., 2001; Fitts, 1954; Meyer et al., 1988; Schmidt et al., 1979; Worringham, 1991). Perhaps this finding reflects somewhat different spatial coding for the two categories of aiming movements. Though reacted and initiated aims both coordinate the visual inputs designed for impulse regulation and limb-target control, the respective contribution of allocentric reference codes elucidating illusory target biases may differ. That is, the longer visual information processing time of initiated aims may have allowed the allocentric reference codes to be more extensively incorporated with the egocentric inputs, which are typically manifested earlier in the movement. This argument is consistent with previous suggestions of egocentric and allocentric reference frames operating in tandem, and perhaps even informing one another (Adam, Mol, Pratt, & Fischer, 2006; Glover, 2004; Roberts et al., 2013). Meanwhile, during fast reacted aims, there is less opportunity in time to incorporate the egocentric and allocentric reference frames, thus generating levels of dispersion that are commensurate with the magnitude of displacement (i.e., less dispersion following perceptually shorter amplitude). In other words, the reacted and initiated aims involve the same control processes for impulse regulation and limb-target control, although potentially differ as a result of the relative contribution of allocentric and egocentric reference codes.

In summary, the present study found performers move faster following a reaction, as opposed to initiating the movement; something referred to as the 'Gunslinger effect'. These temporal differences were localised to the early-mid phases of the movement, and appeared to dissipate near movement termination. The temporal advantage served by reacting translated to an extended amplitude displacement at peak deceleration. Meanwhile, the illusory target context imposed terminal biases that were consistent with the direction of the illusion. Thus, in agreement with the multiple process model of limb control (Elliott et al., 2010), we suggest both the Gunslinger effect and target context primarily exercise early impulse regulation and late limb-target control, respectively. However, the similar times after kinematic landmarks and similar patterns of dispersion leads us to posit that both sets of aims featured a coordinated contribution of visual inputs for the two control processes. That is, the shorter time afforded for visual information processing during reacted aims may have been compensated for by incorporating the visual inputs from earlier in the movement and/or continuous referencing to allocentric cues gathered in movement planning. To our knowledge, these are some of the first findings to demonstrate an adaptation of limb-target control following spontaneous changes in visual feedback processing. Future research may wish to examine the extent of this adapted control by imposing a similarly spontaneous, but more salient, visual processing time difference.

Acknowledgements

This project was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant (386762-2010RGPIN).

References

- Adam, J. J., Mol, R. Pratt, J., & Fischer, M. H. (2006). Moving farther but faster: an exception to Fitts's Law. *Psychological Science, 17*, 794-798.
- Adam, J. J., Nieuwenstein, J. H., Huys, R., Paas, F. G. W. C., Kingma, H., Willems, P., & Werry, M. (2000). Control of rapid aimed hand movements: The one-target advantage. *Journal of Experimental Psychology: Human Perception and Performance, 26*, 295-312.
- Beggs, W. D. & Howarth, C. I. (1972). The accuracy of aiming at a target: Some further evidence for a theory of intermittent control. *Acta Psychologica, 36*, 171-177.
- Carlton, L. (1994). The effects of temporal-precision and time-minimization constraints on the spatial and temporal accuracy of aimed hand movements. *Journal of Motor Behavior, 26*, 43-50.
- Crossman, E. R. & Goodeve, P. J. (1983). Feedback control of hand-movement and Fitts' Law. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 35A*, 251-278.
- Cunnington, R., Windischberger, C., Robinson, S., & Moser, E. (2006). The selection of intended actions and observation of others' actions: a time-resolved fMRI study. *Neuroimage, 29*, 1294-1302.
- Desmurget, M. & Grafton, S. (2000). Forward modelling allows feedback control for fast reaching movements. *Trends in Cognitive Psychology, 4*, 423-431.

- Elliott, D., Chua, R., Pollack, B. J., & Lyons, J. L. (1995). Optimizing the use of vision in manual aiming: the role of practice. *The Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, 48(A), 72-83.
- Elliott, D., Dutoy, C., Andrew, M., Burkitt, J. J., Grierson, L. E. M., Lyons, J. L., Hayes, S. J., & Bennett, S. J. (2014). The influence of visual feedback and prior knowledge about feedback on vertical aiming strategies. *Journal of Motor Behavior*, 46, 433-443.
- Elliott, D., Hansen, S., Grierson, L. E. M., Lyons, J., Bennett, S. J., & Hayes, S. J. (2010). Goal-directed aiming: two components but multiple processes. *Psychological Bulletin*, 136, 1023-1044.
- Elliott, D., Hansen, S., Mendoza, J. & Tremblay, L. (2004). Learning to optimise speed, accuracy and energy expenditure: A framework for understanding speed-accuracy relations in goal-directed aiming. *Journal of Motor Behavior*, 36, 339-351.
- Elliott, D., Helsen, W. F., & Chua, R. (2001). A century later: Woodworth's two-component model of goal directed aiming. *Psychological Bulletin*, 127, 342-357.
- Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, 47, 381-391.
- Glover, S. (2004). Separate visual representations in the planning and control of action. *Behavioral and Brain Sciences*, 27, 3-78.

- Glover, S. & Dixon, P. (2002). Dynamic effects of the Ebbinghaus illusion in grasping: support for a planning/control model of action. *Perception & Psychophysics*, 64, 266-278.
- Grierson, L. E. M. & Elliott, D. (2008). Kinematic analysis of goal-directed aims made against early and late perturbations: An investigation of the relative influence of two online control processes. *Human Movement Science*, 27, 839-856.
- Grierson, L. E. M. & Elliott, D. (2009a). Goal-directed aiming and the relative contribution of two online control processes. *American Journal of Psychology*, 122, 309-324.
- Grierson, L. E. M. & Elliott, D. (2009b). The impact of real and illusory target perturbations on manual aiming. *Experimental Brain Research*, 197, 279-285.
- Hansen, S. & Elliott, D. (2009). Three-dimensional manual responses to unexpected target perturbations during rapid aiming. *Journal of Motor Behavior*, 41, 16-29.
- Hansen, S., Tremblay, L., & Elliott, D. (2008). Real-time manipulation of visual displacement during manual aiming, *Human Movement Science*, 27, 1-11.
- Keele, S. W. (1968). Movement control in skilled motor performance. *Psychological Bulletin*, 70, 387-403.

- Khan, M. A., Franks, I. M., & Goodman, D. (1998). The effect of practice on the control of rapid aiming movements: Evidence for an interdependency between programming and feedback processing. *The Quarterly Journal of Experimental Psychology*, 51(A), 425-444.
- La Delfa, N. J., Garcia, D. B. L., Cappelletto, J. A. M., McDonald, A. C., Lyons, J. L., & Lee, T. D. (2013). The Gunslinger effect: why are movements made faster when responding to versus initiating an action? *Journal of Motor Behavior*, 45, 85-90.
- Martinez de Qual, O. & Bennett, S. J. (2014). Kinematics of self-initiated and reactive karate punches. *Research Quarterly for Exercise and Sport*, 85, 117-123.
- Mendoza, J. E., Elliott, D., Meegan, D. V., Lyons, J. L., & Welsh, T. N. (2006). The effect of the Müller-Lyer illusion on the planning and control of manual aiming movements. *Journal of Experimental Psychology: Human Perception and Performance*, 32, 413-422.
- Meyer, D. E., Abrams, R. A., Kornblum, S., Wright, C. E., & Smith, J. E. K. (1988). Optimality in human motor performance: Ideal control of rapid aimed movements. *Psychological Review*, 95, 340-370.
- Milner, A. D. & Goodale, M. A. (1995). *The visual brain in action*. New York: Oxford University Press.
- Obhi, S. S., Matkovich, S., & Chen, R. (2009). Changing the “when” and “what” of intended actions. *Journal of Neurophysiology*, 102, 2755-2762.

- Pinto, Y., Otten, M., Cohen, M. A., Wolfe, J. M., & Horowitz, T. S. (2011). The boundary conditions for Bohr's Law: when is reacting faster than acting? *Attention, Perception, & Psychophysics*, 73, 613-620.
- Pratt, J. & Abrams, R. A. (1996). Practice and component submovements: the roles of programming and feedback in rapid aiming limb movements. *Journal of Motor Behavior*, 28, 149-156.
- Roberts, J., Burkitt, J. J., Willemse, B., Ludzki, A., Lyons, J., Elliott, D., & Grierson, L. E. M. (2013). The influence of target context and early and late vision on goal-directed reaching. *Experimental Brain Research*, 229, 525-532.
- Rushworth, M. F. S., Hadland, K. A., Paus, T., & Sipila, P. K. (2002). Role of the human medial frontal cortex in task switching: a combined fMRI and TMS study. *Journal of Neurophysiology*, 87, 2577-2592.
- Schmidt, R. A., Zelaznik, H. N., Hawkins, B., Frank, J. S., & Quinn, J. T. (1979). Motor output variability: A theory for the accuracy of rapid motor acts. *Psychological Review*, 86, 415-451.
- Sidaway, B., Sekiya, H., & Fairweather, M. (1995). Movement variability as a function of accuracy demand in programmed serial aiming responses. *Journal of Motor Behavior*, 27, 67-76.
- Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica*, 30, 276-315.

Welchman, A., Stanley, J., Schomers, M. R., Miall, C. R., & Bulthoff, H. H. (2010). The quick and the dead: when reaction beats intention. *Proceedings of the Royal Society of Biological Sciences*, 277, 1667-1674.

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

Worringham, C. J. (1991). Variability effects on the internal structure of rapid aiming movements. *Journal of Motor Behavior*, 23, 75-85.

Figure captions

Figure 1. A schematic of the experimental setup at the side view (A) and top view (B). Participants freely sat opposite each other with the computer stimulus positioned in the sagittal plane near the edge of the workspace. A change in the stimulus display (black-to-white) would indicate to participants the onset of a trial. Movements were detected via the Optotrak (top; A), and aimed at targets affixed to the table-top (tails-in used for this particular example; B).

Figure 2. Illustration of the three target conditions including the tails-in (A), control (B) and tail-out (C) Müller-Lyer configurations. Each target subtended 255 mm amplitude displacement in the mid-sagittal plane.

Footnote

1. A 2 Trial category (react, initiate) x 3 Target (tails-in, control, tails-out) repeated-measures ANOVA on the proportion of trials following a reacted or initiated movement revealed no significant main effects of trial category, $F < 1$, and target, $F(2,30) = 2.14$, $p > .05$, *partial* $\eta^2 = .13$, nor a significant trial category by target interaction, $F < 1$.