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Early impulse control: treatment of potential errors within pre-programming and control

James W. Roberts[1] and Lawrence E. M. Grierson[2,3,4]

[1]: Liverpool Hope University

Psychology, Action and Learning of Movement (PALM) Laboratory

School of Health Sciences

Liverpool, UK, L16 9JD

[2]: McMaster University, Department of Kinesiology

1280 Main Street West

Hamilton, ON, Canada, L8S 4K1

[3]: McMaster Program for Educational Research, Innovation, and Theory,

Faculty of Health Sciences, McMaster University

1280 Main Street West

Hamilton, ON, Canada, L8S 4L8

[4]: Department of Family Medicine

McMaster University

David Braley Health Sciences Centre, 100 Main Street West

Hamilton, ON, Canada, L8P 1H6

Corresponding author:

James W. Roberts

Liverpool Hope University

Psychology, Action and Learning of Movement Group

School of Health Sciences

Liverpool, UK, L16 9JD

E-mail: robertj3@hope.ac.uk

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Abstract

Early aiming adjustments following an online perturbation are made possible by *impulse control*. This process may unfold even earlier when perturbations impose a greater risk of a costly overshoot error. Participants executed upward and downward aims to mediate the cost of potential errors – downward overshoots require more energy to correct against gravity. On 33% of the trials, texture elements on the aiming surface were shifted following onset to appear congruent or incongruent with the aiming direction, and consequently generate a misperception of the limb moving slower or faster, respectively. Thus, the risk of potential errors could be influenced by the online perturbation (e.g., increased perceived likelihood of overshooting following the incongruent background). Findings indicated greater undershooting for down compared to up, which reflects the principle of movement optimization. There was also more undershooting for an incongruent compared to congruent background, which is consistent with early online adjustments counter-acting the misperceived limb velocity. However, there were no interactions throughout the movement trajectory. We suggest that while the initial pre-programme considers the cost of potential errors (target direction), early impulse control fails to discriminate the likelihood of these errors occurring following an online perturbation (moving background).

Keywords: aiming, impulse control, online perturbation, optimization

Introduction

Target-directed aiming movements have traditionally been characterized as featuring two components: *initial impulse* and *current control* (Woodworth, 1899; see also, Beggs & Howarth, 1972; Crossman & Goodeve, 1983; Keele & Posner, 1968). The initial impulse component refers to the early distance-covering portion of the movement, which is primarily attributed to pre-response programming. Meanwhile, the current control component occurs near the end of the movement, and describes discrete movement adjustments following online sensory feedback processing. However, evidence indicating a substantial decline in the estimated time for feedback-based adjustments (e.g., Zelaznik, Hawkins, & Kisselburgh, 1983), combined with a failure to attribute advantages in accuracy to feedback-based secondary submovements (e.g., Elliott, Carson, Goodman, & Chua, 1991), means there are more ways of engaging in online control.

Contemporary views of target-directed aiming now incorporate an early impulse control process, which sees potentially rapid adjustments being made to the limb velocity and direction (Elliott et al., 2010; Elliott et al., 2017). In particular, these accounts adopt the notion of internal forward models, where movements are programmed in anticipation of the upcoming efferent (forward dynamic model) and reafferent (forward sensory model) signals on the basis of an 'efference copy' of the motor output (Wolpert, Miall, & Kawato, 1998; Wolpert & Ghahramani, 2000; see also, von Holst, 1954). The idea is that discrepancies between the anticipated and actual sensory signals provide a rapid indication that the movement may need to be adjusted. For example, a translating background perturbation that causes initial limb movement to be perceived as either faster (incongruent direction to the limb) or slower (congruent direction to the limb) than expected has been shown to elicit trajectory modifications prior to the late secondary submovement phase (>70 mm/s limb velocity; Proteau & Masson, 1997) (adapted from the notion of *linear vection* where motion from surrounding scenes can elicit the perception of self-motion in the opposing direction of the background; Tarita-Nistor, Gonzalez, Spigelman, & Steinbach, 2006). In a similar vein, air-blast perturbations that unexpectedly accelerate and displace the limb early within movement (i.e., before peak acceleration) can be adjusted very quickly so that the limb reaches a similar point within the trajectory (i.e., peak velocity) as an unperturbed (control) condition (Grierson & Elliott, 2008). Presumably, these rapid adjustments are initiated with respect to the pre-response programme, and its associated model of the sensory consequences. Once performers recognise that there is a discrepancy between what was programmed in advance of the movement and what actually unfolds during the movement, they can immediately update their efferent output to specifically combat the perturbation and continue reaching to the intended target. Notably, this form of adjustment is different to that proposed by the traditional view of current control, where performers slowly utilise external afferent information in order to systematically reduce the error between limb and target locations. These two types of control processes may be formally discriminated by the characteristic features of the trajectories in which they emerge, including a seamless early-onset adjustment for impulse control (i.e., <100 ms; Cluff, Crevecoeur, & Scott, 2015) and delayed iterative adjustments for target control (i.e., secondary submovement phase; Elliott et al., 2017; Woodworth, 1899).

Of interest, there is also evidence that the initial programme accounts for the temporal and energy costs associated with particular movement approaches (Wolpert & Ghahramani, 2000; Wolpert & Harris, 1998). For example, performers tend to organize their primary movements (initial impulses) in order to undershoot the target, which has been attributed to avoiding the additional time and energy costs associated with overshoot errors (Elliott, Hansen, Mendoza, & Tremblay, 2004; *cf*. Meyer, Abrams, Kornblum, Wright, & Smith, 1988). Indeed, overshooting the target entails a further initial reach into the distance, as well as the need to overcome inertia and reverse the limb back onto the target. This strategy of movement optimization has been directly tested by having performers aim in the upward and downward directions (Lyons, Hansen, Hurding, & Elliott, 2006). Here, it is suggested that the potential cost of an overshoot error becomes even greater when aiming down compared to up because the limb has to contend with the opposing gravitational force that is associated with reversing the limb back up toward the target. Presumably, this form of adjustment accumulates greater energy-expenditure, which is something performers must avoid in order to perform optimally. As a result, studies have shown that performers tend to undershoot targets even more (Elliott et al., 2014), and prematurely undertake the deceleration phase of movements (Roberts, Burkitt, Elliott, & Lyons, 2016; see also, Bennett, Elliott, & Rodacki, 2012), when aiming down as compared to up.

At this juncture, it is important to consider the combined implications of both these sets of empirical observations because the pre-response programme must mutually contend with adopting an optimal approach (movement optimization) while also anticipating the forthcoming efferent and reafferent signals (early impulse control). Accordingly, it is reasonable to suggest that the prior strategy or approach to reach the target may influence the nature of the corrections during early impulse control. Indeed, a closer assessment of the previous evidence surrounding early impulse control alludes to varying magnitudes of correction when the limb is unexpectedly advanced or constrained by either perceptual or physical perturbations. For example, the corrections that manifest from a translating background perturbation indicate a significantly greater counter-adjustment for the perception of a fast compared to slow moving limb (Proteau & Masson, 1997; see also Grierson & Elliott, 2009a). Likewise, the adjustments that are made to a sudden air-blast perturbation appear to unfold at an earlier point in time and/or closer in space when the blast propels the limb forward as compared to backward (Grierson, Gonzalez, & Elliott, 2009; Grierson, Lyons, & Elliott, 2011). Thus, it would seem that the early-onset corrections unfold even earlier when the unexpected perturbation risks an overshoot (moving faster than expected) as opposed to an undershoot (moving slower than expected). This pattern of behaviour makes sense when we consider how the unexpected perception of a propelled limb violates an optimal approach to initially undershoot, while the unexpected perception of a counter-acted limb continues to conform to the undershoot tendency.

With this in mind, it stands to reason that an unexpected velocity perturbation, which coincidentally risks a perceived overshoot, may be treated more abruptly than one that risks an undershoot (Elliott et al., 2017). Hence, the present study aimed to examine whether early online adjustments could be influenced by the pre-programmed and anticipated cost of potential movement errors. To do this, we had participants execute target-directed aiming movements in the vertical axis (up or down). On a random selection of trials, the elements that comprised the background in front of which the aiming occurred was translated in a direction that was either congruent or incongruent with the moving limb (see Smeets & Brenner, 1995; Whitney, Westwood, & Goodale, 2003). These translations create a misperception that the limb is moving slower or faster than expected, respectively (Proteau & Masson, 1997).

Consistent with previous findings, it was predicted that there an independent and additive influence of target direction and moving background on the latter portions of the movement trajectory (e.g., primary and/or terminal movement endpoints). That is, there would be greater undershooting for downward compared upward aims, as well as for incongruent compared to stationary and congruent moving backgrounds. These outcomes can be explained by the anticipated energy-expenditure of potential error corrections (e.g., Lyons et al., 2006) and a misperception in limb velocity (e.g., Proteau & Masson, 1997), respectively.

However, further theoretical interest was drawn from instances where the perceived cost of an error was either complimented or exacerbated by the occurrence of an unexpected perturbation. For example, the cost of a potential downward overshoot has an increased perceived likelihood of occurrence when the limb is perceived to be moving faster (incongruent), which renders a greater need to generate rapid counter-adjustments and positively avoid an energy-consuming correction against gravity. While the perceived cost of a potential downward overshoot persists when the limb is perceived to be moving slower (congruent), it is deemed less likely to occur because the perceived velocity accommodates the tendency to undershoot. With regards upward aiming, the cost of a potential overshoot is reduced, which means the need to generate early counter-adjustments may also be reduced despite there being an increased or decreased likelihood of occurrence following a perceptually fast or slow moving limb, respectively. In essence, performers may initiate early online adjustments according to a combination of the perceived cost and risk of committing errors – impulse control adjustments will be issued even earlier when an unexpected perturbation heightens the risk of an error that requires more time and energy to correct (Elliott et al., 2017). Thus, it was predicted that there would be an interaction between target direction and moving background during the early portions of impulse control. Specifically, there should be an earlier onset adjustment, as indicated by the initial kinematic landmarks (e.g., peak acceleration, peak velocity, peak deceleration), during downward aims that are combined with an incongruent moving background compared to all other conditions (downward-congruent, upward-congruent, upward-incongruent). These early online adjustments may be characterised by differences within the early kinematic landmarks that precede the primary movement endpoint, and appear to counter-act the precise direction of the illusory background perturbation (e.g., perceptually faster limb following an incongruent background may generate shorter times and/or displacements to peak velocity and/or peak deceleration, lower magnitude peak velocity, and higher magnitude peak deceleration).[1] Meanwhile, the online adjustments for all other conditions featuring an illusory background may similarly counter-act the direction of the perturbation, although this adjustment should be restricted to the latter portions of the movement trajectory (e.g., primary movement endpoint).

Method

Participants: Seventeen participants agreed to take part in the study (15 male and 2 female; age range = 20-24 years). All participants declared themselves to be right-hand dominant and without any sensory or neurological impairment. The study was approved by the local ethics committee, and designed and conducted in accordance with the Declaration of Helsinki (2013).

Apparatus and Task: Stimuli were presented on an LCD computer monitor (47.5 cm x 27.0 cm; temporal resolution = 75 Hz; spatial resolution =1920 x 1080 pixels) covered by a 2-mm thick acrylic sheet. The monitor was rotated 90° so the long-edge appeared vertical courtesy of the monitor's back-mounted rotatable axis. The monitor was placed on a standard table and directly in front of participants with the height adjusted so the centre appeared at participant eye-level.

A custom-designed program generated and controlled the stimuli via integrated Matlab software (The Mathworks Inc., Natick, MA) and Psychtoolbox-3 (Pelli, 2007) software. Aiming targets were presented on the monitor in the form of grey square shapes (5 x 5 mm) at 160 mm above and below a home position, which appeared as a cross-hair (2 x 10-mm intersecting lines) in the centre of the screen. The targets and home position were presented amid background texture elements, which were comprised of a series of black squares (7 x 7 mm) presented against a white background. There were 48 individual texture elements presented on the screen at any one time, and equally distributed across space. These texture elements were initially stationary, but occasionally shifted up or down following the release of an NO/NC button micro-switch that was attached to the pointing index finger (Saia-Burgess Electronics, Murten, Switzerland). These background texture shifts resulted in them being categorised as either congruent or incongruent with respect to the direction of the participants' aiming movements.

Movements were captured by a Vicon camera system (Vicon Vantage, 16-megapixel resolution), which detected the location of retro-reflective markers that were affixed to the participants' dominant upper-limb (index finger, radial styloid process, humeral lateral epicondyle). The marker locations were sampled at 200 Hz and collected for a period of 4 seconds, which included the entire time associated with completing the aiming movements.

Procedure: Across 120 trials, participants were tasked with aiming to one of the targets as quickly and accurately as possible. To begin each trial, participants were presented the home position and the two grey squares indicating the potential target locations against the background texture. Participants would indicate that they were ready to aim by contacting a micro-switch to the central home position on the screen. Thereafter, a single grey, unfilled square (20 x 20-mm; 1-mm thick lines) would surround one of the two potential targets for a period of 1000 ms. This unfilled square served to cue the participant to the appropriate target and, in turn, direction of movement for the upcoming movement attempt (i.e., up or down). Following a random foreperiod of between 800 ms and 2300 ms, the cued target would change colour from grey to yellow, indicating the participant to release the micro-switch from the home position and move toward the target as quickly and accurately as possible before the micro-switch contacted the screen once again.

On a pseudorandom 33% of trials, the background texture would translate at a rate of 0.21 m/s (~70°/s) either up or down following movement onset as indicated by release of the micro-switch.[2] Once individual texture elements had reached the far edge of the screen, they were relocated at the opposing edge of the screen in order to continue their direction of translation. Background translation ceased as soon as the micro-switch regained contact with the screen at the very end of the movement. The direction of aiming movement was pseudorandomized across all trials, such that there were an equal number of upward aiming movements and downward aiming movements (60 trials each). The direction of background translation was also balanced so that there were 5 trials for each of the congruent and incongruent backgrounds within either the up and down aiming directions. This number or rate of perturbation trials promotes the anticipation of standard trial events without a perturbation, and corresponds with previous other studies (e.g., Proteau, Roujoula, & Messier, 2009; Welsh & Elliott, 2005).

Data Collection and Management: Position-time series data from the distal index finger marker of the primary axis of movement was processed and analysed. Position data were single-, double, and triple-differentiated courtesy of the two-point central difference method in order to produce velocity, acceleration, and jerk, respectively. Movements were parsed from the beginning of the recorded trials in order to determine the start and end of each movement. Movement onset was defined as the first frame that was >10 mm/s for a minimal temporal window of 40 ms (8 frames), while movement end was defined by the first frame that was < 20 mm/s for the same temporal window. Therein, we identified key kinematic landmarks including, peak acceleration, peak velocity and peak deceleration. Furthermore, we determined the presence of two-component movements by adopting standard submovement criteria: (i) positive-to-negative zero-crossing in velocity (type 1;

reversal); (ii) negative-to-positive zero-crossing in acceleration following peak deceleration (type 2; *re-acceleration*); (iii) positive-to-negative zero-crossing in jerk following peak deceleration (type 3; *discontinuities*) (Elliott et al., 2014; Fradet, Lee, & Dounskaia, 2008). The sign (+/-) associated with the above criteria was reversed in order to undertake the same parsing algorithm for the downward aiming movements.

Dependent variables were broadly categorised as *outcome measures* or *early online adjustments*. The outcome measures comprised reaction time (i.e., time difference between target onset and the initial release of the button micro-switch), movement time (i.e., time difference between movement onset and movement offset), endpoint constant error (i.e., distance between target-centre and the limb at terminal movement endpoint), and variable error (i.e., population standard deviation of the terminal endpoint constant error). Meanwhile, the early online adjustments comprised the primary movement constant error (i.e., distance between target-centre and the limb at the primary movement endpoint or secondary submovement onset), and the magnitude of, displacement at, and time to, key kinematic landmarks: peak acceleration, peak velocity, and peak deceleration. These landmarks have been highly informative in regard to the impulse control framework as they highlight early-onset adjustments following unexpected sensorimotor perturbations (e.g., Hansen, Tremblay, & Elliott, 2008; Grierson & Elliott, 2008; Grierson et al., 2011; Tremblay, Hansen, Kennedy, & Cheng, 2013).

Statistical Analyses

We recognized that the relationship between the direction of background translation and direction of the aiming movement would dictate the nature of the perceived limb velocity. Thus, we categorised the background perturbations as either *congruent* (downward background translation and downward aiming movement; upward background translation and upward aiming movement) or *incongruent* (downward background translation and upward aiming movement; upward background translation and downward aiming movement).

Trials that featured movement times greater than 1000 ms (i.e., not rapid) and/or absolute terminal constant error scores greater than 30 mm (i.e., not accurate) were removed prior to analyses (3.5% of trials). Mean participant values for each of the outcome and kinematic measures were forwarded to a two-way repeated-measures ANOVA (2 target: up, down; 3 background: congruent, stationary, incongruent). In the event of a violation in the assumption of Sphericity (courtesy of Mauchly's test), the Huynh-Feldt corrected value was adopted providing Epsilon was >.75. If otherwise, then the Greenhouse-Geisser corrected value was adopted. Partial eta-squared (η^2) indicated the size of any treatment effects. Significant effects featuring more than two means were decomposed by the Tukey HSD *post hoc* procedure. Statistically significant effects were declared when $p < .05$.

Results

Outcomes measures

For reaction time, there was no significant main effect of target, $F(1, 16) < 1$, background, $F(2, 32) = 2.04$, $p > .05$, *partial* $\eta^2 = .11$, nor a target x background interaction, $F(2, 32) < 1$ (*grand M* = 346.01 ms, SE = 11.56). Likewise, for movement time, there was no significant main effect of target, $F(1, 16) = 1.84$, $p > .05$, *partial* $\eta^2 = .10$, background, $F(2, 32) = 2.74$, $p = .08$, *partial* $\eta^2 = .15$, nor a target x background interaction, $F(2, 32) < 1$.

Constant error analyses revealed that the aims tended to undershoot the target. Accordingly, in light of our hypotheses, the description of constant error findings can be characterized as more or less undershooting. In this context, one can be assured that increases in undershooting were concomitant with more error, and *vice versa*. Specifically, the main effect of target approached conventional levels of significance, $F(1, 16) = 4.19$, $p = .057$, *partial* η^2 = .21, as downward target movements tended to undershoot more than upward target movements. There was a significant main effect of background, $F(2, 32) = 55.22$, $p < .001$, *partial* η^2 = .78, as the incongruent background caused significantly more undershooting than the stationary background ($p < .05$, $d = 1.51$), which was undershot even more than the congruent background ($p < .05$, $d = 1.55$). Moreover, there was no significant target x background interaction, $F(2, 32) > 1$ (see Figure 1A).

With regards to variable error, there was a significant main effect of target, F(1, 16) = 11.89, p < .01, partial η2 = .43, which indicated greater endpoint variability for the downward (M = 4.01 ms, SE = .28) compared to upward (M = 2.95 ms, SE = .24) target movements. However, there was no significant main effect of background, F(2, 32) = 1.08, p > .05, partial η2 = .06, nor a target x background interaction, F(2, 32) < 1.

[Insert Figure 1 about here]

Early online adjustments

For primary movement constant error, there was a significant main effect of target, $F(1, 16) = 9.61$, $p < .01$, *partial* η^2 = .38, and background, $F(2, 32) = 32.25$, $p < .001$, *partial* η^2 = .67, which indicated a similar direction of effects as the terminal endpoint constant errors (incongruent vs. stationary: $d = 1.22$, incongruent vs. congruent: $d = 1.49$, stationary vs. congruent: $d = 1.21$; *ps* < .05). Meanwhile, there was no significant target x background interaction, $F(2, 32) = 1.20$, $p > .05$, *partial* η^2 = .07 (see Figure 1B).

Mean values of the early kinematic landmarks are shown in Table 1. At peak acceleration, there was no significant main, or interaction effects (background: $F(2, 32)$ = 2.11, $p > .05$, *partial* η^2 = .12; remaining statistical effects: *Fs* < 1) for the magnitude of peak acceleration. Nevertheless, there was a significant main effect of target for displacement, *F*(1,

16) = 14.90, $p < .01$, *partial* $\eta^2 = .48$, and a near significant effect for time, $F(1, 16) = 4.28$, $p = .055$, *partial* $\eta^2 = .21$, to peak acceleration. That is, the downward target movements reached peak acceleration at a later point in time and further in space compared to upward target movements. However, there were no further statistically significant main, or interaction effects featuring the factor of background (*Fs* < 1).

There was a significant main effect of target for the magnitude of peak velocity, $F(1, 16) = 20.09$, $p < .001$, *partial* $\eta^2 = .56$, which indicated a higher magnitude for downward compared to upward target movements. However, there were no main, or interaction effects featuring the factor of background, *Fs* < 1. In a similar vein, there was a significant main effect of target for the displacement at peak velocity, $F(1, 16) = 30.39$, $p < .001$, *partial* $\eta^2 = .66$, as downward target movements reached further than upward target movements. However, there was no main effect of background, $F(2, 32) <1$, nor a target x background interaction, $F(2, 32) = 1.68$, $p > .05$, *partial* $\eta^2 = .10$. Meanwhile, there were no significant main, or interaction effects for the time to peak velocity (target x background: $F(2, 32) = 2.45$, $p > .05$, *partial* $\eta^2 = .13$; remaining statistical effects: *Fs* < 1).

For the magnitude of peak deceleration, there was a significant main effect of target, $F(1, 16) = 52.19$, $p < .001$, *partial* $\eta^2 = .77$, which indicated greater negative acceleration for downward compared to upward target movements. There was also a significant main effect of background, $F(2, 32) = 3.83$, $p < .05$, *partial* $\eta^2 = .19$, indicating lower negative acceleration for the congruent compared to incongruent translating background ($p < .05$, $d = .59$), although there was no significant target x background interaction, $F(2, 32) = 2.72$, $p = .081$, *partial* $\eta^2 = .15$. There was no significant main effect of target, $F(1, 16) < 1$, although there was a significant main effect of background, $F(2, 32) = 13.59$, $p < .01$, *partial* $\eta^2 = .46$, for the displacement at peak deceleration as significantly more undershooting took place following the incongruent compared to congruent background ($p < .05$, $d = .98$). However, there was no significant target x background interaction, $F(2, 32) < 1$. Meanwhile, the time to peak deceleration revealed a significant main effect of target, $F(1, 16) = 5.53$, $p < .05$, *partial* $\eta^2 = .26$, which indicated a shorter time to undertake deceleration for downward compared upward target movements. In addition, there was a significant main effect of background, $F(2, 32) = 10.30$, $p < .001$, *partial* $\eta^2 = .39$, as longer times unfolded for the congruent compared to incongruent background ($p < .05$, $d = .92$). However, there was no significant target x background interaction, $F(2, 32) = 1.65$, $p > .05$, *partial* $\eta^2 = .09$.

[Insert Table 1 about here]

Summary

The primary and terminal movement endpoints indicated a pattern of results that were consistent with the direction of the experimental manipulations: enhanced undershooting for the downward compared to upward target movements, as well as incongruent compared to congruent translating backgrounds. Importantly, while there were main effects of target and background, there appeared to be no interactions across the early kinematic landmarks that preceded the primary movement.

Discussion

The current study examined how early online adjustments within impulse control interact with the perceived cost of potential movement errors. That is, we investigated the potential mediation of early online adjustments when perceived velocity perturbations that threaten an overshoot (perceptually moving faster) coincided with a perceived higher cost of overshooting (downward aiming). Consistent with previous findings, it was hypothesized that downward aims would generate more undershooting than upward aims, and incongruent translating backgrounds would generate more undershooting than congruent and/or stationary backgrounds. Of most interest, we predicted that there would be an interaction between each of the target direction and moving background manipulations during the earlier portions of impulse control. That is, the counter-acting adjustments to perceptually faster limb movements following an incongruent compared to congruent translating background would unfold even earlier (prior to the primary movement) when aiming within the downward, as opposed to the upward, direction. Overall, the findings confirmed a pattern of results that were consistent with the intended direction of the target and background manipulations. That is, there was a tendency to undershoot the target more when aiming down compared to up, whilst there were also greater undershoots for the incongruent compared to congruent translating background. However, at no point across the kinematic landmarks did there appear to be an interaction between the two factors. This finding suggests that any attempt to avoid the time- and energy-expenditure of overshoot errors, does not mediate the early counter-adjustments associated with impulse control. In addition, it also supports the principle that the two processes – pre-programmed movement optimization and early trajectory impulse control – operate in independent and additive fashion with respect to their influence on movement accuracy (e.g., Grierson & Elliott, 2009a; see also, Sternberg,1969, for a review of Additive Factors Logic).

The greater extent of undershooting targets in the downward compared to upward direction is heavily attributed to the perceived cost of potential errors because the potential of a downward overshoot incurs an opposing gravitational force when needing to reverse the limb back to the target (Lyons et al., 2006). Moreover, we show that this undershoot bias coincides with a longer time and displacement to reach early kinematic landmarks (peak acceleration, peak velocity), as well as a more abrupt and larger magnitude deceleration phase (see Roberts et al., 2016). It is possible that this downward aiming trajectory manifests from gravity initially facilitating early limb movement, while a robust counter-acting force later overcomes inertia and avoids an overshoot. Alternatively, the downward aiming trajectories may be conceived as facilitating a feedback-based approach, where a larger proportion of the end trajectory is devoted to visually guided limb corrections (Hansen, Glazebrook, Anson, Weeks, & Elliott, 2006).

While these effects of target direction suggest not all errors are equal, it is perhaps more difficult to reconcile this feature when there was no interaction with the translating background perturbation at the early kinematic landmarks. Indeed, a translating background perturbation that causes a misperception in the limb velocity (Proteau & Masson, 1997), and thus differentially risks undershoot (congruent) and overshoot (incongruent) errors, should lead to performers taking additional measures to avoid the enhanced risk of more time- and energy-expenditure. Specifically, the potential of overshooting following an incongruent translating background may require an earlier counter-adjustment during downward aiming in order to avoid a time- and energy-consuming correction against gravity. Such adjustments would normally manifest within the early kinematic landmarks, including an earlier onset and shorter displacement at peak velocity or peak deceleration (for a review, see Elliott et al., 2017). On current evidence, it appears these indicators of an early counter-adjustment within impulse control could not be discriminated as a function of the perceived cost of errors, which are heavily mediated by the aiming direction (i.e., downward vs. upward).

Consequently, it is perhaps better to conceive of the potential for different errors not being treated equally within offline programming (undershoot vs. overshoot; e.g., Elliott et al., 2004; Lyons et al., 2006), although they may be treated like so during online control. That is, while the pre-programming of the initial primary movement considers the cost of a correction following a potential error, the subsequent adjustments during impulse control unfold regardless of whether there is an enhanced risk of this error occurring. This failure of early online adjustments to discriminate the cost and likelihood of eventual errors can be partially supported by the evidence of non-specific trajectory adjustments (Grierson & Elliott, 2009b). To elucidate, sudden changes to the form of a presented target (e.g., perceptually shorter tails-in or longer tails-out Müller-Lyer configurations) can elicit online adjustments as early as peak acceleration, although they fail to discriminate the relative size characteristics of the target. Thus, early online adjustments may generally work to counter-act the direction of the perturbation by allocating more time and space for the performer to acclimatize to this novel parameter, while disregarding the overall context of the aiming movement (e.g., cost of potential errors, target characteristics, etc).

At the same time, there is evidence to suggest that early trajectory adjustments to unexpected perturbations can be undertaken in a very precise way that permits a relatively seamless continuation of the limb to the target (e.g., Cressman, Franks, Enns, & Chua, 2006; Goodale, Pélisson, & Prablanc, 1986; Grierson & Elliott, 2008; Proteau & Masson, 1997; Proteau, Roujoula, & Messier, 2009). Of interest, it has been shown that when combining two velocity-based perturbations (air-blast, translating background), there was a tendency to undertake adjustments to each of the perturbations at separate points within the trajectory (Grierson et al., 2011). These findings were explained by the potential inability to contend with multiple forms of error, as there were a limited number of available resources to detect and amend different errors. With regards to the present study, it is possible that the two factors failed to interact because the system contends with them separately. That is, the translating background perturbation may be initially detected as a discrepancy with respect to the anticipated limb velocity (forward sensory model) (e.g., moving faster or slower than expected), and may be treated accordingly. At the same time, the attempts to avoid the cost of an overshoot (downward vs. upward) may continue to unfold regardless of any earlier events because such precautions do not come into effect until the very end of the primary movement.

While our translating background perturbation generated similar early-onset adjustments as other studies (e.g., Grierson & Elliott, 2009a; Proteau & Masson, 1997), it is possible that these corrections could be attributed to alternative processes during impulse control. In fact, there is potential to even question the integrity of such a perturbation within the context of misperceiving the limb velocity. That is, the responses generated from the translating background perturbation were also consistent with the notion that the background presented a directional motion artefact, where the perceived retinal motion (e.g., downward translating background generates a more downward aiming amplitude) dictates the spatial location of the limb (Gomi, 2008; Gomi, Abekawa, & Nishida, 2006; Whitney et al., 2003; Zhang, Brenner, Duysens, Verschueren, & Smeets, 2018)[1]. Additionally, it is relevant to consider the fact that the translating background perturbation had an effect at peak deceleration (see also, Grierson et al., 2011), which despite being considered a landmark of impulse control (Elliott et al., 2017), may have entered into a time-course that is synonymous with late limb-target control (~300 ms) (Carlton, 1992; Roberts et al., 2013). With this in mind, it is perhaps useful for future research to expand upon the current framework by incorporating a real limb motion perturbation (e.g., air-blast, prismatic displacement, etc).

In conclusion, we combined manipulations so that participants executed aims in the upward and downward directions, while also contending with a translating background perturbation that elicited the misperception of the limb moving faster or slower than expected. The results confirmed a greater undershoot bias for downward compared to upward aims, while there were attempts to overturn the misperceived velocity as early as peak deceleration. These findings can be attributed to the greater perceived cost of an overshoot error when aiming downwards, and impulse control processes that rapidly register a discrepancy in the movement trajectory, respectively. However, at no point did these two processes interact with one another suggesting the optimal pre-programmed response that is designed to limit the cost of potential errors does not mediate early impulse control processes. Thus, it would appear that there is a cost of potential errors that is factored into offline programming, although this is not the case when it comes to online control. In fact, it appears there is limited regard to the direction of limb trajectory discrepancies even when they risk violating the perceived cost of eventual errors. To-date, we have speculated on how such processes may unfold, although we stress how further research is required to corroborate the present findings and expand upon our current suggestions.

References

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*(3), 171-177.

Bennett, S. J., Elliott, D., & Rodacki, A. (2012). Movement strategies in vertical aiming in older adults. *Experimental Brain Research, 216*(3), 445-455.

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

Cluff, T., Crevecoeur, F., & Scott, S. H. (2015). A perspective on multisensory integration and rapid perturbation responses. *Vision Research, 110*(Pt B), 215-222.

Crossman, E. R. F. W, & Goodeve, P. J. (1983). Feedback control of hand-movement and Fitts' Law. *Quarterly Journal of Experimental Psychology A, 35*(2), 251-278.

Elliott, D., Carson, R. G., Goodman, D., & Chua, R. (1991). Discrete vs. continuous visual control of manual aiming movements. *Human Movement Science, 10*(4), 398-418.

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*(6), 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*(6), 1023-1044.

Elliott, D., Hansen, S., Mendoza, J., & Tremblay, L. (2004). Learning to optimize speed, accuracy, and energy expenditure: A framework for understanding speed-accuracy relations in goal-directed aiming. *Journal of Motor Behavior, 36*(3), 339-351.

Elliott, D., Lyons, J., Hayes, S. J., Burkitt, J. J., Roberts, J. W., Grierson, L. E. M., Hansen S. et al. (2017). The multiple process model of goal-directed reaching revisited. *Neuroscience Biobehavioural Reviews, 72,* 95-110.

Fradet, L., Lee, G., & Dounskaia, N. (2008). Origins of submovements during pointing movements. *Acta Psychologica, 129*(1), 91-100.

Gomi, H. (2008). Implicit online corrections of reaching movements. *Current Opinion in Neurobiology*, *18*(6), 558-564.

Gomi, H., Abekawa, N., & Nishida, S. (2006). Spatiotemporal tuning of rapid interactions between visual-motion analysis and reaching movement. *Journal of Neuroscience, 26*(20), 5301-5308.

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*(6), 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*(3), 309-324.

Grierson, L. E. M. & Elliott, D. (2009b). The impact of real and illusory target perturbations on manual aiming. *Experimental Brain Research, 193*(3), 279-285.

Grierson, L. E. M, Gonzalez, C., & Elliott, D. (2009). Kinematic analysis of early online control of goal-directed reaches: a novel movement perturbation study. *Motor Control, 13*(3), 280-296.

Grierson, L. E. M, Lyons, J., & Elliott, D. (2011). The impact of real and illusory perturbations on the early trajectory adjustments of goal-directed movements. *Journal Motor Behavior, 43*(5), 383-391.

Hansen, S., Glazebrook, C., Anson, J. G., Weeks, D. J., & Elliott, D. (2006). The influence of advance information about target locationand visual feedback on movement planning and execution. *Canadian Journal of Experimental Psychology, 60*(3), 200–208.

Hansen, S., Tremblay, L., & Elliott, D. (2008). Real-time manipulation of visual displacement during manual aiming. *Human Movement Science, 27*(1). 1-11.

Keele, S. W., & Posner, M. I. (1968). Processing of visual feedback in rapid movements. *Journal of Experimental Psychology,* 77(1), 155-158.

Lyons, J., Hansen, S., Hurding, S., & Elliott, D. (2006). Optimizing rapid aiming behaviour: movement kinematics depend on the cost of corrective modifications. *Experimental Brain Research, 174*(1), 95-100.

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*(3), 340-370.

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, *10*(4), 437–442.

Proteau, L. & Masson, G. (1997). Visual perception modifies goal-directed movement control: supporting evidence from a visual perturbation paradigm. *Quarterly Journal of Experimental Psychology, 50*(4), 726-741.

Proteau, L., Roujoula, A., & Messier, J. (2009). Evidence for continuous processing of visual information in a manual video-aiming task. *Journal of Motor Behavior, 41*(3). 219-231.

Roberts, J. W., Burkitt, J. J., Elliott, D., & Lyons, J. L. (2016). The Impact of Strategic Trajectory Optimization on Illusory Target Biases During Goal-Directed Aiming. *Journal Motor Behavior, 48*(6), 542-551.

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*(4), 525–532.

Smeets, J. B., & Brenner, E. (1995). Perception and action are based on the same visual information: distinction between position and velocity. *Journal Experimental Psychology: Human Perception and Performance, 21*(1), 19-31.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica, 30*, 276–315.

Tarita-Nistor, L., González, E. G., Spigelman, A. J., & Steinbach, M. J. (2006). Linear vection as a function of stimulus eccentricity, visual angle, and fixation. *Journal of Vestibular Research, 16*(6), 265-272.

Tremblay, L., Hansen, S., Kennedy, A. & Cheng, D. T. (2013). The utility of vision during action: multiple visuomotor processes. *Journal of Motor Behavior, 45*(2), 91-99.

Von Holst, E. (1954). Relations between the central nervous system and the peripheral organs. *British Journal of Animal Behaviour, 2,* 89-94.

Welsh, T. N. & Elliott, D. (2005). The effects of response priming on the planning and execution of goal-directed movements in the presence of a distracting stimulus. *Acta Psychologica, 119*(2), 123-142.

Whitney, D., Westwood, D. A., & Goodale, M. A. (2003). The influence of visual motion on fast reaching movements to a stationary object. *Nature*, *423*(6942), 869-873.

Wolpert, D. M., & Ghahramani, Z. (2000). Computational principles of movement neuroscience. *Nature Neuroscience, 3,* 1212-1217.

Wolpert, D. M., Miall, C. R., & Kawato, M. (1998). Internal models in the cerebellum. *Trends in Cognitive Sciences*, *2*(9), 338-347.

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

Zelaznik, H. Z., Hawkins, B., & Kisselburgh, L. (1983). Rapid visual feedback processing in single-aiming movements. *Journal of Motor Behaviour, 15*(3), 217-236.

Zhang, Y., Brenner, E., Duysens, J., Verschueren, S., & Smeets, J. B. J. (2018). Postural responses to target jumps and background motion in a fast pointing task. *Experimental Brain Research, 236*(6), 1573-1581.

Footnote

1) The appearance of early onset adjustments have been known to vary as a function of magnitude, time and/or displacement of kinematic landmarks (e.g., magnitude of peak acceleration; Grierson & Elliott, 2009b; displacement at peak velocity; Grierson & Elliott, 2008). Thus, early onset adjustments are not defined by a select dependent variable at a precise landmark, but broadly identified before the end of the primary movement (i.e., preceding the potential secondary submovement). In addition, the combination of these kinematic measures captures the potential complementarity within the trajectory itself (e.g., earlier time to peak deceleration following high-magnitude peak acceleration; Roberts et al., 2016). Thus, these kinematic measures render a potentially more complete assessment of trajectory control.
2) The same number of leftward and rightward translating background directions were incorporated into the trial procedure. However, these trials were not featured within the present design as they pertain to a separate set of analyses and related research question, which are to be addressed within a separate study.

Disclosure Statement

No potential conflict of interest was reported by the authors

Tables

Table 1. Mean of the kinematic measures taken from peak acceleration (PA), peak velocity (PV) and peak deceleration (PD) as a function of target (up, down) and background (congruent, stationary, incongruent). Symbols indicate significant main effects of target (*) and background (†) (*p* < .05).

	Congruent		**Stationary**		**Incongruent**	
	Up	**Down**	**Up**	**Down**	**Up**	**Down**
Magnitude						
PA (mm/s^2)	6753.40	6792.34	6560.52	6579.49	6737.91	6473.02
*PV (mm/s)**	664.89	729.37	659.66	722.60	657.73	717.38
*PD (mm/s^2)**†	-4111.53	-5852.15	-4259.64	-5383.25	-4347.74	-6095.70
Time						
PA (ms)	73.378	81.24	74.80	80.50	73.22	82.42
PV (ms)	174.84	182.27	180.81	179.10	177.37	183.71
*PD (ms)**†	310.31	284.32	323.01	302.54	288.66	279.82
Displacement						
*PA (mm)**	10.62	13.26	10.51	13.44	10.82	13.17
*PV (mm)**	63.54	70.62	65.31	69.93	64.27	70.03
PD (mm)†	132.06	128.93	136.753	136.74	124.33	125.63

Figure Captions

Figure 1. Mean (±SE) for the terminal endpoint constant error (A) and primary movement constant error (B). Potential adjustments to the limb position following the primary movement can be broadly observed by values reaching closer to zero prior to the terminal endpoint. On average, two-component submovements were evident for 70.4% of trials.