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The impact of strategic trajectory optimization on illusory target biases during goal-directed aiming

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Abstract

During rapid aiming, movements are planned and executed to avoid “worse-case” outcomes that require time and energy to correct. As such, downward movements initially undershoot the target to avoid corrections against gravity. Illusory target context can also impact aiming bias. Here, we sought to determine how strategic biases mediate illusory biases. Participants aimed to Müller-Lyer figures in different directions (forward, backward, up, down). Downward biases emerged late in the movement and illusory biases emerged from peak velocity. The illusory effects were greater for downward movements at terminal endpoint. These results indicate that strategic biases interact with the limb-target control processes associated with illusory biases. Thus, multiple control processes during rapid aiming may combine, and later affect endpoint accuracy (Elliott et al., 2010, Psychol Bull 136:1023-1044, 2010).

Introduction

The multiple process model of limb control posits two types of online control during goal-directed reaching and aiming: early impulse regulation, and late limb-target control (Elliott, Hansen, Grierson, Lyons, Bennett, & Hayes, 2010). The early impulse regulation modulates limb velocity and direction, and depends on feedforward processes involving a comparison between the predicted and actual sensory consequences (Desmurget & Grafton, 2000; Wolpert, Miall, & Kawato, 1998). In contrast, limb-target control occurs toward the end of the movement trajectory as the limb approaches the target. It constitutes discrete corrective processes based on the spatial position of the moving limb with respect to the target location.

Initial movement planning is designed to not only reduce the need for online corrective processes, but also to optimize the movement time and energy expenditure. Meyer and colleagues' (Meyer, Abrams, Kornblum, Wright, & Smith, 1988) optimized submovement model holds that aiming movements are planned and executed to strike a balance between movement velocity and the greater endpoint variability associated with faster, more forceful movements (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979; Worringham, 1991). According to their model, primary movement endpoints should be normally distributed around the center of the target in order to reduce the frequency of endpoints outside of the target boundary, and therefore the need for a corrective submovement (i.e., limb-target control). However, it has been shown that the distribution of primary movement endpoints is frequently centered short of the target location (Elliott, Hansen, Mendoza, & Tremblay, 2004; Engelbrecht, Berthier, & Sullivan. 2003; Khan, Franks, & Goodman, 1998; Worringham, 1991). This strategic undershooting occurs because not all errors are equal in terms of the movement time and energy costs (Elliott, Helsen, & Chua, 2001; Elliott et al., 2010). Specifically, target overshoots are avoided because they typically require more time and energy to correct than target undershoots (Lyons, Hansen, Hurding, & Elliott, 2006; Oliveira, Elliott, & Goodman, 2005). This is because following an initial overshoot, the limb has not only travelled a longer distance, but must also overcome inertia at the point of reversal by alternating the role of muscle groups (i.e., the agonist becomes the antagonist, and vice versa) (Elliott et al., 2004). In the context of our current study, Lyons et al. (2006) showed that primary movement undershooting was more pronounced under vertical aiming conditions when participants were moving downward to targets below the home position. Consistent with the predictions of the multiple process model of limb control (Elliott et al., 2010), this strategic undershooting occurs to avoid limb-target corrective submovements that must be made against gravity following a downward overshoot. This type of correction requires both more time and energy expenditure than corrective movements made in the horizontal plane, or corrective movements made with gravity (following an upward overshoot) (Bennett, Elliott, & Rodacki, 2012).

In a more recent vertical aiming study, the presence of visual feedback was manipulated for both online control (within-trial) and offline planning (between-trial) (Elliott et al., 2014). It was found that when aiming downward performers sometimes fail to correct a target undershoot with a corrective submovement. This type of strategy is particularly evident when visual feedback is not available to reliably judge the relative positions of the limb and the target during limb deceleration. As well, when corrections are made to downward aiming movements, the corrective submovement is typically of shorter amplitude than when aiming upward. Consistent with Lyons et al. (2006), and the tenets of the multiple process model of limb control, performers prepare and control their aiming movements to reduce the temporal and energy costs associated with correcting endpoint errors.

Over the last two decades, there has also been growing interest in the impact of illusory target context on both movement planning and limb-target corrective processes (e.g., Binsted & Elliott, 1999; Elliott & Lee, 1995; Mendoza, Elliott, Meegan, Lyons, & Welsh, 2006; Roberts et al., 2013). Typically, when moving to the vertex of a Müller-Lyer figure, participants undershoot the target for the tails-in configuration (↑), and either overshoot, or undershoot the vertex to a lesser extent, when aiming to a tails-out figure (Y). Of interest are the movement planning and online control conditions that mediate these biases (see Mendoza, Hansen, Glazebrook, Keetch, & Elliott, 2005 and Westwood, 2010 for reviews). With respect to the multiple process model of limb control, and the research reported here, Grierson and Elliott (2009a) used the Müller-Lyer illusion to vary target context and a moving background illusion (see Proteau & Masson, 1997) to manipulate the perceived velocity of the moving limb. When these two illusory protocols were introduced together, their effects on endpoint bias were found to be additive and independent. Following the additive factor logic of independent factors manifesting additive and noninteractive impacts on dependent measures (Sternberg, 1969), Grierson and Elliott (2009a) took this to mean that control of limb velocity (i.e., impulse control) and limb-target control are relatively independent of each other (cf. Grierson & Elliott, 2008). This finding, and findings like it, helped provide the basis for the multiple process model of goal-directed aiming (Elliott et al., 2010).

In this study, we examined the nature of the control processes underpinning the multiple process model (Elliott et al., 2010) by determining the relative independence or interaction between displacement biases associated with energy optimization (i.e., avoiding energy-consuming corrections against gravity) and target context. In addition, we determined where in the trajectory control processes related to these two manipulations began to influence each other. We took a similar approach to Grierson and Elliott (2009a; see also Grierson & Elliott, 2008 and Grierson, Lyons, & Elliott, 2011). Specifically, we introduced participants to two protocols known to produce movement biases in the same experiment. In particular, we used a vertical aiming protocol that has been shown to elicit strategic undershooting of the primary movement (Bennett et al., 2012; Lyons et al., 2006) and/or the movement endpoint (Elliott et al., 2014) when aiming downward. In tandem, we used Müller-Lyer figures to create an illusory target context (Elliott & Lee, 1995). Although both manipulations are thought to impact movement planning, and thus subsequent limb-target regulation (see Glover & Dixon, 2001, 2002; Lyons et al., 2006; Mendoza et al., 2006), the multiple process model holds that vertical aiming biases are strategic in nature. In contrast, Müller-Lyer biases appear to be associated with the implicit coding of allocentric space (Glover, 2004; Milner & Goodale, 1995). This coding biases the perceived position of the limb relative to the target both during movement planning (Glover, 2004; Mendoza et al., 2006) and during the final approach to the target location (Roberts et al., 2013).

Based on the notion that perceived target location is important for both Müller-Lyer effects and the strategic control associated with undershooting the center of the target, we expected the two manipulations to have interactive effects. That is, the target context should elicit greater illusory biases following strategic primary movements that result in greater limb-target control (longer secondary submovements) (cf. Glover, 2004; Bruno & Franz, 2009). Following Elliott et al. (2014), reduced limb-target control for downward aiming should also be associated with smaller illusory biases than aiming in the other directions.

Method

Participants

Nine males and eight females, with an age range of 19-37 years, agreed to take part in the study. All participants were self-declared right handed and had normal or corrected-to-normal vision with no history of neurological disorder. The study was designed and conducted in accordance with the Declaration of Helsinki and was approved by the local ethics committee.

Apparatus and Procedure

The stimuli were presented on a 57 cm x 34 cm monitor with a temporal resolution of 60 Hz and spatial resolution of 1024 x 768 pixels. The monitor was covered by a 5 mm-thick piece of Plexiglas. An in-house designed wall-mount apparatus (58.7 cm x 38 cm x 10.5 cm) was installed to allow aiming within the vertical axis. The wall-mount secured placement of the monitor and covered only 2 cm of the upper and lower portions of the aiming surface. A 180 cm high stand was used to hold the wall-mount upright and adjust the vertical height accordingly. For the horizontal axis, a 43.0 cm x 35.5 cm steel ledge was attached to the stand and the wall-mount was reoriented so the computer stimuli faced upwards with respect to the participant view (see Figure 1). An infrared emitting diode was attached to the distal end of the right index finger. Movements were recorded via Optotrak (Northern Digital Instruments) collecting at 200 Hz, and triggered via a custom parallel port connected to the computer.

The trial events were displayed and controlled by E-prime (Psychology Software Tools Inc). The home position was a 1-cm diameter black circle located at screen center. The target stimuli featured a Müller-Lyer configuration including tails-in, control or tails-out (see Figure 2), and were presented in black with a white background. The long shaft was 19 cm from the home center to shaft end, and the tails were 5 cm from the shaft end to tail end. All lines were 0.5 cm in width. Participants were instructed to execute aiming movements toward the end of the shaft and to hit the point where the lines intersected (i.e., the vertex). They were instructed to be as fast and accurate as possible. Prior to target onset, the participant placed their right index finger over the home position and was presented one of two target pre-cues designed to instruct them whether the target would appear up/forward or down/backward. The pre-cue was a red or grey-colored square outline (2.5 cm x 2.5 cm) surrounding the home position and presented for 2 s (for similar methodology, see Blinch, Cameron, Hodges, & Chua, 2012; Hansen, Glazebrook, Anson, Weeks, & Elliott, 2006). Movement direction was initially pre-cued because greater undershooting in downward compared to upward movements is typically associated with the pre-programming phase of the movement (Elliott et al., 2010). That is, the performer plans for the “worse-case” outcome prior to movement onset by avoiding time- and energy-consuming corrections against gravitational forces following a downward overshoot. Thus, pre-cue information provides integral information on the forthcoming sensorimotor environment, and subsequent cost of potential errors. Following a random foreperiod (800-1500 ms), the target would then appear for 3 s and would be one of the three forms of the Müller-Lyer configuration. Participants received online and terminal visual feedback of the limb throughout the entire experiment.[1] There was no performance-related augmented feedback (e.g., constant error, movement time) provided to the participants.

There were a total of 240 trials with 120 trials for each of the horizontal and vertical orientations. In each block of horizontal and vertical aims, there were 20 trials presented randomly for each combination of direction (up, down, forward, back) and Müller-Lyer configuration (tails-in, control, tails-out). Short breaks were given following the completion of sets of 20 trials with further rest provided in the event of fatigue during the trial procedure. The pre-cue assignment and block order were counter-balanced across participants.

Insert Figure 1 and Figure 2 about here

Dependent variables and analysis

Position data were filtered using a second-order Butterworth filter at a low-pass cut-off frequency of 10 Hz. Data were differentiated and double-differentiated to obtain velocity and acceleration respectively. Movement onset was determined by marking the frame where velocity reached above +10 mm/s in the primary movement axis during up/forward trials, or fell below -10 mm/s during down/backward trials, for a period of at least 40 ms (8 samples). In turn, movement offset (END) was marked as the frame where velocity reached below +10 mm/s during upward/forward aims, or above -10 mm/s during downward/backward aims, for 40 ms or more. Within each movement trial, we identified peak acceleration, peak velocity, peak deceleration and the primary movement endpoint. The primary movement endpoint was detected following peak velocity by determining a) a zero-line crossing in velocity that exceeded both the magnitude criteria (+/-10 mm/s) and temporal window (40 ms) (synonymous with a movement reversal), b) a zero-line crossing in acceleration that coincided with an increase in velocity featuring a relative maxima of 5 mm/s and remained above the magnitude of the initial velocity inflection for the duration of the temporal window (synonymous with a re-acceleration), c) deviations in acceleration involving a change in direction of the acceleration profile that upheld a relative magnitude of 10% of the greatest absolute magnitude for the duration of the temporal window (synonymous with a discontinuity or ‘braking’) (see Burkitt, Staite, Yeung, Elliott, & Lyons, 2015; Chua & Elliott, 1993; Khan et al., 2006).

Measures of central tendency included reaction time (RT; time between stimulus onset and movement onset), movement time (MT; time between movement onset and movement offset), the displacement to the primary movement endpoint from the center of the home position and constant error (CE; signed distance of the limb from the target at the end of the movement) in the primary direction of the movement. CE was calculated based on the known distance of 19 cm from the center of the home position to the target figure vertex.

Movement kinematics were quantified by the magnitude and displacement at peak acceleration (PA), peak velocity (PV) and peak deceleration (PD). Measures of dispersion included variable error (VE; standard deviation of the signed error differences), and spatial variability of the primary movement endpoint. As an examination of delayed target control, we extracted the frequency of trials featuring a secondary submovement, along with time and displacement after the primary movement endpoint. Mauchly's test of Sphericity was conducted to test for unequal variance of differences and the Greenhouse-Geisser correction value was adopted in the event of a violation (the presented degrees of freedom were consistent with the assumption of Sphericity however). Dependent measures were analysed using a 2 Axis (horizontal, vertical) by 2 Direction (up/forward, down/backward) by 3 Target (tails-in, control, tails-out) repeated-measures ANOVA. Significant effects featuring more than two means were decomposed using Tukey HSD post hoc procedure ($p < .05$).

Results

Temporal Performance Measures

For RT, there was a significant main effect of direction, $F(1, 15) = 49.75$, $p < .05$, *partial* $\eta^2 = .77$, and target, $F(2, 30) = 12.05$, $p < .05$, *partial* $\eta^2 = .45$, which indicated an extended RT for the tails-in target ($M = 350$ ms) compared to the control ($M = 342$ ms) and tails-out ($M = 346$ ms) targets. There was a significant axis by direction interaction, $F(1, 15) = 7.43$, $p < .05$, *partial* $\eta^2 = .33$, indicating that it took more time to initiate forward ($M = 363$ ms) compared to upward movements ($M = 350$ ms). In addition, RT was longer for upward than backward ($M = 334$ ms) and downward movements ($M = 336$ ms). For MT, there was a significant main effect of direction, $F(1, 15) = 11.51$, $p < .05$, *partial* $\eta^2 = .43$, and a significant axis by direction interaction, $F(1, 15) = 14.18$, *partial* $\eta^2 = .49$. Post hoc analyses revealed upward movements (*M* = 424 ms) were executed more quickly than forward (*M* = 463 ms), backward (*M* = 459 ms) and downward movements (*M* = 466 ms).

Aiming Bias and Variability

The analysis of the primary movement endpoints yielded a significant main effect of target, *F*(2, 30) = 47.48, $p < .05$, *partial* $\eta^2 = .76$. Post hoc analysis indicated a shorter displacement for tails-in figures (*M* = 185.5 mm) compared to control figures (*M* = 187.8 mm), which were also shorter than tails-out figures (*M* = 189.7 mm). There was a significant axis by direction interaction, *F*(1, 15) = 13.28, $p < .05$, *partial* $\eta^2 = .47$, indicating a shorter primary movement for downward and forward compared to backward movements (see Table 1). Moreover, there was a significant direction by target interaction, *F*(2, 30) =5.40, $p < .05$, *partial* $\eta^2 = .27$ (see Table 2). For down/backward movements, tails-in figures were associated with shorter primary movements than control figures which were also shorter than movements to tails-out figures. For up/forward movements, tails-in and control primary movements were similar, though both were shorter than primary movements to tails-out figures. For spatial variability at the primary movement endpoint, there was a significant main effect of axis, *F*(1, 15) = 12.24, $p < .05$, *partial* $\eta^2 = .45$, indicating greater endpoint dispersion for the vertical axis (*M* = 9.1 mm) compared to the horizontal axis (*M* = 7.6 mm).

Insert Table 1 and Table 2 about here

At the termination of the complete movement, many of the same biases were still evident in CE. Specifically, there were main effects for both axis, *F*(1,15) = 5.66, $p < .05$, *partial* $\eta^2 = .27$, and target, *F*(2,30) = 114.42, $p < .05$, *partial* $\eta^2 = .88$. Participants exhibited slightly greater undershooting in the vertical axis (*M* = -2.0 mm) than the horizontal axis (*M*

= -1.3 mm). As well, all three forms of the illusion were significantly different from each other (TI: *M* = -3.3 mm, CTL: *M* = -1.8 mm, TO: *M* = +0.2 mm). There were also significant interactions of axis by direction, $F(1,15) = 14.60$, $p < .05$, *partial* $\eta^2 = .49$, and direction by target, $F(2,30) = 25.97$, $p < .05$, *partial* $\eta^2 = .63$. As is evident in Figure 3A, downward movements were shorter than upward and backward movements, but not forward movements. For moving down/backward however, all three forms of the illusion were different (see Figure 3B). When moving up/forward, there was no significant difference between the tails-in and the control figure, but both were associated with greater undershooting than the tails-out figure. The analysis of VE revealed a significant main effect of axis, $F(1,15) = 8.37$, $p < .05$, *partial* $\eta^2 = .36$, and direction, $F(1,15) = 47.53$, $p < .05$, *partial* $\eta^2 = .76$, as well as an axis by direction interaction, $F(1,15) = 23.93$, $p < .05$, *partial* $\eta^2 = .62$. Post hoc analysis of the interaction revealed significantly increased endpoint dispersion for the backward movements (*M* = 4.3 mm) compared to forward (*M* = 3.7 mm) and upward movements (*M* = 3.6 mm), although the greatest endpoint dispersion was indicated in downward movements (*M* = 5.5 mm).

Insert Figure 3 about here

Other Kinematic measures

In order to examine how biases unfold over the course of the movement, we also examined mean displacement at peak acceleration, peak velocity and peak deceleration. This can be seen in Figure 4. At peak acceleration, there was a significant main effect of axis, $F(1, 15) = 22.54$, $p < .05$, *partial* $\eta^2 = .60$, and direction, $F(1, 15) = 165.57$, $p < .05$, *partial* $\eta^2 = .92$, as well as an axis by direction interaction, $F(1, 15) = 31.12$, $p < .05$, *partial* $\eta^2 = .68$. Post hoc analysis revealed a significantly shorter displacement to reach peak acceleration when moving forward and upward compared to backward. Backward movements were also significantly shorter than downward movements.

For the displacement at peak velocity, there was a significant main effect of direction, $F(1, 15) = 205.80$, $p < .05$, *partial* $\eta^2 = .93$, and target, $F(2, 30) = 15.92$, $p < .05$, *partial* $\eta^2 = .52$. Post hoc analysis revealed less displacement for tails-in ($M = 80.9$ mm) compared to control figures ($M = 82.0$ mm), which was shorter still, compared to the tails-out figures ($M = 83.0$ mm). The axis by direction interaction approached conventional levels of significance, $F(1, 15) = 3.14$, $p = .058$, *partial* $\eta^2 = .17$, indicating greater displacement for backward and downward aims than the other directions.

For the displacement of peak deceleration, there was a significant main effect of direction, $F(1, 15) = 22.69$, $p < .05$, *partial* $\eta^2 = .60$, and target, $F(2, 30) = 25.33$, $p < .05$, *partial* $\eta^2 = .63$, as well as an axis by direction interaction, $F(1, 15) = 7.05$, $p < .05$, *partial* $\eta^2 = .32$. Post hoc analysis of the target effect revealed that displacement was again different for all three forms of the illusion. Thus, the same biases were evident as at the termination of the movement (i.e., lower displacements for tails-in figures and the largest displacement for tails-out figures; see CE results) (TI: $M = 161.0$ mm, CTL: $M = 163.6$ mm, TO: $M = 165.9$ mm). Post hoc analysis of the interaction effect confirmed that displacement at peak deceleration was significantly longer in backward movements than the other remaining conditions. It appears then that the final impact of target context on aiming bias emerges earlier in the trajectory than strategic biases associated with the axis of the movement or movement direction.

Insert Figure 4 about here

For the magnitude of kinematic landmarks, there was a significant main effect of direction, $F(1, 15) = 111.31$, $p < .05$, *partial* $\eta^2 = .88$, and target, $F(2, 30) = 5.46$, $p < .05$, *partial* $\eta^2 = .27$, for peak acceleration. Post hoc analysis revealed a significantly lower peak for tails-in ($M = 14.90$ m/s^2) compared to control ($M = 15.17$ m/s^2) and tails-out ($M = 15.19$ m/s^2). For peak velocity, there was also a significant main effect of target, $F(2, 30) = 10.10$, $p < .05$, *partial* $\eta^2 = .40$, and a direction by target interaction, $F(2, 30) = 5.71$, $p < .05$, *partial* $\eta^2 = .28$, indicating a lower peak for tails-in ($M = 1104$ mm/s) compared to control ($M = 1130$ mm/s) and tails-out ($M = 1137$ mm/s) when aiming down/backward, but only a difference between tails-in ($M = 1119$ mm/s) and tails-out ($M = 1133$ mm/s) when aiming up/forward (control: $M = 1125$ mm/s). Finally, peak deceleration showed a significant main effect of direction, $F(1, 15) = 33.46$, $p < .05$, *partial* $\eta^2 = .69$, indicating a more pronounced peak for the down/backward ($M = 11.90$ m/s^2) compared to up/forward ($M = 9.35$ m/s^2) targets.

Secondary submovements occurred on 78.7% of the trials and their frequency did not vary with experimental condition (*ps* > .05). For trials involving a secondary submovement, an analysis of their temporal duration revealed an axis by direction interaction that approached conventional levels of significance, $F(1, 15) = 4.56$, $p = .05$, *partial* $\eta^2 = .23$. Down corrective movements ($M = 145$ ms) took slightly more time to complete than up corrective movements ($M = 127$ ms), while there was no difference between corrective submovements in the horizontal plane (forward: $M = 139$ ms, backward: $M = 136$ ms). Meanwhile, the displacement during the secondary submovement analysis revealed a significant main effect of axis, $F(1, 15) = 23.63$, $p < .05$, *partial* $\eta^2 = .61$, and significant axis by direction interaction, $F(1, 15) = 5.42$, $p < .05$, *partial* $\eta^2 = .27$. Interestingly, the post hoc analysis revealed a significantly longer displacement for down movements ($M = 6.9$ mm) compared to forward ($M = 4.8$ mm) and backward ($M = 4.4$ mm) movements (upward: $M = 5.3$ mm; cf. Elliott et al., 2014).

Discussion

The present study examined limb-target control during goal-directed aiming under strategic conditions implemented to accommodate for the cost of potential errors. We had participants execute discrete aiming movements in upward, downward, forward and backward directions toward Müller-Lyer configurations: tails-in, control, and tails-out. Based on Sternberg's (1969) additive factor logic, a statistical interaction between these direction/axis (strategic) and target (illusory) manipulations would indicate that they impact similar information processing systems. On the other hand, the absence of an interaction would speak to their relative independence. We showed some evidence of a strategic bias nearing the end of the movement following a larger magnitude deceleration and subsequent undershoot for the downward direction, and an illusory bias exhibited as early as peak velocity that continued throughout the entire movement. Moreover, there was an interaction between the two manipulations, which was isolated toward the end of movement. That is, there was a greater illusory bias for movements in the downward/backward (tails-in was shorter than the control, which was also shorter than the tails-out) compared to the upward/forward (i.e., tails-in and control were equally shorter than tails-out) directions. This interaction coincided with a longer time and displacement in the secondary corrective submovement for downward movement (cf. Elliott et al., 2014). It would appear then that the information processes associated with *limb-target control* are influenced by the pre-planned strategic approach adopted earlier in the movement associated with *impulse regulation* (Elliott et al., 2010). These findings elaborate on the multiple process model of limb control as impulse control and limb-target-control were initially thought to be independent (Grierson & Elliott, 2009a).

When aiming in the vertical plane, the final end point of the limb undershot the target to a greater extent when participants moved downward from the home position than when they moved upward. This finding is consistent with the notion that participants plan and execute their movements to avoid corrective movements made against gravity, and thus reduce the likelihood of trajectory modifications that are costly in terms of time and energy expenditure (Bennett et al., 2012; Elliott et al., 2014; Lyons et al., 2006; see also Oliveira et al., 2005). In addition, when moving in the horizontal plane, participants appeared to undershoot the target to a greater extent when moving away from the body than toward the body. The same pattern of results was also evident in the primary movement endpoints. That is, there was greater undershooting when moving downward and forward than when moving upward and backward.

The increased undershoot for forward compared to upward and backward movements is not without precedence (Lyons et al., 2006). It is important to recognize, however, that despite the similar termination points for the downward and forward movements, the bias associated with these two types of movement unfold differently. That is, forward movements were associated with a shorter displacement to reach peak acceleration, and peak velocity, much like the upward movement. In contrast, the termination of downward movements manifests via greater displacement at peak acceleration, and peak velocity, before large magnitude deceleration. Therefore, the strategic movement biases associated with downward movements did not begin to emerge until after peak deceleration, during the final stages of the aiming trajectory. For downward movements, part of this effect could result from counteracting the added acceleration associated with gravity, and/or an appropriate strategy to cope with the increasing inertia.

The illusory target configurations elicited limb displacement biases that were consistent with the direction of the perceived illusion. Specifically, participants undershot the target vertex to a greater extent when aiming to the tails-in configuration than the tails-out configuration, while the aiming bias for the control figure was generally intermediate. These findings are consistent with previous work on discrete aiming to a Müller-Lyer configuration (e.g., Elliott & Lee, 1995; Mendoza et al., 2006). Moreover, the displacements at kinematic landmarks showed the illusory bias manifested as early as peak velocity and continued throughout the entire trajectory. In a similar vein, when aiming toward an alternating combination of Müller-Lyer tail ends (> > / < < / < > / > <), Glazebook et al. (2005) showed that the tails-in end target configuration generated consistently shorter movement displacement than the tails-out from peak velocity onwards. Therefore, it would appear the perceived illusory context has at least some influence on both movement planning and limb-target control (Franz, 2001; Mendoza et al., 2006; cf. Glover, 2004 and Milner & Goodale, 1995).

Statistical interactions between target configuration and direction were evident in the primary movement endpoints and constant error. That is, the impact of the illusory configurations was more robust for aiming downward and backward than for aiming upward and forward. It is important to note, however, that the covariation between the two manipulations only occurred late in the trajectory during the final corrective process (i.e., after peak deceleration). Prior to this point the manipulations had relatively independent effects on limb control processes. Indeed, the final undershooting bias associated with moving downward was likely a result of avoiding an error against gravity toward the end of the movement. Meanwhile, the illusory biases associated with the Müller-Lyer configuration were a result of misperceiving the location of the target relative to the limb, and unfolded it seems in movement planning and limb-target control. This relative or allocentric spatial judgment is different from the type of control associated with impulse regulation, which concerns the parameterization and judgement of limb velocity and direction (i.e., internal model). In terms of spatial organization, this process is more egocentric in nature (see Milner & Goodale, 1995 and Westwood, 2010), and remains relatively unaffected by illusory target context (see Roberts et al., 2013; cf. Grierson & Elliott, 2009a). Herein, the illusory context may influence movement throughout its entire course (Mendoza et al., 2006), although the magnitude of illusory bias could differ as a result of the impending control process (impulse regulation, limb-target control) (Grierson & Elliott, 2009b). To elucidate, the allocentric cues sub-serving illusory biases may influence at any portion of the trajectory, although impulse regulation processes may somewhat restrict this influence until the end of the movement (during limb-target control).

Following this logic, strategic biases that impose a greater undershoot may accommodate further limb-target control, which could then generate increased illusory biases. We argue this strategic outcome underlies the interaction between the two manipulations (illusory and strategic). That is, when moving short of the target following a downward response, there is an extended time and displacement in the secondary submovement, and thus, increased limb-target control (cf. Elliott et al., 2014; see below for further explanation).[2] This elicits greater illusory limb-target control and generates displacement biases that are even more consistent with the perceived target context (i.e., tails-in was shorter than the control, which was also shorter than the tails-out). On the other hand, situations that entail less undershooting, and thus shorter time and displacement in the secondary submovement (upward, forward), elicit a smaller illusory bias (i.e., tails-in and control are equally shorter than tails-out).

To this end, strategic and illusory biases affect similar processing systems (Sternberg, 1969). However, the relation is isolated toward the end of the movement following the onset of corrective processes associated with the target context. The interaction likely unfolds toward the end because the strategic bias primarily concerns the position of limb following the primary movement, while the perceptual-motor system updates limb position using the target context. In a similar vein, Grierson and Elliott (2008) found that the perturbation of limb velocity (using forward and backward air blasts in the horizontal axis) during simultaneous short and long target perturbations resulted in a greater undershoot compared to an unperturbed velocity condition. Notably, the independent and interactive relations investigated in this study concerned separate classes of control (impulse regulation and limb-target control). However, the present study examines the independence and interaction of two displacement biases that appear to impact limb-target control. With respect to the multiple process model (Elliott et al., 2010), it appears the control processes underlying goal-directed aiming are not as dichotomous as first thought. Furthermore, we suggest the strategic biases associated with avoiding energy-consuming corrections against gravity amalgamate with the limb-target control processes associated with the target context.

The following proposal assumes illusory biases take place within, but not limited to, limb-target control. More specifically, the position of the limb is updated by the observed relative metrics of the target (i.e., orientation of the tail ends) after the limb enters foveal vision and gets closer to the target. Indeed, the illusory biases were almost identical for the end of the primary movement and in constant error when the entire movement was complete. Thus, although limb-target control explicitly occurred on 78% of the trials, it did not contribute to reducing the illusory bias. Though there are cases of limited illusory biases in alternative visuomotor tasks (e.g., Aglioti, DeSouza, & Goodale, 1995; Glover & Dixon, 2001; 2002), the current findings are consistent with other studies on discrete manual aiming toward a Müller-Lyer configuration (e.g., Grierson & Elliott, 2009a, b; Mendoza et al., 2006; Roberts et al., 2013; see also Elliott et al., 2010) (for further discussion, see Westwood, 2010).

Recent evidence from a similar vertical aiming procedure showed that secondary submovements (attributed to limb-target control) occurred on a lower proportion of trials, and involved shorter displacement when moving down compared to up (Elliott et al., 2014). Thus, it would appear that the underlying limb-target control for each of these directions is different. Specifically, when moving downward, participants appear to not only undershoot the target with the primary movement, but are sometimes content to land only in the vicinity of the target without engaging in potentially costly corrective submovements. The current data however indicate limited differences in the frequency of submovements, and an extended displacement of the secondary submovement for downward movements. It is noteworthy that despite these differences between the studies, they together provide a clearer picture of limb-target control. That is, in the Elliott et al. (2014) study, the differences in the secondary submovement were found during perturbations to visual sensory feedback. Thus, it could be that when moving down, individuals plan for what is known as the "worse-case scenario" (Elliott et al., 2004; Hansen et al., 2006). Specifically, Elliott et al. (2014) proposed that in preparation for no vision, or at least the potential for no vision, the cost of corrective submovements against gravity was avoided by terminating the limb following the primary movement. However, when moving up, despite the initial disadvantage toward online control, the presence of visual information is taken advantage of in order to correct for any movement errors when, or if, vision becomes available. The strategic approaches mentioned above failed to unfold in the current study as participants were presented visual information throughout the entire experimental procedure.

In summary, our findings are consistent with the notion that both movement direction/axis and illusory target context manipulations affect limb-target control. The influence of movement axis and direction are strategic in nature. That is, participants take into consideration the inherent spatial variability associated with endpoint aiming variability and plan primary aiming movements that reduce the likelihood of aiming errors that overshoot the target. This strategy is particularly pronounced when aiming downward because any corrective movements that involve a reversal following an initial overshoot must be made against gravity. This type of corrective submovement requires additional time and energy. Meanwhile, illusory biases involve an implicit misperception of target position that impacts both movement planning and discrete corrective processes late in the movement. Because of the initial impact of illusory context on movement planning, biases associated with target context emerge early in the movement trajectory and grow slightly stronger as the movement progresses. The two manipulations begin to interact near the end of the movement, and thus indicate a common process underlying the two biases. More specifically, strategic undershoots in the downward direction render increased limb-target control, which in turn, accommodates limb positioning relative to the observed target context. These findings elaborate on the multiple process model (Elliott et al., 2010) by showing the interaction of control processes can be partitioned specifically within limb-target control.

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Figure captions

Figure 1. Illustration of the experimental setup in the sagittal view for the vertical (A) and horizontal (B) conditions. The computer monitor was held within an in-house designed box (*upper black*) and secured to the stand (*white*) via a bracket/ledge (*grey*). The performer would move up/down for the vertical, and forward/backward for the horizontal.

Figure 2. Tails-in (A), control (B) and tails-out (C) Müller-Lyer target configurations. Note the following illustration displays only the upward/forward direction.

Figure 3. Constant error as a function of axis and direction (A), and direction and target (B). Error bars represent standard error of the mean. (*) indicates difference at $p < .05$.

Figure 4. Displacement at kinematic landmarks (peak acceleration; PA, peak velocity; PV, peak deceleration; PD, movement termination; END) as a function of axis and direction. Error bars represent standard error of the mean.

Footnotes

1. Previous work has shown that similar movement environments featuring visual feedback of the limb typically elicits a robust Müller-Lyer effect (e.g., Mendoza et al., 2006).
2. Though we recognise the backward aims indicate equally greater illusory biases compared to upward and forward aims, the shorter time and displacement in the secondary submovement (limb-target control) suggests it unfolded for very different reasons. We speculate the backward aims may have garnered a predominantly allocentric frame of reference following movement directed toward the performer's space (Forsyth, Puckering, & Bryden, 2015).