The Influence of Visual Feedback and Prior Knowledge About Feedback on Vertical Aiming Strategies

Digby Elliott [1,2], Chris Dutoy [1], Matthew Andrew [1], James J. Burkitt [2], Lawrence E.M. Grierson [3], James L. Lyons [2], Spencer J. Hayes [1], and Simon J. Bennett [1]

1. Faculty of Science, Liverpool John Moores University, Liverpool, UK
2. Department of Kinesiology, McMaster University, Hamilton, Ontario, CANADA
3. Department of Family Medicine, McMaster University, Hamilton, Ontario, CANADA

Corresponding Author: Digby Elliott, Department of Kinesiology, McMaster University, Hamilton, Ontario, L8S 4K1, CANADA (Elliott@mcmaster.ca)

Phone: 1-613-332-2508

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Abstract

Two experiments were conducted to examine time and energy optimization strategies for movements made with and against gravity. In Experiment 1, we manipulated concurrent visual feedback, and knowledge about feedback. When vision was eliminated upon movement initiation, participants exhibited greater undershooting, both with their primary submovement and their final endpoint, than when vision was available. When aiming downward, participants were more likely to terminate their aiming following the primary submovement or complete a lower amplitude corrective submovement. This strategy reduced the frequency of energy-consuming corrections against gravity. In Experiment 2, we eliminated vision of the hand and the target at the end of the movement. This procedure was expected to have its greatest impact under no vision conditions where no visual feedback was available for subsequent planning. As anticipated, direction and concurrent visual feedback had a profound impact on endpoint bias. Participants exhibited pronounced undershooting when aiming downward and without vision. Differences in undershooting between vision and no vision were greater under blocked feedback conditions. When performers were uncertain about the impending feedback, they planned their movements for the worst-case scenario. Thus movement planning considers the variability in execution, and avoids outcomes that require time and energy to correct.

Keywords: aiming, vision, speed-accuracy, gravity, energy optimization, movement planning

The Influence of Visual Feedback and Prior Knowledge About Feedback on Vertical Aiming Strategies

One of the most influential two-component models of speed-accuracy relations in goal-directed aiming has been Meyer, Abrams, Kornblum, Wright and Smith's (1988) optimized submovement model. This model posits that goal-directed aiming is organized to optimize movement time while taking into account target size, as well as the neural noise associated with the movement velocities that might be selected to achieve the specific target goal. Higher movement velocities require greater muscular forces, which are characterized by greater force variability that results in greater trial-to-trial spatial variability (Schmidt, Zelaznik, Hawkins Frank & Quinn, 1979). This added spatial variability increases the probability that the primary submovement will fall outside of the target boundaries (Meyer et al., 1988), and thus the incidence of a corrective submovement (or submovements) to bring the limb to the target. However, corrective submovements take time to complete and thus increase the overall movement time. Thus the objective, of any aiming attempt, is to optimize the velocity/duration of the primary submovement so that the limb gets to the target area quickly, but not so quickly that a corrective submovement is required on a large proportion of trials.

The optimized submovement model (Meyer et al., 1988) is based on stochastic principles that predict a normal distribution of primary movement endpoints around the movement goal (i.e., center of the target). Thus when corrective submovements are required, it is equally probable that they will involve a further movement in the original direction to correct a target undershoot, or a reversal to correct a target overshoot. Although the optimized submovement model provides an excellent foundation for explaining the relationship between movement speed and end-point accuracy/spatial variability, at least one tenet of the model is inconsistent with empirical evidence regarding the spatial-temporal characteristics of most movement trajectories. Specifically, it is well-documented that primary movement endpoints are centered short of the target, and often outside of the actual target boundaries (e.g., Chua & Elliott, 1993; Engelbrecht, Berthier & Sullivan, 2003; Elliott, Hansen, Mendoza & Tremblay, 2004; Woodworth, 1899; Worringham, 1991). In terms of optimizing movement time, this type of trajectory, and the associated mean movement endpoint, makes sense because target undershooting is easier to correct than target overshooting (Elliott, Helsen & Chua, 2001; Elliott et al., 2004; Elliott, Hansen, Grierson, Lyons, Bennett & Hayes, 2010). For example, if the initial submovement overshoots the target and a correction is required, the limb travels a greater distance, thus requiring more time and a greater expenditure of energy (Elliott et al., 2004; Oliviera, Elliott & Goodman, 2005; Sparrow & Newell, 1998).[1] Under most circumstances, a more efficient movement organization strategy is to plan an aiming movement that will fall short of the target center (i.e., perhaps the near target boundary) so that, given the stochastic properties of endpoint distributions, only a small proportion of aiming attempts will terminate beyond the far target boundary and require a corrective reversal.

Based on the reasoning that the degree of primary movement undershooting should be related to the relative temporal and energy costs associated with performing a subsequent correction, Lyons, Hansen, Hurding and Elliott (2006; see also Bennett, Elliott & Rodacki, 2012) proposed that the distribution of primary movement endpoints should be affected by gravitational constraints. Testing this hypothesis involved participants performing vertical aiming movements to a target located up or down from a central home position. Thus movements were made either with or against gravity (i.e., the target below the home position and the target above the home position, respectively). As predicted, primary movement undershooting was most pronounced when the primary movement was made with gravity (i.e., the target below the home position). This outcome occurred because overshooting the target would have required a corrective submovement (i.e., a reversal in direction) against gravity that required more energy and more time than corrective submovements that overshot the upward located target.

Lyons et al. (2006) suggested that their findings reflected learned strategic behaviors that minimize both the temporal and energy costs associated with precision aiming. Presumably, given that such aiming movements would typically be performed in conditions of normal vision, it follows that the learned behavior would take advantage of available visual information in feedforward planning and feedback-based corrections. For instance, performers would understand that concurrent visual feedback could be compared to expected sensory consequences, whereas terminal visual feedback would provide useful information on the final outcome that could be used in subsequent aiming attempts. However, it remains to be determined how participants strategically organize aiming behavior when they do not have access to visual information of the limb and the target for the online regulation of manual aiming movements to vertically arranged targets. Here, then, participants were required to aim as rapidly and accurately as possible from a central home position to equally probable targets located either directly above or below the home position. On some trials, participants had full visual information about the position of their limb and the target over the course of the movement, while on other trials vision was eliminated upon movement initiation via liquid crystal goggles. Because strategic behavior associated with manual aiming depends on participants knowing in advance whether or not vision will be available, we also manipulated prior knowledge about the visual circumstance for each aiming attempt (Hansen, Glazebrook, Anson, Weeks & Elliott, 2006; Heath, Hodges, Chua & Elliott, 1998). Thus participants performed under conditions in which vision was available or not available for a complete block of trials (i.e., participants had prior knowledge about the feedback they would receive) and also under conditions in which the availability of vision was randomly changed from trial-to-trial (i.e., $p = .5$ for each vision condition; see Elliott & Allard, 1985 and Zelaznik, Hawkins & Kisselburgh, 1983).

Our expectation was that we would replicate Lyons et al. (2006) under blocked full vision conditions. Of greater interest was how participants would perform under no vision conditions and conditions of uncertainty. One possibility is that primary movement undershooting would be reduced. The notion here is that, because participants cannot depend on visual feedback to correct either target undershooting or overshooting, primary movements would be planned to terminate closer to the center of the target. Thus the overall presence of corrective submovements would be reduced. Alternatively the absence of visual feedback or uncertainty about its presence might make participants even more conservative about planning their primary submovements, particularly when moving down. In this case, we would expect even greater undershooting in the absence of vision or under conditions of visual uncertainty (e.g., Elliott & Lee, 1995).

Experiment 1

Method

Participants

Data were collected from twelve young adults (18-25 years; 6 females and 6 males) from the McMaster University community. All were right-hand dominant and had normal or corrected-to-normal vision. Our protocol in both experiments was approved by McMaster Research Ethics Board, and all participants provided written informed consent. In spite of instructions regarding how to hold the stylus, one participant performed in such a manner that the infrared emitting diode (IRED) on the stylus was hidden from the optoelectric cameras on the majority of trials. Thus, this participant and his partial data, were eliminated from the analyses. Missing IRED trials for other participants were 10.6%.

Apparatus and Procedure

Participants sat at a table with an LCD monitor (Samsung Syncmaster 213T) 35 – 40 cm in front of them. The center of the monitor was at the participant's midline and at eye level. The monitor surface was flush with the edge of the table so that the hand would not hit the table-top on downward aiming movements. The task required participants to move a hand held stylus from the home position at the center of the monitor to one of two targets 18 cm above or below the home position. The home position diameter and the target diameters were 10 mm and 9 mm respectively. All aiming was done with the right hand. A microswitch was mounted at the contact end of the stylus, and controlled the opaque and transparent state of liquid crystal goggles (Milgram, 1987) worn by participants throughout testing. An

Optotrak 3020 collected position data from an IRED attached to the end of the stylus. The sampling rate was 500 Hz and data were collected for 2 s on each trial. A custom-written program in E-prime software triggered the Optotrak and, based on the position of the stylus switch, controlled the transparent vs. opaque state of the liquid crystal goggles.

To begin a trial, the participant placed the tip of the stylus on the home position. The experimenter provided a verbal “ready” signal and pushed the enter key on the computer keyboard to initiate a trial. The home position immediately disappeared and, following a variable foreperiod (200-800 ms), one of the two targets was presented. Participants were instructed to move to that target position as quickly and as accurately as possible. For ease of subsequent data processing, they were asked to maintain their limb position in the target area until they were asked to return to the home position (approximately 1 s later). Participants were given several practice trials aiming both with and without vision. For no vision trials, the goggles became opaque when the stylus left the monitor surface. They became transparent again when the tip of the stylus impacted the monitor surface, thus providing terminal visual feedback. On vision trials, the goggles remained in the transparent state throughout the trial. After 2s, the target disappeared from the screen and the participant returned the stylus to the home position ready for the next trial.

During the actual protocol, vision and no vision trials were presented in either a blocked or random order. Target position was random with the constraint that each target was presented equally often within a block of trials. In total, each participant completed 160 experimental trials, which were arranged as 2 blocks of 20 vision trials and 20 no vision trials, plus 2 blocks of 40 trials in which vision was randomized. The randomization was done with the constraint that there were 10 vision and 10 no vision trials to each of the 2 targets within each block of 40 trials. The order of the vision blocks, no vision blocks, and the randomized blocks was systematically alternated across participants.

Data Analysis

Missing Optotrak data of fewer than four frames were linearly interpolated prior to subjecting the full data set to a 2nd order low pass (8Hz) Butterworth filter. Filtered displacement data were differentiated to obtain velocity, acceleration, and jerk. Measures of overall performance included reaction time, movement time and movement time variability, as well as constant and variable error in the direction of the movement. Reaction time was defined as the time from presentation of the target until the stylus was lifted off the home position. A velocity criterion of greater than 10 mm/s in the primary axis (i.e., vertical) was used to define the beginning of the movement (stylus lift-off) in the upward and downward directions. Occurrence of velocity of less than 10 mm/s was defined as the end of the movement. In both instances, this criterion had to be maintained for at least 40 ms. Therefore, for movement termination, this velocity criterion coincided with the impact of the stylus on the target-aiming surface where the velocity immediately fell to almost zero (i.e., the end of the primary movement plus any corrective submovements). Movement time was the time between movement onset and movement end. We identified peak velocity and then calculated the time taken to achieve peak velocity. For calculation of constant error and variable error in the primary direction of the movement, the distance from the center of the target (taken from digitized target files) to the position of the stylus tip at the end of the movement was extracted. Movements that undershot the target were coded with a negative sign while overshoots were coded positive.

Of particular importance to this study were the primary movement endpoints and the presence of subsequent corrective submovements. To this end, a custom-written routine, implemented in Matlab that was similar to Lyons et al. (2006), was used to search for corrective submovements that occurred before the end of the movement. These were identified as: 1) zero crossing in velocity between peak velocity and movement end (i.e., movement reversal); 2) zero crossing in acceleration between peak deceleration and movement end; 3) zero crossing in jerk between peak deceleration and movement end. The routine searched for these submovements in the prescribed order. When a submovement was identified that moment was defined as the end of the primary movement, and no further search for submovements was made. We then calculated the duration of the primary movement, as well as the spatial position of the primary movement endpoint point relative to the position of the target. These latter data were used to calculate constant error and variable error of primary movement endpoints, as well as the submovement correction amplitude.

Most within-participant means (central tendency) and standard deviations (dispersion) of the dependent variables were calculated from the 20 trials/condition. For dependent variables associated with a submovement, calculations were conducted on fewer than 20 observations. Means and within-participant standard deviations, where appropriate, were submitted to separate 2 Order (Blocked, Random) x 2 Vision Condition (Vision, No Vision) x 2 Direction (Up, Down) repeated measures ANOVAs. Significant interaction effects were decomposed using Tukey's HSD post hoc procedure. Alpha was set at $p < 0.05$.

Results and Discussion

Performance-Temporal

The reaction time analysis yielded only a main effect for Direction, $F(1,10) = 8.43$, $p < .02$, with participants taking slightly more time to organize their movements when moving down (288 ms) than up (275 ms). Analysis of movement time revealed a main effect for Vision Condition, $F(1,10) = 14.33$, $p < .01$, and a Vision Condition by Direction interaction, $F(1,10) = 8.56$, $p < .02$. Overall, participants took more time to execute their movements when vision was available (524 ms) than when it was eliminated upon movement initiation (487 ms). This finding is consistent with previous research (Hansen et al., 2006; Khan, Elliott, Coull, Chua & Lyons, 2002) and reflects the fact that the performer takes additional time to use vision when it is available. Interestingly, this vision effect was most pronounced when participants were aiming to the lower (vision = 529 ms; no vision = 481 ms) compared to upper (vision =

519 ms; no vision = 494 ms) targets. The analysis of movement time standard deviations revealed only an interaction between Vision Condition and Order, $F(1,10) = 7.71$, $p < .05$, with participants being slightly more variable under vision-blocked (96 ms) and no vision-random (89 ms) conditions than vision-random (83 ms) and no vision-blocked (75 ms) conditions.

Performance-Error

The constant error analysis revealed only a main effect for Vision Condition, $F(1,10) = 5.93$, $p < .05$. Although participants undershoot the target in both vision conditions, their undershooting was greater when vision was eliminated upon movement initiation (-3.4 mm) than when they had full visual feedback over the course of the movement (-1.1 mm).

For variable error there were main effects for Vision Condition, $F(1,10) = 93.31$, $p < .001$, Order, $F(1,10) = 5.95$, $p < .05$, and Direction, $F(1,10) = 31.44$, $p < .001$, as well as a Vision Condition by Direction interaction, $F(1,10) = 14.66$, $p < .01$. Overall participants were more variable when they had no visual feedback (vision = 4.0 mm, no vision = 8.7 mm), when they had no prior knowledge about the upcoming feedback condition (blocked = 6.1 mm, random = 6.7 mm) and when they were aiming downward (up = 5.4 mm, down = 7.5 mm). Post hoc analysis on the interaction revealed that while there was no difference in variability when vision was available, participants exhibited greater inconsistency when moving downward than upward under no vision conditions (see Figure 2).

Insert Figure 2 About Here

Kinematics

The analysis of peak velocity revealed only a main effect for Direction, $F(1,10) = 17.45$, $p < .01$. Participants achieved higher peak velocities when moving downward (945 mm/s) than upward (865 mm/s). For time to peak velocity, there was once again only a main effect for Direction, $F(1,10) = 31.62$, $p < .001$, with participants achieving peak velocity later when moving down (187 ms) than up (163 ms).

In order to examine corrective processes occurring after peak velocity, we initially conducted an analysis of the proportion of trials that contained a corrective submovement. This analysis revealed a main effect for Vision Condition, $F(1,10) = 6.92$, $p < .05$, and Direction, $F(1,10) = 74.54$, $p < .0001$. As one would expect, there were more trials with corrective submovements when vision was available (.79) than when it was absent (.70). Interestingly, participants had a lower proportion of trials with corrective submovements when they were aiming down (.58) than up (.90). Analysis of amplitude of the corrective phase also revealed a main effect of Vision Condition, $F(1,10) = 7.13$, $p < .05$, and Direction, $F(1,10) = 9.24$, $p <.05$. In trials with a correction, this phase of the movement had larger amplitude in the no vision condition (4.8 mm) compared to the vision condition (2.5 mm) and when moving up (5.8 mm) compared to down (1.4 mm).

For mean error at the end of the primary movement, there was only a main effect for Vision Condition, $F(1,10) = 13.72$, $p < .01$, with participants exhibiting less undershoot when vision was available (-3.3 mm) than when it was absent (-6.9 mm). The absence of a main effect for Direction is different from Lyons et al. (2006) where undershooting with the primary submovement was more pronounced when aiming downward. However, for variability in the primary movement endpoint there were main effects for Vision Condition, $F(1,10) = 10.48$, $p < .01$, Order, $F(1,10) = 5.66$, $p < .05$, and Direction, $F(1,10) = 9.64$, $p < .02$, as well as a Vision Condition by Direction interaction, $F(1,10) = 5.31$, $p < .05$. Primary movement endpoints were more variable when vision was eliminated upon movement initiation (12.3 mm) than under full vision conditions (9.8 mm), as well as under random (11.6 mm) compared to blocked conditions (10.6 mm). Importantly, primary movement endpoints were also more variable when moving up (12.7 mm) than moving down (9.4 mm). Moreover, as is evident in Figure 3, the up-down difference was more pronounced when vision was available than when it was absent.

Insert Figure 3 About Here

In combination, the kinematic data indicate that when moving down participants adopted a strategy of, more often, terminating the movement, without a corrective submovement, compared to when moving up. This strategy was associated with lower spatial variability at completion of the primary movement phase, and was similarly successful in terms of constant error at end of the movement and total movement time. Thus, although somewhat different from Lyons et al. (2006), participants in the current study still appeared to adopt a conservative strategy when aiming downward that limited the frequency and amplitude of corrective submovements. As in previous studies (Bennett et al., 2012; Lyons et al., 2006), this movement strategy during aiming limits the number of corrections that must be made against gravity. It is also consistent with the idea that performers plan their movements for worst-case outcomes, which here would be a target overshoot when moving downward that would require a correction against gravity (e.g., Elliott et al., 2004).

Experiment 2

One of the empirical problems with manipulating vision during the movement trajectory is determining whether or not any differences in aiming accuracy (particularly under blocked feedback conditions) are due to visual online regulation during each individual trial or an advantage associated with visual feedback about endpoint error on trial N being used to adjust feedforward planning of trial N + 1 (Cheng, Luis & Tremblay, 2008; Zelaznik et al., 1983). In an attempt to clarify the relative contribution of online and terminal feedback we introduced a further manipulation. Whereas in Experiment 1 participants always had terminal visual feedback about their aiming error at the end of each trial, in Experiment 2, the goggles always closed on stylus impact. Accordingly, participants were not given terminal visual feedback in the no-vision conditions. Under vision conditions performers had vision of both their hand and the target until stylus impact on the aiming surface (i.e., the termination of the movement). Thus although they had information about endpoint error, they had less time to consolidate this visual feedback after stylus impact (i.e., the 1 s that the limb remained in the target area after impact). We expected that limiting the time available to use endpoint visual feedback, under full vision conditions, would increase the importance of online visual feedback and thus prior knowledge about feedback. We also expected was that, under no vision conditions, final aiming error and endpoint variability associated with the primary submovement, would be higher in Experiment 2 than Experiment 1. This is because there would be no visual information available for trial-to-trial feedforward planning. Overall our manipulation was designed to increase the importance of online feedback in Experiment 2 relative to Experiment 1.[2]

Method

Participants

Data were collected from twelve young adults (18-26 years; 8 females and 4 males) from the McMaster University community. All participants were right-hand dominant and had normal or corrected-to-normal vision, and gave written informed consent. None of the participants had taken part in Experiment 1. Again, it was necessary to remove one participant because the IRED on the stylus was hidden from the optoelectric cameras on the majority of trials. For all other participants, the hidden IRED trials were 9.5%.

Apparatus, Procedure and Data Analysis

The apparatus and procedures, as well as the analysis, were identical to those of Experiment 1 except that access to terminal visual feedback was either restricted or not provided. In the vision condition, the goggles remained transparent when the stylus left the home position and throughout the movement. Once the participant had completed the movement and the microswitch came in contact with the monitor surface, the goggles became opaque, thus restricting access to terminal visual feedback (i.e., the interval between contact and returning to the home position). They remained opaque until the participant returned to the area of the home position after which the experimenter returned the goggles to the transparent state. Thus, in

Experiment 2, while participants had visual information about the position of their hand and the target up until contact with the target-aiming surface, they did not have continued access to this information after the aiming movement had been completed. Under no vision conditions, the goggles became opaque on stylus lift-off and throughout the movement. The goggles remained closed until the stylus returned to the area of the home position. Thus concurrent and terminal visual feedback was not available in the no vision conditions.

Within-participant means (central tendency) and standard deviations (dispersion) of the dependent variables were calculated from the 20 trials per combination of independent variables and submitted to separate 2 Order (Blocked, Random) x 2 Vision Condition (Vision, No Vision) 2 Direction (Up, Down) repeated measures ANOVAs. Significant interaction effects were decomposed using Tukey's HSD post hoc procedure. Alpha was set at $p < 0.05$.

Results and Discussion

Performance-Temporal

The reaction time analysis once again revealed only a main effect for Direction, $F(1,10) = 15.26$, $p < .01$, with participants taking more time to organize their movements to lower (298 ms) than upper (272 ms) targets. The analysis of movement time yielded a main effect for Vision Condition, $F(1,10) = 17.38$, $p < .01$, as well as a Vision Condition by Direction interaction, $F(1,10) = 4.97$, $p < .05$. Overall participants took more time to execute their movements under vision conditions (512 ms) compared to no vision (480 ms) conditions. This difference was only significant, however, when participants were aiming down (vision-down = 514 ms; no vision-down = 466 ms) compared to up (vision-up = 511 ms, no vision-up = 494 ms). Thus, particularly when moving downward, participants took extra time to use vision for limb control when it was available. The variability in movement time analysis yielded only a main effect for Direction, $F(1,10) = 5.29$, $p < .05$. Participants were slightly more variable when moving down (85 ms) than when moving up (71 ms).

Performance-Error

The analysis of constant error revealed main effects for both Vision Condition, *F*(1,10) = 10.56, *p* < .01, and Direction, *F*(1,10) = 104.70, *p* < .0001. Overall, participants undershot the target to a greater extent under no vision conditions (-14.6 mm) than vision conditions (-5.8 mm), and when aiming down (-19.9 mm) as opposed to up (-0.5 mm). These main effects were superseded by interactions involving Vision Condition and Direction, *F*(1,10) = 19.88, *p* < .01, and Vision Condition, Order and Direction, *F*(1,10) = 5.92, *p* < .05. Although there was a significant difference between up and down movements under all order and feedback conditions (Tukey HSD, p < .05), as is apparent in Figure 4, participants exhibited the largest directional differences under no vision conditions. When vision was eliminated upon movement initiation, participants exhibited profound undershooting when aiming downward, particularly under blocked feedback conditions. This conservative aiming strategy is consistent with planning for a worst-case outcome (Elliott et al., 2004).

Insert Figure 4 About Here

The variable error analysis revealed only a main effect for Direction, *F*(1,10) = 9.83, *p* < .02, with participants exhibiting greater end point variability when aiming down (10.85 mm) as opposed to up (6.96 mm). Of interest was the absence of a main effect for Vision Condition, which only approached conventional levels of significance, *F*(1,10) = 3.79, *p* = .08 (vision = 7.26 mm, no vision = 10.56 mm).

Kinematics

The peak velocity analysis yielded main effects for both Vision Condition, *F*(1,10) = 14.56, *p* < .01, and Direction, *F*(1,10) = 5.91, *p* < .05, as well as interactions involving Vision Condition and Order, *F*(1,10) = 6.02, *p* < .05, and Vision Condition and Direction, *F*(1,10) = 13.29, *p* < .01. Participants achieved higher peak velocities when aiming downward (917 mm/s) than upward (868 mm/s), and in the vision (905 mm/s) as opposed to no vision (880 mm/s) conditions. The interaction of these two variables indicated that peak velocity was particularly pronounced when moving downward in the vision condition (937 mm/s) compared to the other conditions (vision-up = 873 mm/s, no vision-down = 896 mm/s, no vision-up = 863 mm/s). Post hoc analysis of the Vision Condition by Order interaction indicated that higher velocities were attained under vision-blocked conditions (924 mm/s) than in any of the other 3 situations (vision-random = 886 mm/s, no vision-blocked = 877 mm/s, no vision random = 883 mm/s). The time to peak velocity analysis yielded only a main effect for Direction, $F(1,10) = 21.17$, $p < .001$. Participants took longer to reach peak velocity when moving downward (178 ms) than upward (159 ms).

The analysis of the proportion of trials with a corrective submovement revealed only a main effect for Direction, $F(1,10) = 50.75$, $p < .0001$, with participants exhibiting corrective submovements on the vast majority of the trials when moving upward (.94) but not downward (.62). Analysis of amplitude of the corrective phase revealed no significant effects with a grand mean of 5.7 mm.

For mean error at the end of the primary movement, there were main effects for Vision Condition, $F(1,10) = 12.89$, $p < .01$ and Direction, $F(1,10) = 39.68$, $p < .0001$, and interactions involving Vision Condition and Order, $F(1,10) = 5.15$, $p < .05$, and Vision Condition and Direction, $F(1,10) = 17.30$, $p < .01$. Overall, participants were further away from the target in the no vision (-18.7 mm) than vision (-10.7 mm) conditions at completion of the primary movement. As with CE, their undershooting with the primary movement was much greater when moving downward (-22.9 mm) than upward (-6.5 mm). The Vision Condition by Direction interaction is depicted in Figure 5. Although the difference between upper and lower targets was significant in both situations, undershooting of the lower targets was more pronounced in the no vision condition. The post hoc analysis of the interaction involving Vision Condition and Order revealed that the difference between the vision and no vision conditions was more pronounced in blocked conditions (vision-blocked = -9.3 mm, vision-random = -12.1 mm, no vision-blocked = -20.3, no vision-random = -17.0 mm). Analysis of variability of the primary movement endpoint failed to reveal any significant effects with a grand mean of 13.3 mm.

Insert Figure 5 About Here

In combination, and similar to Experiment 1, the kinematic data indicate that when moving downward participants were more likely to terminate their movement short of the target without making a corrective submovement. Here, though, the effect of vision condition and direction was more acute and pervasive. Participants were particularly conservative when aiming down and exhibited profound undershooting if they did not have visual feedback available during and upon completion of the movement. Thus the subtle “play-it-safe” strategies associated with aiming downward in Experiment 1 were replaced by more robust strategies for minimizing time and energy in Experiment 2.

General Discussion

Our goal was to examine the roles of visual feedback and prior knowledge about upcoming availability of feedback on movement organization in a vertical aiming task. An important foundation for the work is the idea that human adults understand that, due to variability in the motor system, rapid goal-directed movements will not always unfold as planned. Specifically, on any given trial there will be an amplitude error that, over multiple trials, results in the movement end-points being distributed around the intended movement outcome. Moreover, it has been shown the distribution of end-point errors (i.e., target undershoot or overshoot) depends on the types of movement correction required (e.g., Bennett et al., 2012; Lyons et al., 2006). In most cases (cf. Oliviera et al., 2005, Task 2), the performer will plan a movement that slightly undershoots the target goal because the cost of a correction requiring a reversal in direction is more costly than a correction that involves a further movement in the original direction (Elliott et al., 2004). Such movement organization in manual aiming is even more exaggerated when a correction to a target overshoot must be made against gravity, as when aiming downward. To date, however, evidence for a strategic influence on aiming behavior has been found in conditions that enable the participant to use visual feedback, proprioceptive feedback and feedforward information to correct the primary endpoint error. Here we were interested in determining whether or not participants would engage in the same type of strategic behavior when the opportunity for online and/or terminal visual feedback utilization was either restricted or reduced due to uncertainty. Manipulating access to terminal visual feedback about movement outcome was based on the notion that visual outcome information from trial N is important for the planning of trial N + 1 (Cheng et al., 2008; Elliott et al., 2004; Zelaznik et al., 1983) and, in the form of terminal feedback, may offset the effect of not having access to visual information as a trial unfolds (i.e., the no vision condition in Experiment 1).

In Experiment 1, our visual manipulation produced results that are broadly consistent with the existing aiming literature. Specifically, participants took more time to complete their movements when vision was available than when it was eliminated upon movement initiation (see Elliott et al., 2001 for a review). This extra time is probably responsible for lower variable error and reduced undershooting in the full vision compared to no vision conditions. This extra precision and consistency was not just present at the termination of the movement, but also at the primary movement endpoint. This latter finding suggests that visual regulation of the limb is not confined to the homing phase of the movement as Woodworth's (1899) and Meyer et al.'s (1988) two-component models of speed-accuracy relations propose. Rather, visual control is also possible early in the limb trajectory (e.g., Bard, Hay & Fleury, 1985; Elliott, Carson, Goodman & Chua, 1991; Proteau, Roujoula & Messier, 2009; Saunders & Knill, 2004). In our recent multiple process model of speed-accuracy relations, we have termed this impulse control (Elliott et al., 2010). The multiple process model holds that this type of control involves the early comparison of perceived limb velocity and direction to an internal model of expected velocity and direction. Unlike discrete corrective processes (i.e., limb-target control), impulse control does not depend on the relative position of the limb to the target.[2]

In terms of our directional manipulation, there is again evidence that participants "play-it-safe" when moving downward compared to upward. However the manner in which this conservative approach to aiming was realized was different from Lyons et al. (2006) and Bennett et al. (2012). In those studies, it was found that participants produced shorter primary submovements when moving downward compared to upward, and then on most trials corrected the extreme undershoot with a second submovement in the original movement direction. Here, rather than producing shorter primary movements when aiming downward, participants were more likely to produce a primary movement of a similar length to the upward aiming direction, and then simply terminate the movement without a corrective submovement (42% of downward trials vs. 10% of upward trials). On the trials in which a corrective submovement was made (58%), the amplitude of the correction was much shorter when moving downward (1.4 mm) than upward (5.8 mm). Together these two types of trials allowed participants to produce a mean aiming error that was only slightly short of the target without the need for corrective submovements made against gravity.

Although once again there is evidence for participants planning their movements for a worst-case outcome, the manner in which strategic undershooting (i.e., play-it-safe strategy) was realized was different from previous research. Given that our full vision-blocked situation was almost identical to Lyons et al. (2006), we speculate that the differences in the form of the movement trajectories in Experiment 1 may be related to the overall experimental context (cf. Experiment 2). That is, in Lyons et al. (2006) participants were always certain that vision would be available for limb control, while here this was true on only 25% of the trials. This context difference may have motivated participants to adopt a single overall approach to aiming that would maximize speed and minimize energy expenditure on downward aiming trials under both visual contexts. That is, they prepared a movement to terminate short of the target when aiming downward and only corrected that movement when the primary submovement was deemed to be substantially short of the target. When that movement was amended, it was with a conservative (low amplitude) correction.

It is also possible that the difference between Experiment 1 and Lyons et al. (2006) reflects the changes in the task setup and procedure we were required to adopt to accommodate the inclusion of no vision trials. Specifically Lyons et al. (2006) required participants to hit the target to terminate the trial. Thus the authors constrained accuracy via target size did not measure target-aiming error. In the two studies reported here, we could not expect accurate aiming when vision was eliminated upon movement initiation. Thus we measured endpoint error and in fact found at least some degree of target undershooting under both full vision (-1.1 mm) and no vision (-3.4 mm) conditions. Once again this overall undershooting reflects a play-it-safe approach at least in terms of time and energy.

Interestingly, our order manipulation ended up having more impact on movement variability than on spatial bias. Specifically, spatial variability was less under blocked feedback conditions, both at the end of the primary submovement and at the termination of the movement, than under random feedback conditions. This occurred independent of vision condition or movement direction. The advantage probably stems for the fact that within a block of trials, information (visual and/or proprioceptive) associated with trial N can be more effectively used to plan and control trial N + 1 (Cheng et al., 2008; Elliott et al., 2004). The absence of any important interactions between vision condition and order could reflect the fact that the movement times in this experiment were in the vicinity of 500 ms. Typically, blocked vs random feedback differences are most pronounced for movement times that challenge visual processing speed (e.g., < 200 ms; Elliott & Allard, 1985). Further, in order to be consistent with Lyons et al. (2006), we adopted a protocol in which the specific target (i.e., up or down) was not known in advance, but rather served as the reaction time signal. As Hansen et al. (2006) have reported, advance information about the availability of visual feedback is used more effectively when the performer is also cued as to the spatial goal of the movement (i.e., the specific target).

In most manual aiming studies, it is difficult to determine the trial-to-trial adjustments in strategic behavior due to online feedback available during the execution of an aiming attempt and those that reflect changes in movement planning based on terminal feedback about the relative positions of the limb and the target at the end of the movement (Khan et al., 2002). In Experiment 2, we eliminated the opportunity for terminal feedback processing under no vision conditions by ensuring that vision was not available after the stylus impacted the target area. Under vision conditions, participants did have visual information about endpoint error available, but were expected to show a slight deterioration in performance because they were denied the opportunity to consolidate that information once the stylus contacted the aiming surface.[3] Overall, final target undershooting and undershooting with the primary submovement were profound when participants were aiming downward but not upward. Although this directional difference was significant under both vision conditions, it was most pronounced when vision was eliminated upon movement initiation. As in Experiment 1, part of the overall undershooting when moving downward was related to the finding that participants frequently terminated their movement at the end of the primary movement without making subsequent corrective submovements. Once again, this finding is consistent with the tenets of our multiple process model of limb control (Elliott et al., 2010), which holds that performers prepare for worst-case outcomes. In this context, a worst-case outcome would be a target overshoot when moving downward that would result in a correction against gravity. Moreover, Experiment 2 provides additional evidence for a conservative aiming strategy when moving downward. Specifically, participants took more time to both prepare their movements (i.e., longer RTs) and execute their movement when vision was available (i.e., longer MTs) when moving to the lower target.

Of particular relevance was the finding that Order had a greater impact on performance in Experiment 2 than Experiment 1. Specifically, for the primary movement endpoint, participants exhibited larger differences in bias under blocked compared to random feedback conditions. This finding would seem to indicate that when the time for visual feedback processing is limited (i.e., Experiment 2), participants plan trial N + 1 to a greater extent based on their expectations for online visual information than they might otherwise. That is, when terminal feedback is limited and thus contributes less to movement planning, vision for online control and expectancies about the availability of concurrent visual feedback become more important (cf. Experiment 1). Under random feedback conditions in Experiment 2, participants simply hedged their bets in favor of the worst-case/no vision situation.

As well as the subtle difference between Experiment 1 and Experiment 2 in terms of participants' strategic behavior, one cannot ignore the huge overall difference in constant error and primary movement endpoint between the two experiments. Although these differences were particularly apparent when participants were moving downward, the overriding factor would seem to be the availability of visual feedback (i.e. concurrent or terminal) about endpoint error for subsequent movement planning. As well as trial-to-trial error reduction that contributes to more precise movement planning, this type of feedback is potentially important for the development of an internal model of limb control that includes expectancies about the anticipated visual and proprioceptive feedback on subsequent trials. These expectancies are important for what we have previously termed impulse control (Elliott et al., 2010). Impulse control, in this case, would involve a comparison of expected limb velocity to perceived limb velocity. On a related note, it is instructive that large differences in constant error between the two experiments were not accompanied by differences in variable error between conditions in Experiment 2. Perhaps this is not surprising given that trial-to-trial variability between trials, within an experimental condition, not only reflects neural noise but also changes in strategic behavior designed to reduce directional errors from previous trials. Without visual feedback about performance, it would appear that performers adopt a strategic approach to the task that, while consistent, can result in profound amplitude error (e.g., the no vision blocked condition when moving downward).

In summary, the results of this work are consistent with the notion that adult humans are extremely flexible in the manner in which they prepare their movements to take advantage of the information that is available, while minimizing the energy and movement time costs associated with worst-case outcomes. Although we have approached the undershooting issue strictly from an energy and time minimization point of view, it is possible that undershooting may be a generalized behavior associated with various other factors. There are, for example, many situations in everyday life where there are costs associated with overshooting a target. One only needs to think of working with a circular saw or knife (e.g., losing a finger) or taking a pot of soup off the stove (e.g., burning one’s hand) to understand the advantages associated with initially undershooting the target in a goal-directed task.[4]

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Acknowledgements

This research was supported by the Natural Sciences and Engineering Research Council of Canada. We thank Dan Garcia for technical help with the experimental setup.

Footnotes

1. For corrections associated with target undershoots, the limb still has a positive velocity in the direction of the target. When correcting overshoots however, the limb must overcome the inertia of a zero velocity situation at the point of the reversal. Moreover the neuromuscular demands of a reversal are greater than a second acceleration because the roles of the agonist and antagonist muscles groups are changed (Elliott et al., 2010).

2. Both terminal feedback and online feedback can also be used to refine the expected sensory consequences associated the internal model of the aiming movement. These expected consequences can then be compared to online feedback on subsequent trials for impulse control.

3. Although slight compared to no vision conditions, the difference between the full vision constant error in Experiment 1(-1.1 mm) and the full vision constant error in Experiment 2 (-5.8 mm) was significant, t (20) = 3.61, $p < .01$. This difference may be due to the more limited time that participants had to process feedback in Experiment 2. Alternatively, there may be some sort of advantage associated with seeing the hand return to the home position (i.e., Experiment 1).

4. Ferraz de Oliveira and colleagues (2006, 2007) have found that even skilled basketball players undershoot foul and jump shots to a greater extent when vision of the last portion of the shot is reduced or degraded. Because of the backboard, undershooting is completely maladaptive in this context, but occurs none the less.

Figure Captions

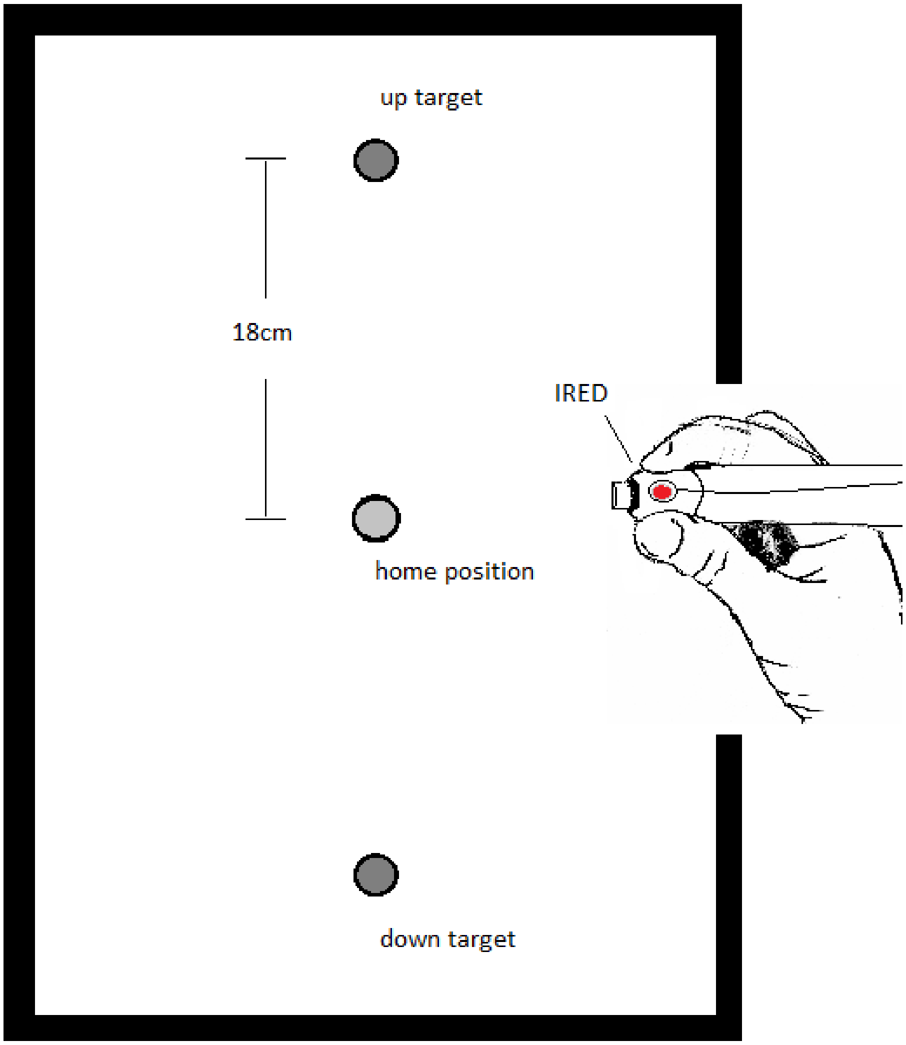
Figure 1. Schematic of target-aiming setup.

Figure 2. Variable error in Experiment 1 as a function of Vision Condition, Order and Direction. All main effects were significant. As well, there was a significant Vision Condition by Direction interaction ($p < .05$).

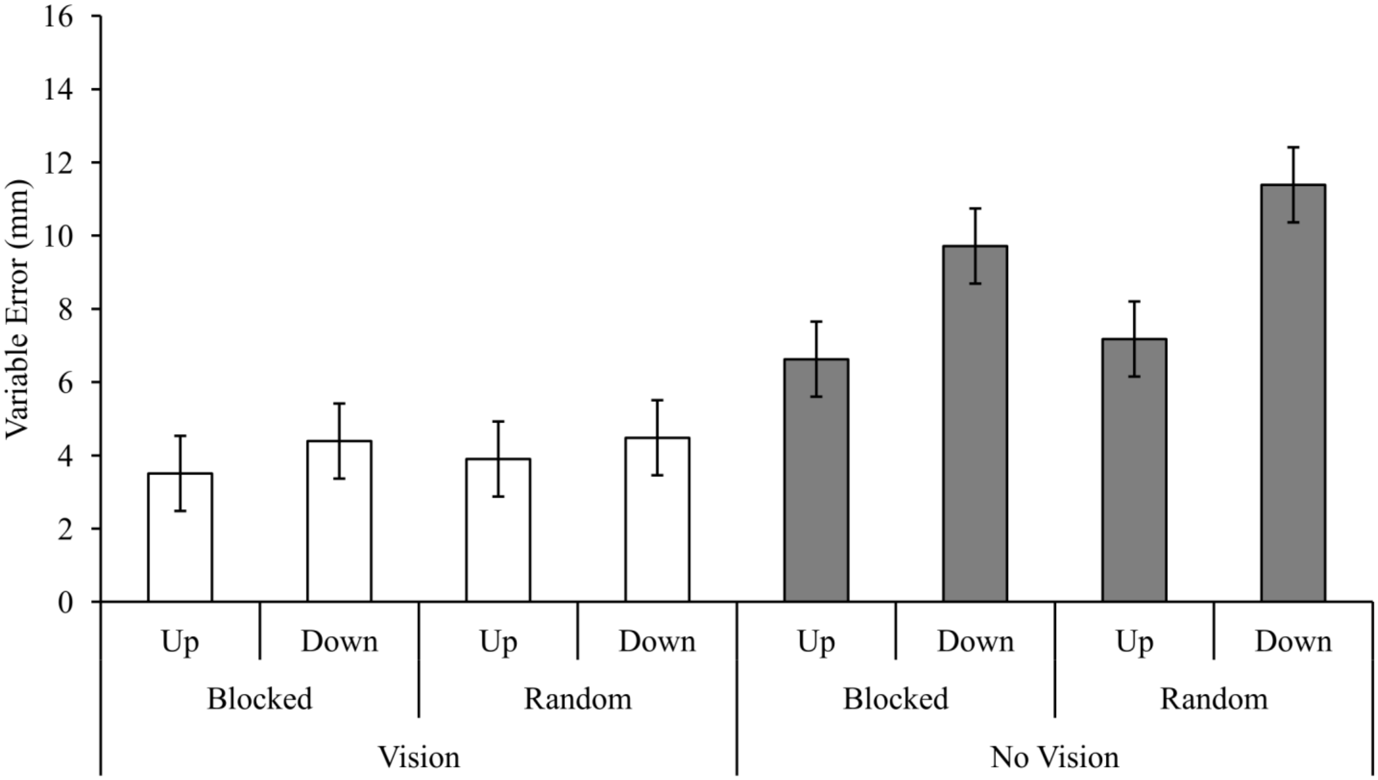
Figure 3. Variability (standard deviation) of primary movement endpoints in Experiment 1 as a function of Vision Condition, Order and Direction. All main effects were significant. As well, there was a significant Vision Condition by Direction interaction ($p < .05$).

Figure 4. Constant error in Experiment 2 as a function of Vision Condition, Order and Direction. The main effects for Vision Condition and Direction were significant. As well, there were significant Vision Condition by Direction and Vision Condition by Order by Direction interactions ($p < .05$).

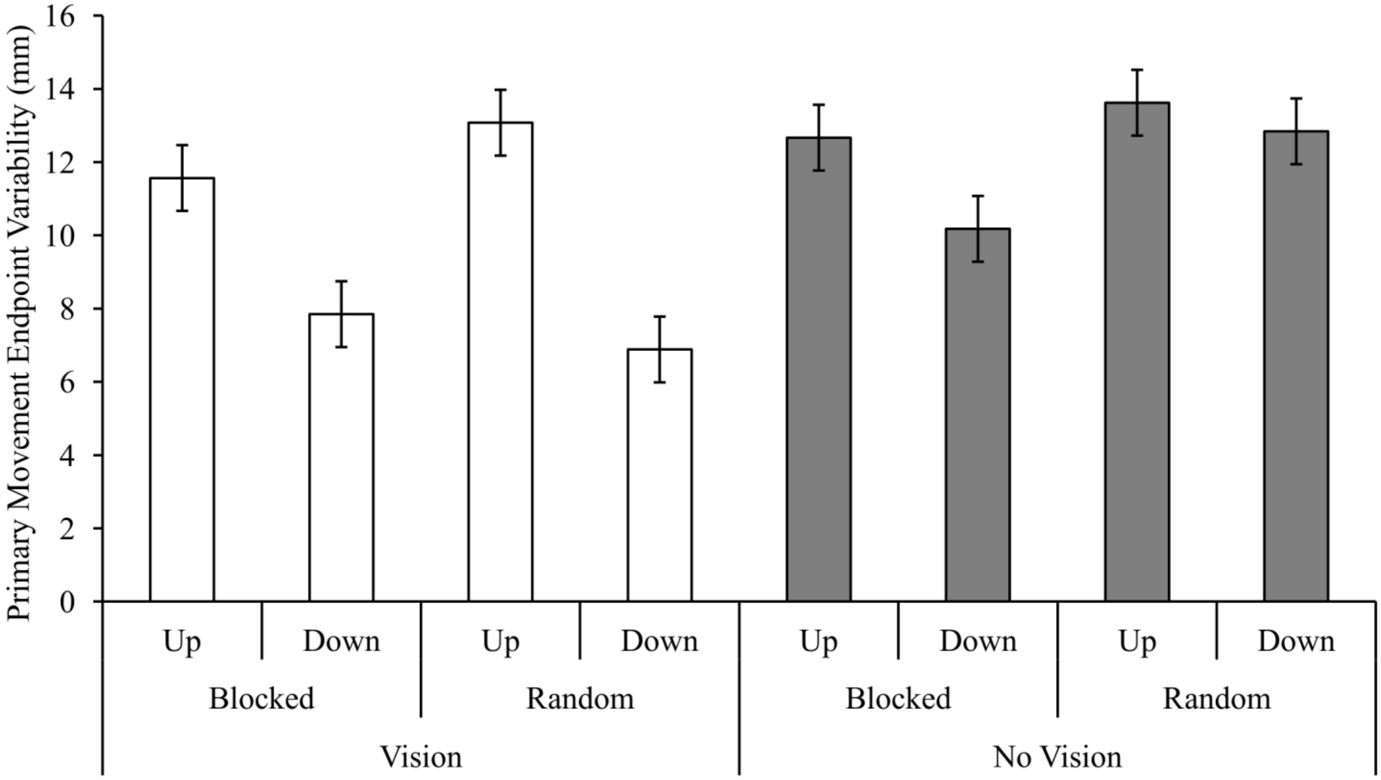
Figure 5. Primary movement endpoint in Experiment 2 as a function of Vision Condition and Direction. Both the two main effects and the interaction were significant ($p < .05$).


up target
18cm
IRED
home position
down target

2


16
14
12
10
8
6
4
2
0
Variable Error (mm)
Up
Down
Up
Down
Up
Down
Up
Down
Blocked
Random
Blocked
Random
Vision
No Vision

3


Primary Movement Endpoint Variability (mm)
16
14
12
10
8
6
4
2
0
Up
Down
Up
Down
Up
Down
Up
Down
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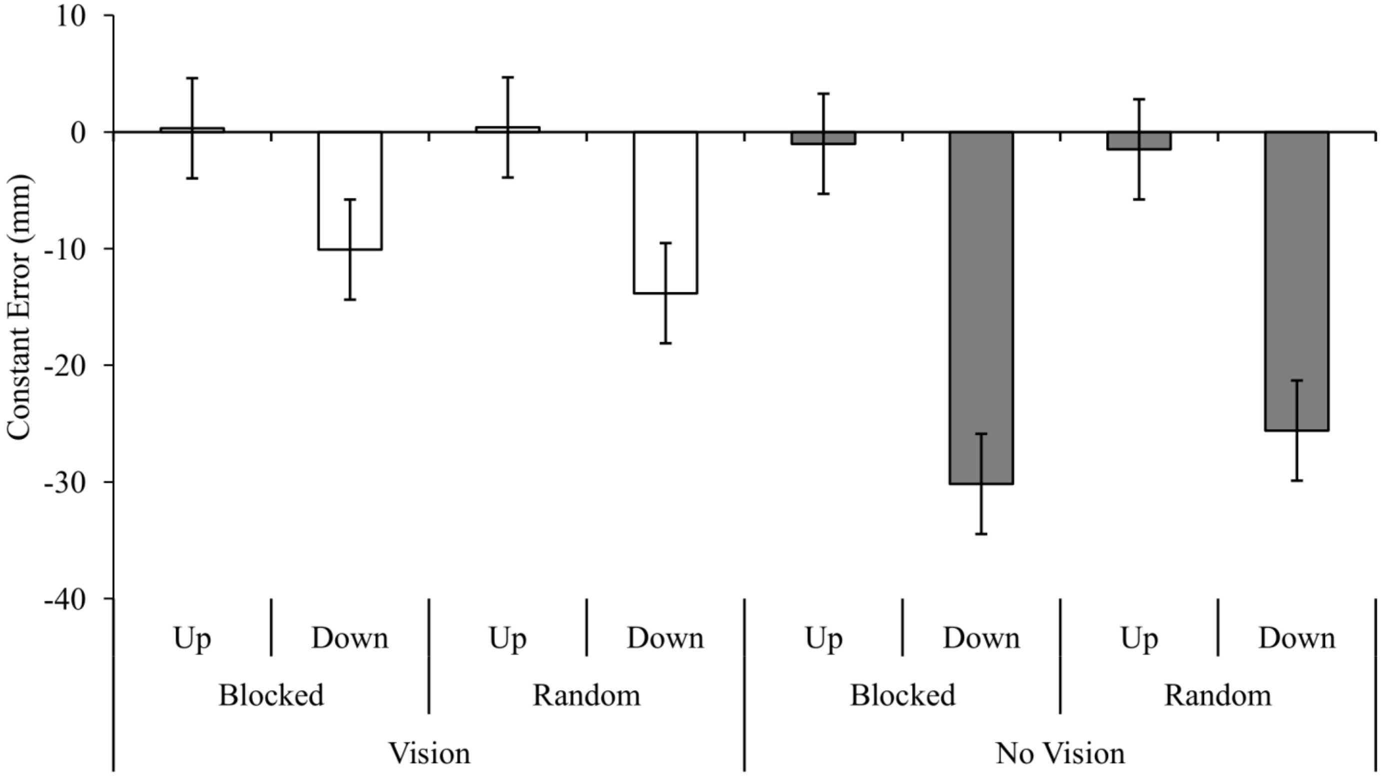
Random
Blocked
Random
Vision
No Vision

4


10
0
-10
-20
-30
-40
Constant Error (mm)
Up
Down
Up
Down
Up
Down
Up
Down
Blocked
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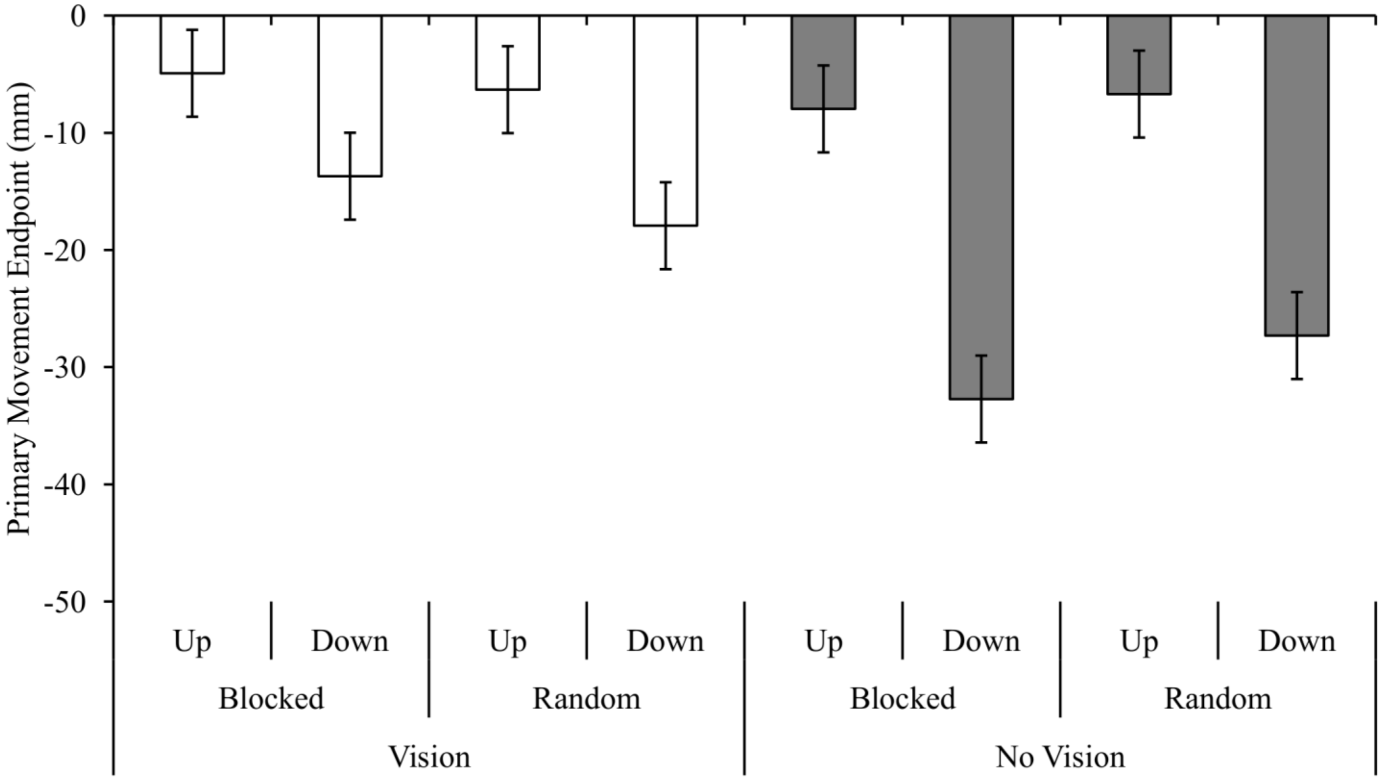
Blocked
Random
Vision
No Vision

5


Primary Movement Endpoint (mm)
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-20
-30
-40
-50
Up
Down
Up
Down
Up
Down
Up
Down
Blocked
Random
Blocked
Random
Vision
No Vision