Effector mass and trajectory optimization in the online regulation of goal-directed movement

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Abstract

Goal-directed aiming movements are planned and executed so that they optimize speed, accuracy and energy expenditure. In particular, the primary submovements involved in manual aiming attempts typically undershoot targets in order to avoid costly time and energy overshoot errors. Furthermore, in aiming movements performed over a series of trials, the movement planning process considers the sensory information associated with the most recent aiming attempt. The goal of the current study was to gain further insight into how the sensory consequences associated with the recent and forthcoming aiming attempts impact performance. We first examined if performers are more conservative in their aiming movements with a heavy, as opposed to a light, stylus by determining whether primary submovements undershot the target to a greater extent in the former due to an anticipated increase in spatial variability. Our results show that movements with the heavy stylus demonstrated greater undershoot biases in the primary submovements, as well as greater trial-to-trial spatial variability at specific trajectory kinematic landmarks. In addition, we also sought to determine if the sensory information experienced on a previous aiming movement affected movement planning and/or online control on the subsequent aiming attempt. To vary the type sensory consequences experienced on a trial-to-trial basis, participants performed aiming movements with light and heavy styli in either blocked or random orderings of trials. In the random order conditions, some participants were provided advance information about stylus mass for the upcoming trial while others were not. The blocked and random trial orders had minimal impacts on end point aiming performance. Furthermore, similarities in the times to key kinematic landmarks in the trajectories of the random order groups suggests that recent trial experience had a greater effect on the upcoming aiming movement compared to advance task knowledge.

Keywords: aiming, online control, trial history, impulse control

Introduction

Traditionally, goal-directed aiming movements are considered to be composed of two identifiable components: an initial "ballistic" component that brings the limb into the proximity of the target and a secondary "corrective" component that directs the limb onto the target (Woodworth 1899). These two components have been referred to as the primary and secondary submovement(s), respectively (e.g., Meyer et al. 1988). The primary submovement is considered to reflect the planning processes that occur prior to movement onset, while secondary submovement(s) is (are) considered to be guided by a process of online control that reduces any discrepancy between the location of the limb at the end of the primary submovement and the location of the target (Elliott et al. 2001; Grierson and Elliott, 2008, 2009). However, feedback-based control can also occur during the primary submovement/initial impulse. This type of control involves a comparison of perceived sensory consequences to expected sensory consequences and does not require a change to the overall movement plan. Elliott et al. (2010) have termed this type of control "impulse control" to distinguish it from the type of late "limb-target" control first identified by Woodworth (1899). The impulse control discussed by Elliott et al. (2010) is similar in some ways to the type of early, continuous control discussed by Desmurget and Grafton (2000) in their Hybrid Model. Desmurget and Grafton suggest that aiming movements proceed on the basis of an initial crude movement plan that is continuously updated using rapid corrections based on position and velocity estimations provided by forward modeling in internal feedback loops. Although impulse control for Elliott et al. (2010) includes rapid adjustments to limb velocity and direction, corrective processes associated with the relative position of the effector and the target occur late in the movement (i.e., discrete limb-target control; cf. Desmurget et al. 1999).

A significant contributor to discrepancy between the primary submovement end point location and the location of the target is the variability inherent in human movement (see Faisal et al. 2008). Since greater force variability is associated with movements that involve the specification of greater muscular force (Schmidt et al. 1979), the end point spatial variability of the effector increases along with the force requirements of the intended task. Meyer et al.'s (1988) optimized submovement model was the first to conceptualize the planning process involved in goal-directed aiming by explaining how the performer takes variability into consideration when preparing individual aiming movements. In this model, the forces involved in aiming movements are scaled so that they are large enough to get the limb to the target area rapidly, but are not so large that the end point locations of the primary submovements are highly variable and consistently fall outside of the target boundaries (and require time consuming trajectory modifications). Over a series of aiming trials, Meyer et al. suggested that the distribution of primary submovement end point locations is centred over the target, with only the tails of this distribution extending beyond the target boundaries.

However contrary to Meyer et al.'s expectations, in most target-aiming contexts, the central tendency of the distribution of primary submovement end point locations is centred short of the target in the form of an undershoot bias (Engelbrecht et al. 2003; Elliott et al. 2004). Furthermore, the extent of this undershoot bias is directly related to the variability of the aiming movements (Worringham 1991), as well as the time and energy costs attributed to specific target relative end point errors (Lyons et al. 2006; see also Oliveira et al. 2005). In order to explain these results, Elliott and colleagues posited that goal-directed aiming movements are organized to optimize speed, accuracy, and energy expenditure (see Elliott et al., 2010; see also Elliott et al., 2004 and Elliott et al., 2001). Critical to this concept is the idea that target overshoot errors are associated with greater time and energy costs compared to target undershoot errors. This added cost is due to the former involving a longer path to the target, the reversal of a zero-inertia situation (i.e., a secondary acceleration in the direction opposite to the initial direction of travel) and a reversal in the roles of the agonist and antagonist muscle groups (Elliott et al. 2009). Thus, while it is more beneficial to achieve the target with the primary submovement and not make any secondary adjustments (Elliott et al., 2009; Welsh et al. 2007), human performance is biased by the time and energy costs associated with end point variability. That is, the undershooting bias represents a trade-off that, over the course of performing many trials, optimizes speed, accuracy and energy expenditure.

When performed over a series of trials, aiming movements have also been demonstrated to depend on the sensory information experienced on the most recent aiming attempt. Cheng et al. (2008; see also Cheng et al. 2013) demonstrated this in a task where participants performed randomly oriented sequences of trial blocks that could consist of either one, two, three or four successive trial types (i.e., vision or no vision). They found that the sensory context of the previous trial strongly impacted the trajectory characteristics of the current trial, regardless of whether the two trials had matching sensory contexts (i.e., vision or no vision). In addition, this occurred whether or not participants had advance information about the sensory context to be expected on the current trial. Thus, the results of Cheng et al. suggest that the sensory information gathered on trial “N” can be used to guide performance on trial “N + 1”.

Research involving the manipulation of visual feedback has also shown that prior knowledge about the availability of vision during the upcoming trial influences both movement planning and online control (Hansen et al. 2006; Khan et al. 2002). Specifically if participants are uncertain about the availability of vision on the upcoming trial, they plan their movement for the worst-case (no vision) outcome (Hansen et al. 2006). According to Elliott et al (2010), this approach also influences “impulse control” because uncertainty about the sensory experience (e.g., availability of vision) of an upcoming movement impacts early trajectory comparisons between the predicted and actual sensory experiences. These comparisons are fundamental to early limb regulation.

The purpose of this study was to determine if optimal aiming performance depends on advance knowledge about the trial-to-trial aiming variability associated with the forces involved in moving two differently weighted styli. This is based on the expectation that movements made with a heavy mass involve greater initial force requirements and greater trial-to-trial variability in the primary submovement end point locations (see Schmidt et al. 1979) compared to those made with a light mass. In particular, this study examined whether primary submovement undershooting is affected by the weight of the effector and its associated trial-to-trial aiming variability. Building on research involving the manipulation of visual feedback, we also examined whether or not optimal aiming performance depends on the participants’ prior aiming experiences and expectations about the weight of the effector preceding each aiming attempt. Thus three groups of participants performed a series of goal-directed aiming movements with a light and heavy stylus. Two groups of participants performed these movements with random trial orders; a random prior knowledge group (RPK) was precued prior to each trial about the weight of the stylus and a random no knowledge group (RNK) was not aware of the stylus weight until after movement initiation. A blocked group (B) performed trials with the light and heavy styli in blocked trial order.

To avoid the occurrences of costly time and energy overshoot errors, our expectation was that primary submovement end point locations would, on average, undershoot the target location. Furthermore, to accommodate the greater variability expected in the heavy stylus movements, compared to the light stylus movements, we expected participants to undershoot the target to a greater extent when aiming with the heavy stylus. If participants used the sensory consequences of the most recent aiming attempt to plan their current one, the primary submovements performed by the Blocked and Random groups would demonstrate two different patterns of undershoot biases. By repeatedly experiencing the same trajectory characteristics within a series of trials, it was expected that participants in the Blocked group would scale the end points of their primary submovements to the patterns of variability associated with the two different styli. That is, primary submovements with the heavy stylus would undershoot the target to a greater extent than those with the light stylus. This is because this group has knowledge of the type of movement they will be performing on the upcoming trial and has the recent experience of performing this movement type over the course of many consecutive trials. Furthermore, as a result of experiencing different (and random) trajectory characteristics within a series of trials, participants in the Random groups were expected to show a smaller discrepancy between the primary submovement end point locations in movements with the two styli. However, with respect to the two Random groups, we expected the RPK participants to exhibit overall performance advantages (e.g., shorter movement times, lower variable error) compared to RNK participants. This prediction is consistent with the notion that precise information about the force requirements of a movement and expectancies about its sensory consequences are important for movement planning and impulse control respectively.

Methods

Participants

Thirty young adults (15 male, 15 female) with a mean age of 22.10 (sd = 2.70) years were recruited from the McMaster University student community. These participants were randomly assigned to three equally sized groups (see below) that had equal male-female representation. All participants had normal or corrected-to-normal vision, were self-reported right-hand dominant and used their right hand to complete the experiment. Participants were naive to the purpose of the study and provided written, informed consent prior to starting the experiment in accordance with the ethical guidelines of the McMaster University Research Ethics Board and the 1964 Declaration of Helsinki.

Apparatus

The aiming apparatus consisted of a computer monitor (Samsung SyncMaster 910_T) that was fitted with a flat piece of clear Plexiglas to cover the liquid crystal display (LCD) screen. With this set-up, the monitor was used to display the target location (and other relevant task information) generated by E-Prime software (Psychology Software Tools Inc., Sharpsburg, PA, United States), while the Plexiglas was used as the aiming surface. This apparatus was oriented on the flat surface of a table so that the screen and Plexiglas surface faced upward. Participants were seated so that the apparatus was aligned with the midline of their body.

Attached on the edge of the aiming surface nearest to the participant was a starting block. The starting block consisted of a 4.0cm (length: perpendicular to the aiming direction) x 2.2cm (width: parallel to the aiming direction) x 1.0cm (height) rectangular piece of foam glued directly on the Plexiglas surface (see Figure 1A). Cut out of this piece of foam was a triangular notch that aligned with the distally located target and was used to house the stylus at the beginning of each trial. Placed on the aiming surface in the apex of this notch was a circular felt pad that not only served as the home position, but also dampened any potential sounds created by the experimenter when placing one of the styli at this location at the start of every trial (see below). An additional 1.8cm (length: perpendicular to the aiming direction) x 1.6cm (width: parallel to the aiming direction) x 1.0cm (height) rectangular piece of foam was glued to the top of the first piece of foam in a manner that did not impede the triangular cut-out. This second piece of foam enabled participants to place their thumb and index finger on the starting block in the form of a pinch grip.

Aiming movements were performed to a white circular target that was 1.2cm in diameter and located 25cm distal to the starting block. Thus the index of difficulty of the aiming movements was 5.38 bits (Fitts 1954).[1] Movements were performed with two styli that were visibly identical (length = 16.5cm, circumference at top = 6.8cm, circumference at tip = 1.3cm) but different in mass (see Figure 1B). One stylus was constructed of plastic and weighed 36g, while the other stylus was constructed of steel and weighed 243g.[2] These styli will henceforth be referred to as the Light stylus and Heavy stylus, respectively. To make these styli identical to both sight and touch, they were wrapped in black electrical tape. Attached to the bottom of each stylus near the narrow tip was an infrared light emitting diode (IRED). The position of the IRED was captured by an Optotrak 3020 (Northern Digital, Waterloo, ON, Canada) optoelectric camera for 2s at a frequency of 500Hz following the start of every trial.

Participants wore liquid crystal goggles (Translucent Technologies; see Milgram, 1987) that occluded vision while in the translucent state and permitted vision while in the transparent state. The goggles changed state in approximately 5ms. Participants were permitted vision during the aiming movements, but vision was occluded during the inter-trial intervals to prevent participants from seeing the experimenter select and position the stylus.

-- Insert Figure 1 about here --

Procedure

The protocol consisted of 100 trials, 50 that were performed with the Light stylus and 50 that were performed with the Heavy stylus. The order of these trials depended on the group to which participants were randomly assigned. Specifically, participants in the Random Prior Knowledge (RPK) and Random No Knowledge (RNK) groups received random orders of trials involving the Light and Heavy styli; while participants in the Blocked (B) group received the Light and Heavy styli in separate blocks of 50 trials, the order of which were counterbalanced across participants. Participants in the RPK group received prior knowledge before the start of every trial regarding the stylus that would be used for the upcoming movement. Participants in the RNK group did not receive prior knowledge before the start of every trial regarding the stylus that would be used for the upcoming movement. Participants in the B group were told at the beginning of a block and cued before every trial about the stylus weight. The participants did not receive any practice trials prior to starting the experiment.

Trials were initiated by a screen that displayed the word “ready” in yellow letters against a black background (see Figure 1C). At this time, participants placed their thumb and index finger (in the form of a pinch grip) around the top piece of foam on the starting block. Once in this position, the experimenter initiated a second screen that was displayed for 1500ms and either contained: i) prior knowledge information about the stylus that the participant was scheduled to receive on the immediately forthcoming trial (RPK and B groups); this information was always correct and was presented to participants on a black screen that contained the words “HEAVY

STYLUS" or "LIGHT STYLUS" in yellow letters, or ii) remained as an empty black screen (RNK group). Following the presentation of the second screen, all participants were shown the target location for 1500ms. This consisted of a white target (see above) presented on a black background. After this target display, the liquid crystal goggles occluded the participant's vision for a random foreperiod of 3s to 4s, which was used to prevent participants from anticipating the signalled start of the movements. At this time, the second experimenter placed and held the appropriate stylus in front of the participant at the home position. After the random foreperiod, the target was once again presented and aiming movements were initiated with an auditory tone that coincided with the liquid crystal goggles returning to a transparent state (i.e., the return of vision).[3] Aiming movements required participants to move their hand from the starting block, grasp the stylus at the home position, and move the stylus to the target location. Participants were instructed to complete this sequence in one continuous motion. The participants did not receive any specific instructions as to where to grasp the stylus along its shaft. All participants were instructed to perform movements that were fast and accurate, with the specific instruction to attempt to hit the target on the majority of trials.

Once movements were completed, participants were instructed to hold the stylus at the end location until vision was once again occluded by the liquid crystal goggles. This occurred 2s after the auditory start signal. At this time, the second experimenter removed the stylus from the participant's hand and the experimenter manually triggered the goggles into a transparent state (i.e., return of vision). The participant then moved their hand back to the starting block to await the next trial. Mandatory breaks were provided to participants after every 25 trials to reduce the onset of fatigue.

Data Analysis

The data were analyzed using custom MatLab (Mathworks, Natick, MA) software. For each trial, a cumulative displacement profile was constructed using the methods outlined in Hansen et al. (2007). This displacement profile reflected contributions from all three axes of measurement (i.e., x, y and z). The displacement profile was then filtered using a 10Hz dual-pass Butterworth filter, after which it was differentiated and double differentiated using a three-point difference algorithm to produce velocity and acceleration profiles, respectively.

The movement start and end (END) points were defined as the first frames where the velocity profile rose above and fell below, respectively, 10mm/s and remained as such for at least 40ms. Once the movement start and end points were defined, the peaks of acceleration (PA), deceleration (PD) and velocity (PV) were identified on their respective profiles. The primary submovement end point was also located. This was defined using criteria similar to Chua and Elliott (1993) to identify a discontinuity in the movement trajectory. We then marked the beginning of that discontinuity as the end of the primary submovement and the start of a corrective submovement.

Corrective submovements associated with initial target undershooting included zero crossings in acceleration and significant deviations in acceleration, both identified after peak velocity. A zero-crossing was identified as a negative to positive transition in the acceleration profile. More specifically, the resulting inflection in the velocity profile had to achieve a value of at least 5mm/s between the start and peak of the inflection, and there had to be a temporal duration of at least 35ms between the point of initial inflection and the point that dropped below this initial inflection in the velocity profile. Significant deviations were considered reversals in the acceleration trace that did not cross zero. In order to be deemed a significant deviation, the amplitude of the change in the initial inflection and the subsequent inflection (that returned the trajectory to its original course) had to reach a magnitude of at least 10% of peak acceleration/deceleration, and also had to achieve a temporal duration of at least 35ms.

Corrections associated with target overshooting (i.e., reversals) were identified as zero crossings in the velocity profile, since a change in velocity from positive to negative reflects a movement back toward the body following a target overshoot. These positive to negative transitions in velocity needed to correspond to an inflection in the cumulative displacement profile that moved the stylus a distance of at least 5mm in the direction opposite that of initial travel. For a full discussion of these parsing procedures see Khan et al. (2006).

Prior to analysis, trials were removed in which the IRED was not visible to the camera at any point during the movement (this included approximately 11.5% of trials). In addition, the first trial of every session and the trials following the mandatory breaks (i.e., every 25 trials) were removed due to the fact that they were associated with no immediate trial history (this included approximately 1% of trials). Finally, outliers were removed on the basis of a Grubbs' Test performed using constant error and movement time (this included approximately 1% of trials). The numbers of removed trials were distributed evenly across groups and conditions ($p > .4$).

The dependent variables of interest were constant error (CE; mean signed end point error) and variable error (VE; standard deviation of the mean signed end point error) in the primary direction of the movement, movement time (MT), time to peak acceleration (ttPA), time to peak velocity (ttPV), time after peak velocity (taPV), time to peak deceleration (ttPD), the magnitude of peak velocity (PV), the distance traveled by the primary submovement (in the primary direction of movement; PSM) and the within-participant variability of the distance traveled by the primary submovement (in the primary direction of movement; vPSM). These dependent measures were first submitted to separate 3 Group (RPK, RNK, B) by 2 Stylus (Light, Heavy) mixed factors ANOVAs, with repeated measures on the last factor. This was done in order to make between group comparisons about performance with the light and heavy styli and the different forms of advance knowledge. In order to provide a more in-depth look at how the trajectories unfolded over the course of the movements with the light and heavy styli, we examined the variability in the distances traveled at the trajectory kinematic landmarks of PA, PV, PD and END (see Khan et al. 2002). These data were submitted to a 3 Group (RPK, RNK, B) by 4 Kinematic Marker (PA, PV, PD, END) by 2 Stylus (Light, Heavy) mixed factors ANOVA, with repeated measures on the last two factors.

For the Random order groups, we also performed an analysis to determine whether the type of stylus used on trial n-1 impacted performance on trial n (Tremblay et al., 2005; see also Elliott et al., 2004). For this analysis, trials were grouped on the basis of previous trial stylus and current trial stylus (i.e., light-light, heavy-light, light-heavy and heavy-heavy) and the dependent measures were submitted to 2 Predictive Knowledge (Knowledge, No Knowledge) by 2 Stylus (Light, Heavy) by 2 Previous Trial (Light, Heavy) mixed factors ANOVAs, with repeated measures on the last two factors.

All significant effects from ANOVAs involving more than two means were decomposed using Tukey's HSD. Alpha for all analyses was set at $P < .05$.

Results

Analysis of constant error (grand mean = -.61mm) revealed no significant effects, while a main effect of Stylus in variable error, $F(1,27) = 4.36$, $p < .05$, demonstrated greater end point variability in movements with the heavy stylus (3.48mm) compared to the light stylus (3.22mm). There were no significant effects in the analyses of movement time (grand mean = 621ms), time to peak acceleration (83ms), time to peak deceleration (454ms) and time after peak velocity (grand mean = 381ms). However, a main effect of Stylus in the time to peak velocity, $F(1,27) = 12.95$, $p < .01$, demonstrated that movements with the heavy stylus (229ms) took less time to reach peak velocity than movements with the light stylus (253ms; cf. Carson et al. 1993). In addition, a main effect of Stylus for the magnitude of peak velocity, $F(1,27) = 16.20$, $p < .001$, demonstrated that movements with the light stylus (947mm/s) achieved an overall greater magnitude of peak velocity than movements with the heavy stylus (905mm/s). This latter effect is similar to Carson et al. (1993). Analysis of the distance traveled by the primary submovement revealed a main effect of Stylus, $F(1,27) = 24.31$, $p < .001$, which demonstrated that primary submovements covered greater distances in movements with the light stylus (190mm) compared to the heavy stylus (164mm). Considering that the target was located 250mm from the home position, this represents a greater target undershoot bias in the heavy stylus condition.

Analysis of the variability in the distance traveled by the primary submovement revealed no significant effects (grand mean = 50mm). However, analysis of the variability in the distance traveled at the movement kinematic landmarks demonstrated main effects of Stylus, $F(1,27) = 14.70$, $p < .01$, and Marker, $F(3,81) = 103.61$, $p < .001$, that were superseded by interactions involving Stylus by Marker , $F(3,81) = 8.35$, $p < .001$, and Stylus by Group, $F(2,27) = 3.75$, $p < .05$. As was demonstrated in Khan et al. (2002), spatial variability increased as the movements progressed from peak acceleration to the peaks of velocity and deceleration, after which it decreased substantially between peak deceleration and the movement end (PA = 6.14mm, PV = 26.59mm, PD = 32.79mm, END = 3.45mm). Furthermore, movements with the heavy stylus were spatially more variable than those with the light stylus at peak velocity and peak deceleration, while there was no difference between stylus conditions at peak acceleration and the movement end (see Figure 2). These results reflect the fact that movements with the heavy stylus involved the specification of greater force (see Schmidt et al. 1979). According to the Stylus by Group interaction, movements with the heavy stylus were more variable than those with the light stylus in the RPK and RNK groups; whereas there was no difference between styli in the B group (see Figure 3). Since the spatial variability of the higher force movements (i.e., heavy stylus) was only minimized in the group that repeated aiming movements over a trial-to-trial basis, prior knowledge of the upcoming stylus had no impact on the consistency of muscular force specification (see Whitwell et al., 2008).

-- Insert Figures 2 and 3 about here --

To further examine how the availability of prior knowledge influenced trial-to-trial performance in the two random order groups, analyses were conducted using Previous Trial as a factor. For these analyses, only the significant findings involving Predictive Knowledge and Previous Trial are discussed (see Table 1 for the means of the Stylus main effects). This is because the main effects involving Stylus are similar to those mentioned in the analyses above. The analysis of constant error revealed no significant effects (grand mean = -.78), while the analysis of variable error demonstrated a Predictive Knowledge by Previous Trial interaction, $F(1,18) = 6.53$, $p < .05$. According to the interaction, variable error in the RPK group was not influenced by the previous trial (light = 3.65mm; heavy = 3.48mm), whereas variable error in the RNK group was greater in movements following heavy stylus trials (3.78mm) versus light stylus trials (3.35mm). The analyses involving time to peak velocity, time to peak deceleration and movement time all demonstrated Previous Trial main effects [$F(1,18) = 5.95$, $p < .05$, $F(1,18) =$

14.03, $p < .01$, $F(1,18) = 31.30$, $p < .001$, respectively]. For each of these measures, times were greater in the movements following heavy stylus trials compared to light stylus trials (ttPV: light = 233ms, heavy = 242ms; ttPD: light = 451ms, heavy = 473ms; MT: light = 602ms, heavy = 618ms). The analysis of time to peak acceleration revealed a Stylus by Previous Trial interaction, $F(1,18) = 5.08$, $p < .05$. Accordingly, heavy stylus movements performed after heavy stylus trials took less time to reach peak acceleration than heavy stylus movements performed after light stylus trials. In light stylus movements, time to peak acceleration did not depend on the previous trial (see Figure 4). Analysis of the time after peak velocity also revealed a significant Stylus by Previous trial interaction, $F(1,18) = 5.46$, $p < .05$. Interestingly, light stylus movements performed after light stylus trials exhibited less time after peak velocity compared to light stylus movements performed after heavy stylus trials. In heavy stylus movements, time after peak velocity did not depend on the previous trial (see Figure 5).

-- Insert Table 1, and Figures 4 and 5 about here --

Discussion

Movements involving the stylus with the greater mass were associated with shorter distances traveled by the primary submovements and greater spatial variability in the intermediary portions of the movement trajectories. This finding suggests that participants considered the spatial attributes of their movements in order to minimize target overshoot errors. Presumably this is due to the relatively greater time and energy costs associated with target overshoot errors compared to target undershoot errors (Elliott et al., 2010; Lyons et al., 2006; cf. Oliveira et al., 2005). However, despite these clear kinematic differences in how movements with the light and heavy styli were performed, group differences in trial order and prior knowledge had little impact on the end point spatial attributes of the aiming movements. This is highlighted by the similarity in constant and variable errors amongst the three groups.

Other studies that have examined upper limb movements using manipulations of trial orders have been concerned with trial-to-trial changes in the availability of visual feedback. These studies have shown that recent trial history results in differences in task performance (Cheng et al., 2008; Whitwell et al., 2008; Whitwell and Goodale, 2009). This suggests that the offline processing involved in optimized performance is based on what the motor system has recently experienced. For example, by examining how grip aperture unfolded over the course of a reaching-and-grasping movement, Whitwell et al. (2008) found that differences in the size of peak grip aperture between vision and no vision movements (which represented the margin of error involved in object grasping) depended on the trial order experienced. Specifically, the difference in grip aperture between vision and no vision movements was considerably reduced when participants were provided with either a random or alternating order of trials. However, when participants were provided with a blocked ordering of trials, there was a greater difference between the scaling of grip apertures between the vision and no vision movements. Thus, there was a distinct advantage to performing a movement in the same sensory context over a series of trials as opposed to knowing whether visual feedback would be available on the upcoming movement (see also Jakobson and Goodale, 1991).

What is interesting in the current study is that the group that received stylus information in a blocked format (the B group) did not demonstrate any performance advantages (i.e., MT, CE) compared to the groups that received random trial orders (the RPK and RNK groups). One possibility related to this finding is that an emphasis on movement planning may not have been necessary to allow for optimal performance in the current aiming task. That is, the kinematic and performance differences brought about by less precise planning under random conditions could have been rectified online, since participants always knew that vision would be available and that the target information (i.e., size and location) would be consistent on a trial-to-trial basis. Consistent with this suggestion, it has previously been demonstrated that participants can accurately perform target directed movements that, unbeknownst to participants, have different force requirements at the start of the movement (i.e., unexpected magnetic resistance; Elliott et al. 1999b).[4] This has been attributed to a continuous mode of online control that involves adjusting the antagonist muscle gain on the basis of dynamic visual information about limb velocity and direction (Elliott et al. 2010; Grierson and Elliott 2009; see also Elliott et al. 1999a). Because movements with the heavy stylus were spatially more variable than those with the light stylus at the peaks of velocity and deceleration, but not at the primary submovement end point, this process was implemented before completion of the primary submovement (see also Grierson and Elliott, 2008). In their multiple process model of manual aiming, Elliott et al. (2010) have termed this type of visual regulation impulse control. It involves an early comparison of visual feedback about movement velocity and direction to an internal representation of the expected sensory/visual consequences of the movement. This form of visual regulation involves a rapid and graded regulation of the primary movement trajectory. Impulse control is more immune to strategic influences than the discrete corrective process at the end of the movement that Elliott et al. (2010) term limb-target control (i.e., a visual comparison of the limb and target positions at the end of the primary submovement; Woodworth 1899).

Other studies have shown that the sensory information gathered in the early part of a movement trajectory can be used for online control (e.g., Bard et al. 1985; Prablanc and Martin

1992; Saunders and Knill 2003). For instance, Fukui and Inui (2006, 2013) demonstrated that visual information of a target object presented 150 to 350 milliseconds following movement onset can be used to adjust peak grip aperture in reaching-and-grasping movements, despite trial-to-trial variability (and -uncertainty) in the availability of visual information. In the current task, precise information about stylus mass could have been acquired early in the movement trajectory (i.e., before peak velocity) and used to guide a process of graded online regulation during the primary submovement.

Examining the effect of previous trial in the two Random groups provides a more detailed insight into how the aiming trajectories unfolded following different previous trial sensory experiences. Overall, the current results support the contention that recent aiming experience has a greater impact on an upcoming aiming attempt than advance task knowledge (Whitwell et al., 2008; Whitwell and Goodale, 2009; Cheng et al., 2008; Song & Nakayama, 2007). This is because both the RPK and RNK groups demonstrated similar time advantages when performing a consecutive trial with the same stylus. Specifically, heavy stylus movements took relatively less time to reach peak acceleration following heavy stylus trials, while light stylus movements spent relatively less time after peak velocity following light stylus trials. A possible explanation for these findings is that participants were more effective at specifying the force involved in transporting the limb from the starting position towards the target after immediately performing a trial with the same stylus. In particular, we suggest that a lingering sensorimotor representation from the previous trial improves force specification for the upcoming trial. That is, a greater initial force is generated for a heavy stylus trial that follows a heavy stylus trial, while a lower initial force is generated for a light stylus trial that follows a light stylus trial. For the light and heavy styli, this more effective force specification is reflected in less time spent in the parts of the trajectory associated with early and late online control, respectively (see Elliott et al., 2010). That is, the light-following-light movements exhibited less time in the portion of the trajectory associated with late continuous online control, while the heavy-following-heavy movements spent less time in the portion of the trajectory associated with impulse control.

Presumably then, the sensorimotor representations of movements immediately previous to a "matched" trial (i.e., heavy-to-heavy; light-to-light) influence that second trial in unique ways. This more effective force specification likely reduces the need for online corrections compared situations where the trial-to-trial stylus conditions are mismatched. In such situations, the force output would need to be increased (via feedforward processes) if the initial force is too weak or decreased (in order to counteract the effects of force/trajectory variability) if the initial force is too strong. Considering that heavy stylus movements were associated with greater trajectory variability at the early kinematic landmarks (compared to light stylus movements), less time spent achieving peak acceleration in the heavy-following-heavy movements can be considered an indicator of more effective force specification. Due to the lower spatial variability in the light stylus movements, the impact of improved force specification in the light-following-light movements is reserved for later in the trajectory (i.e., time after peak velocity).

In other studies that have examined the effects of trial history and advance task knowledge on different goal-directed tasks, various explanations have been used to interpret the outcome performances. For instance, Whitwell and Goodale (2009) showed that predictive knowledge about the visual context of the upcoming movement failed to optimize precision grasping (i.e., peak grip aperture). Similar to the current study, they demonstrated that precision grasping depended on the (visual) information provided in the recent aiming attempts. Their interpretation was that the visuomotor system was "cognitively impenetrable" to the explicit knowledge provided about the sensory consequences of the upcoming grasping movements (see also Whitwell et al., 2008). In another study, Fajen (2005) used a simulated braking task to show that the time and extent of braking also depended on the previous trial experience. On a given trial within a random order, participants in their study braked earlier and harder when the previous trial involved a weak brake, and later and less when the previous trial involved a strong brake. This finding was used to suggest evidence of rapid recalibration in a perceptual-motor system that was continuously updating to changing environmental dynamics (see Fajen, 2007). However, other studies show performance advantages associated with knowing the sensory conditions of upcoming trials (e.g., Tijtgat et al., 2011). For instance, Hansen et al. (2006) demonstrated that the performance of goal-directed aiming movements depended on the known availability of vision (or lack thereof); and that when advance information was not provided, movements were prepared for the worst-case scenario. Considering the various types of tasks and precued sensory information (e.g., vision, force) involved in these studies, further exploration regarding the effects of previous trial and advance task knowledge is warranted.

In summary, participants appear to prepare their movements taking into consideration worst-case outcomes. That is, they prepare a primary submovement that falls short of the target in order to avoid corrective processes associated with, time and energy consuming, target overshoots. When movements are made with a heavier stylus, participants anticipate greater spatial variability in the primary movement and thus hedge their bets by preparing even shorter primary submovements than when using a light stylus. Although one might anticipate more precise movement planning when the stylus weight was consistent from trial-to-trial, the blocked ordering of stylus weight failed to impact the spatial attributes of the movement end points. Interestingly, the manner in which the trajectories in the Random groups unfolded suggests that recent aiming experience had a greater impact on the upcoming aiming movement compared to advance task knowledge. Future work could explore the relationship between previous trial and advance knowledge by using a task where the need to control for early trajectory error becomes more extreme. This could be accomplished by combining the current methods with aiming backgrounds that move upon movement initiation (e.g., Grierson et al., 2011; Proteau and Masson, 1997).

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Footnotes

1. In previous work (see Elliott et al. 2010), we have shown that an index of difficulty in this area allows for reasonably rapid movements (i.e., less than 700 ms) while still challenging corrective processes.
2. The 36g and 243g masses were a result of the materials used and were not preconceived to be relative to any particular day-to-day objects. They were both designed to be of a size and mass that would allow them to be easily grasped and manipulated by the participants; something we feel that we achieved. Furthermore, given the many relevant Stylus main effects, we also feel that the relative mass difference between the styli effectively resulted in different constraints on movement control.
3. Participants in the RNK group were asked at the end of the experiment if they gathered any information about stylus mass prior to movement onset on any of the trials. All participants in the group responded that they did not, although no formal responses were collected (i.e., questionnaires, etc.).
4. Elliott et al. (1999) used an electromagnetic home position to unexpectedly change the resistance required to release the stylus from the home position. When visual feedback was available for online control, this perturbation had little impact on movement outcome. However when vision was eliminated upon movement initiation, movement times were longer in conditions in which the resistance to movement initiation was either increased or decreased compared to the control condition.

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Figure Captions

Fig 1. A. Dimensions of the foam starting block that sits on top of the aiming surface. The triangular notch is used to house the stylus and the top block is where the participants form a pinch grip. B. Dimensions of the styli. The black dot represents the position of the IRED. C. Typical trial sequences for participants in the RPK (top), RNK (middle) and B (bottom) groups. The top sequence shows the procedure for a heavy stylus trial and the bottom sequence shows the procedure for a light stylus trial. In the B group, the instructions screen (shown in this figure to the right of the sequence) was presented once every 25 trials. The arrow alongside each sequence indicates the order of presentation, and the boxes along the arrow indicate the length of time each screen was displayed for. The box at the bottom of the last screen in each sequence indicates the position of the foam starting block.

Fig 2. Spatial variability at the kinematic markers of peak acceleration (PA), peak velocity (PV), peak deceleration (PD) and movement end (END) in movements performed with the light and heavy styli. Asterisks indicate significant differences.

Fig 3. Average spatial variability of the light and heavy stylus movements in the RPK, RNK and B groups. Error bars represent one standard deviation. Asterisks indicate significant differences.

Fig 4. Time to peak acceleration in the light and heavy stylus movements based on the stylus used on the previous trial. Error bars represent standard deviation. Asterisk indicates the significant difference.

Fig 5. Time after peak velocity in the light and heavy stylus movements based on the stylus used on the previous trial. Error bars represent one standard deviation. Asterisk indicates the significant difference.

Table 1.

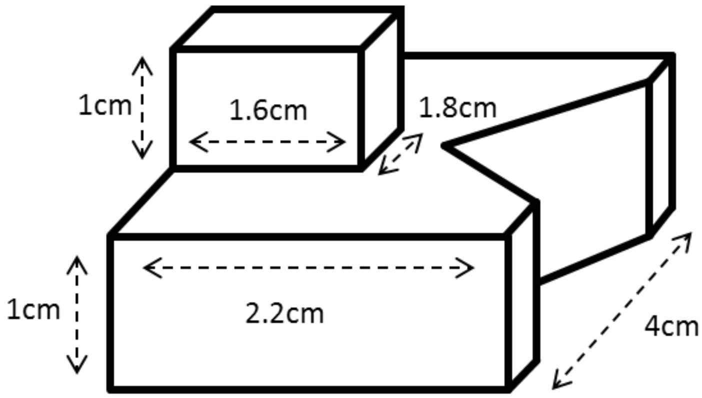
Means for the significant Stylus main effects from the 2 Predictive Knowledge by 2 Stylus by 2 Previous Trial ANOVAs.

Variable	Light Stylus	Heavy Stylus
PSM (mm)	186	158
varPSM (mm)	46	55
VE (mm)	3.36	3.78
PV (mm/s)	973	916
ttPV (ms)	249	226

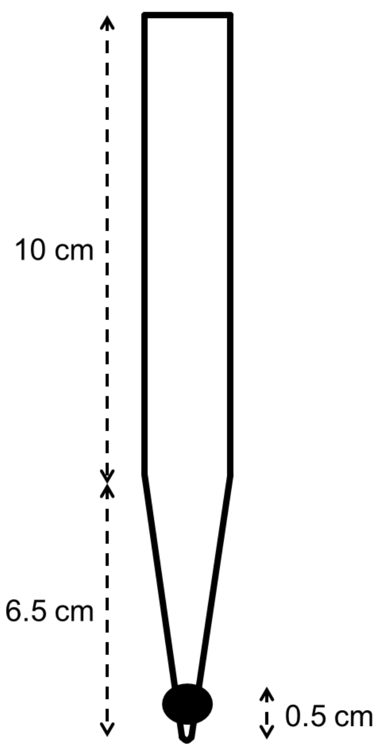
Note: Units are in brackets. With the exception of varPSM, all effects listed here are similar to those in the 3 Group by 2 Stylus analysis; varPSM did not demonstrate any significant effects in that analysis. PSM = distance traveled by the primary submovement; varPSM = variability of the distance traveled by the primary submovement; VE = variable error; PV = peak velocity; ttPV = time to peak velocity.

Figure 1.

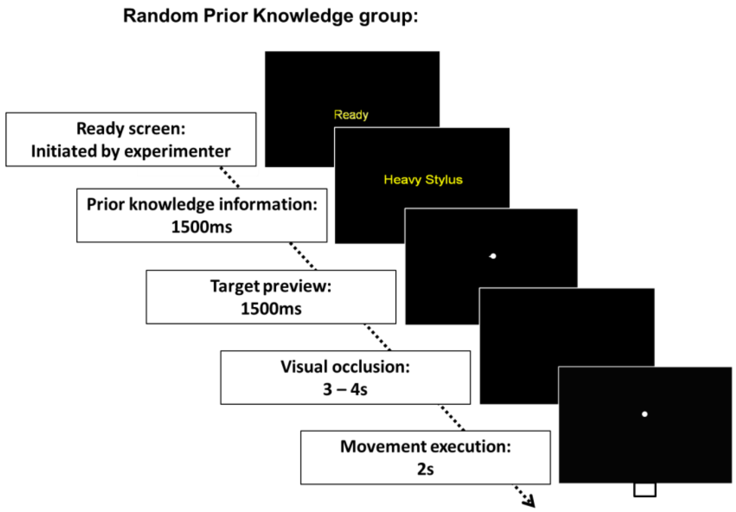
A.



B.



C.


Random Prior Knowledge group:
Ready
Heavy Stylus
Ready screen:
Initiated by experimenter
Prior knowledge information:
1500ms
Target preview:
1500ms
Visual occlusion:
3 – 4s
Movement execution:
2s

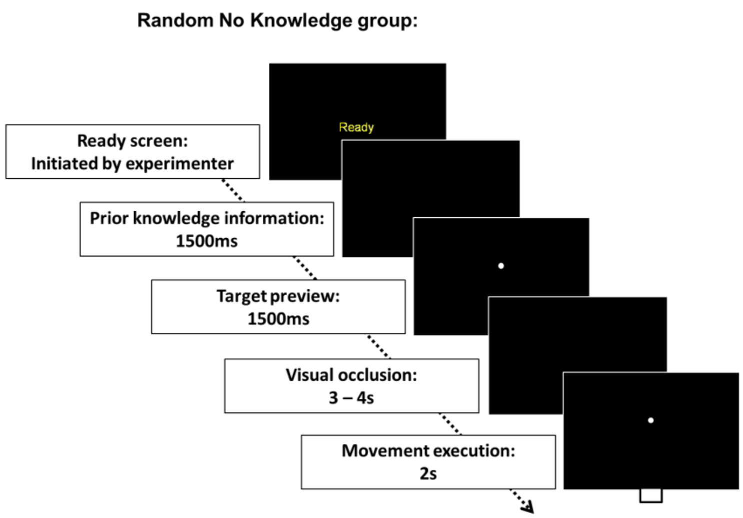

Random No Knowledge group:
Ready
Ready screen:
Initiated by experimenter
Prior knowledge information:
1500ms
Target preview:
1500ms
Visual occlusion:
3 – 4s
Movement execution:
2s

Figure 2.

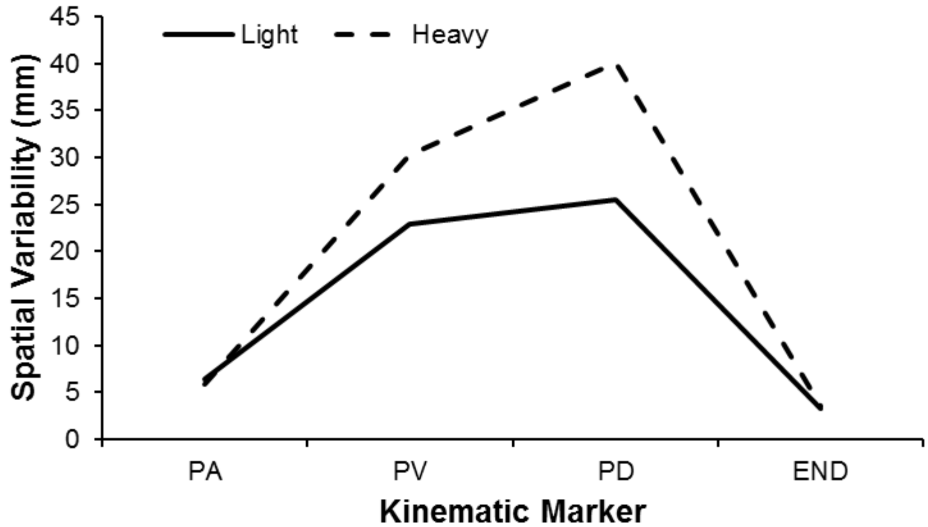
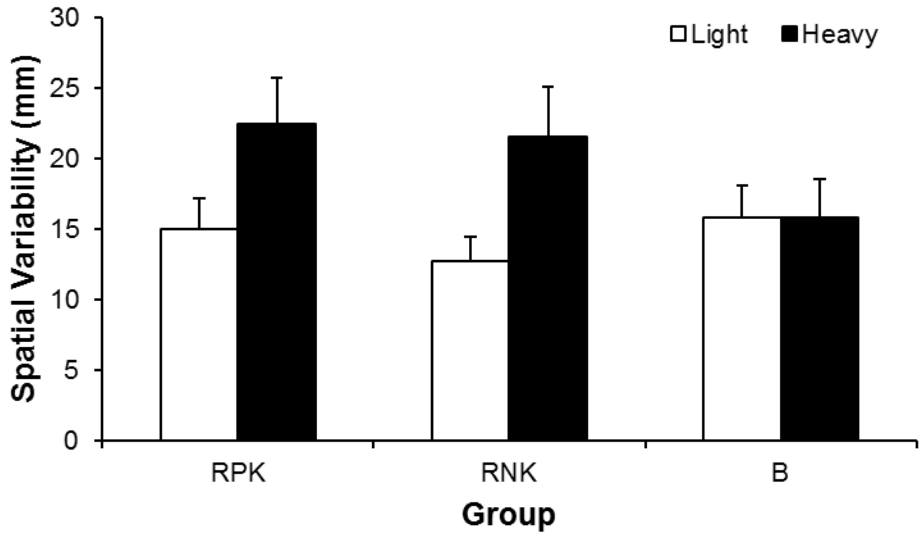

Light
Heavy
Spatial Variability (mm)
0
5
10
15
20
25
30
35
40
45
PA
PV
PD
END
Kinematic Marker

Figure 3.



30
25
20
15
10
5
0
Spatial Variability (mm)
Light
Heavy
RPK
RNK
B
Group

Figure 4.

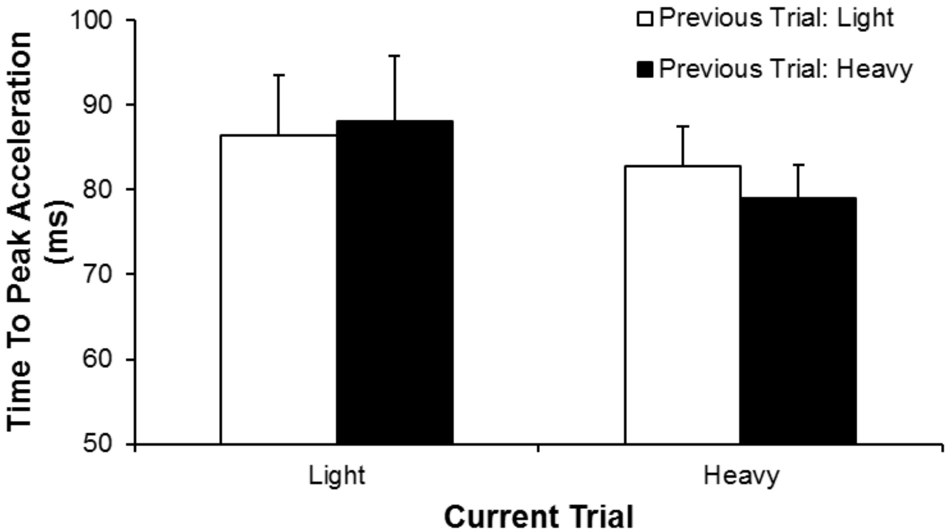
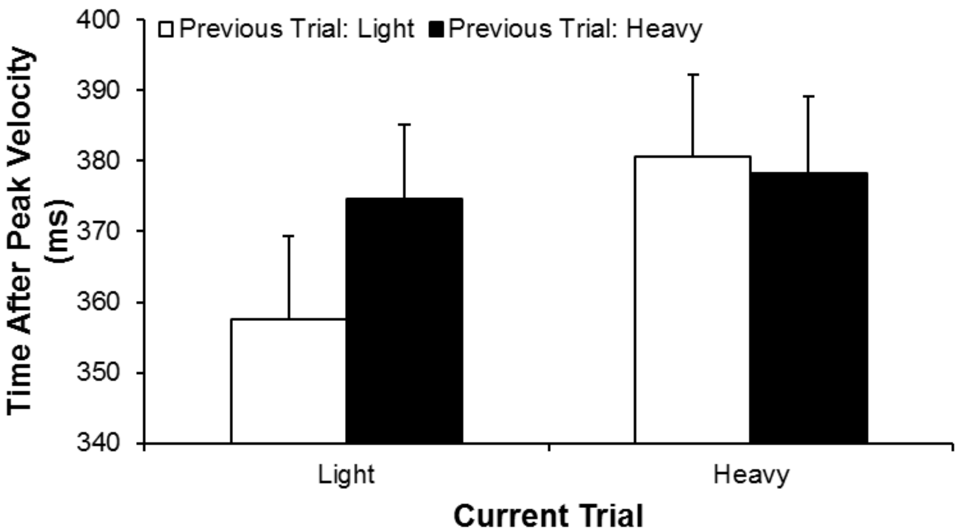

Previous Trial: Light
Previous Trial: Heavy
Time To Peak Acceleration (ms)
100
90
80
70
60
50
Light
Heavy
Current Trial

Figure 5.



Previous Trial: Light
Previous Trial: Heavy
Time After Peak Velocity (ms)
400
390
380
370
360
350
340
Light
Heavy
Current Trial