Antipointing Adherence to Fitts' Equation is Amplitude-Dependent

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Abstract

Goal-directed reaches performed with spatial overlap between stimulus and response (i.e., propointing) are supported by dedicated visuomotor networks that provide absolute visual information for movement planning and control. Furthermore, propointing adheres to speed-accuracy relations as defined by Fitts' equation such that movement time (MT) is predicted by the log/linear relationship between movement amplitude and target width. It is, however, unknown whether reaches with dissociable spatial relations between stimulus and response adhere to Fitts' equation. To that end, I examined whether antipointing (i.e., reaching mirror-symmetrical to a target) adheres to Fitts' equation in the same vein as propointing. Results showed that propointing MTs adhered to Fitts’ equation, whereas antipointing adherence was amplitude-dependent. Further, that the deceleration phase of antipointing responses did not scale to ID_{Fitts} suggests a mode of control (i.e., offline) distinct from their propointing counterparts.

Keywords

Perception action model
Fitts’ equation
Index of difficulty
Online control
Visually guided reaching
Antipointing
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And to Randy: Thank you for unconditionally believing in me. You are my rock, my light, and my biggest fan. How sweet it is.
Table of Contents

Abstract ................................................................................................................................. i
Acknowledgments ................................................................................................................. ii
List of Tables .......................................................................................................................... v
List of Figures ......................................................................................................................... vi
1 Introduction ......................................................................................................................... 1
2 Methods ................................................................................................................................. 9
  2.1 Participants ......................................................................................................................... 9
  2.2 Apparatus ......................................................................................................................... 9
  2.3 Stimuli and Procedure ....................................................................................................... 10
  2.4 Data Collection and Reduction ....................................................................................... 12
  2.5 Dependent Variables and Statistical Analyses .................................................................. 12
3 Results ..................................................................................................................................... 13
  3.1 Performance Measures .................................................................................................... 13
  3.2 Constant Error .................................................................................................................. 17
  3.3 Variable Error .................................................................................................................. 18
4 Discussion ............................................................................................................................... 20
  4.1 Response planning: reaction time influenced by ID_{Fitts} ............................................. 20
  4.2 Propointing and ID_{Fitts} ............................................................................................... 21
  4.3 Antipointing and ID_{Fitts} .............................................................................................. 22
  4.4 Antipointing governed by offline mode of control ....................................................... 23
  4.5 The role of limb vision .................................................................................................... 24
  4.6 Study limitations .............................................................................................................. 25
5 Conclusions ............................................................................................................................ 26
6 References .............................................................................................................................. 27
7 Appendices.................................................................................................................. 32

7.1 Ethics approval....................................................................................................... 32

Curriculum Vitae ........................................................................................................... 33
List of Tables

Table 1. Presents the distinct processing features of the dorsal and ventral visual pathways. ....... 2

Table 2. Experimental means and between-participant standard deviations for reaction time (RT: ms), movement time (MT: ms), peak velocity (PV: mm/s), percent time after peak velocity (%TAPV), constant (CE_p: mm) and variable (VE_p: mm) error for antipointing limb visible and limb occluded trials as a function of ID_Fitts condition. Means are reported for both proximal (Prox) and distal target amplitudes. .......................................................... 19
List of Figures

Figure 1. The left panel (A) represents an allocentric frame of reference wherein the objects in the visual scene are processed relative to the other objects. The right panel (B) represents an egocentric frame of reference wherein the individual processes objects in the visual scene relative to her/himself. ................................................................. 2

Figure 2. The Titchener/Ebbinghaus circles illusion. The target circles in the center of the two arrays appear to be different sizes although they are physically equivalent. The target surrounded by the annulus of smaller circles (A) appears to be larger than the circle in the annulus of larger circles (B). ........................................................................................................ 3

Figure 3. The Müller-Lyer illusion. The central lines are perceived to be of different size even though they are physically identical. The central line flanked by the outward facing arrows (A) is perceived as being shorter than the line flanked by inward facing arrows (B)......................... 4

Figure 4. Reaching apparatus........................................................................................................ 10

Figure 5. Schematic of visual and motor events in the LV (A) and LO (B) conditions. In LV trials, the LED remained illuminated throughout the duration of the trial, whereas in LO trials the LED was extinguished once the participant released pressure from home position switch. ........ 11

Figure 6. Reaction time for pro- and antipointing limb visible (LV) and limb occluded (LO) trials as a function of ID<sub>Fitts</sub>. Error bars represent 95% within-participant confidence intervals and linear regression equations and associated proportion of explained variance are shown for each limb vision by ID<sub>Fitts</sub> combination........................................................................................................ 13

Figure 7. Movement time for pro- and antipointing limb visible (LV) and limb occluded (LO) trials as a function of ID<sub>Fitts</sub>. Error bars represent 95% within-participant confidence intervals and linear regression equations and associated proportion of explained variance are shown for each limb vision by ID<sub>Fitts</sub> combination........................................................................................................ 14

Figure 8. Peak velocity for pro- and antipointing limb visible (LV) and limb occluded (LO) trials as a function of ID<sub>Fitts</sub>. Error bars represent 95% within-participant confidence intervals and
linear regression equations and associated proportion of explained variance are shown for each limb vision by $ID_{Fitts}$ combination.

Figure 9. The percentage of time after peak velocity (i.e., %TAPV) for pro- and antipointing limb visible (LV) and limb occluded (LO) trials as a function of $ID_{Fitts}$. Error bars represent 95% within-participant confidence intervals and linear regression equations and associated proportion of explained variance are shown for each limb vision by $ID_{Fitts}$ combination.

Figure 10. Constant error in the primary movement direction (i.e., $CE_P$) for pro- and antipointing limb visible (LV) and limb occluded (LO) trials as a function of $ID_{Fitts}$. Error bars represent 95% within-participant confidence intervals and linear regression equations and associated proportion of explained variance are shown for each limb vision by $ID_{Fitts}$ combination.

Figure 11. Variable error in the primary movement direction (i.e., $VE_P$) for pro- and antipointing limb visible (LV) and limb occluded (LO) trials as a function of $ID_{Fitts}$. Error bars represent 95% within-participant confidence intervals and linear regression equations and associated proportion of explained variance are shown for each limb vision by $ID_{Fitts}$ combination.
1 Introduction

Convergent behavioural, neuropsychological, and neuroimaging studies have shown that the neural networks dedicated to visual perceptions are distinct from those supporting goal-directed actions (for review see Goodale, 2014). In particular, the perception-action model (PAM) asserts that perceptual judgments are supported by visuo perceptual networks residing in the inferotemporal cortex of the ventral visual pathway, whereas goal-directed actions are supported via visuomotor networks located in the posterior parietal cortex (PPC) of the dorsal visual pathway (Goodale & Milner, 1992). The PAM contends that although the two streams are interconnected, each operates via distinct processing features (Goodale & Westwood, 2004) (see Table 1 for overview). For example, the ventral pathway is thought to process relative visual cues in an allocentric frame of reference (i.e., relative to other objects), whereas the dorsal stream is thought to use absolute visual cues and processes visual information in an egocentric frame (i.e., relative to one’s self) (see Figure 1). The first demonstration of this dissociation stemmed from work involving an individual (i.e., DF) with bilateral lesions to the lateral occipital cortex of her ventral visual pathway (i.e., visual form agnosia). In an initial study by Goodale et al. (1991), it was found that although DF was unable to report the perceptual properties of visual forms, she was able to use absolute visual information to metrically scale her visually guided actions. In turn, Jeannerod et al. (1994) studied an individual (AT) with bilateral lesions to the posterior parietal cortex of the dorsal visual pathway (i.e., optic ataxia). Results showed that despite AT’s normal performance in a perceptually-based manual estimation task she was unable to metrically scale her reaching and grasping movements. For example, both aforementioned studies used grasping tasks to observe changes in grip aperture in relation to the changing width of target objects. Although DF was unable to provide a perceptual report of target width, she was able to systematically scale her grip aperture to target size during a grasping task. In contrast, AT demonstrated the converse performance showing impaired grip aperture scaling in spite of her preserved ability to accurately report target size.
Table 1. Presents the distinct processing features of the dorsal and ventral visual pathways.

<table>
<thead>
<tr>
<th>Dorsal Visual Pathway</th>
<th>Ventral Visual Pathway</th>
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<tbody>
<tr>
<td>• Supports goal-directed actions</td>
<td>• Supports perceptual judgments</td>
</tr>
<tr>
<td>• Supports online vision control</td>
<td>• Functions primarily offline</td>
</tr>
<tr>
<td>• Egocentric processing (i.e., uses absolute visual cues)</td>
<td>• Allocentric processing (i.e., uses relative visual cues)</td>
</tr>
<tr>
<td>• Operates in real-time</td>
<td>• Operates under slow-mode of cognitive control</td>
</tr>
<tr>
<td>• Supports propointing</td>
<td>• Supports antipointing</td>
</tr>
</tbody>
</table>

Figure 1. The left panel (A) represents an allocentric frame of reference wherein the objects in the visual scene are processed relative to the other objects. The right panel (B) represents an egocentric frame of reference wherein the individual processes objects in the visual scene relative to her/himself.
The perception/action dissociation has been further observed in non-clinical populations via pictorial illusions. In an elegant demonstration of this dissociation, Aglioti et al. (1995) reported that participants’ perceptual report of the size of a central stimulus contained in the Titchener/Ebbinghaus circles (see Figure 2 for illusion demonstration) were influenced by the size of surrounding annuli, whereas grasping movements directed to the same target were largely refractory to surrounding stimulus. Similarly, Bernardis, Knox, and Bruno (2005) employed the Müller-Lyer illusion and demonstrated that verbal judgments of the size of a central line connected by inward or outward arrows (see Figure 3 for illusion demonstration) were “tricked” by the illusion, whereas amplitudes associated with pointing to the vertex of the illusion were refractory to the illusion’s contextual properties. Indeed, the fact that the contextual features surrounding a target influence perception – but not actions – is entirely consistent with the PAM’s contention that perceptions and actions are respectively coded in allocentric and egocentric frames of reference.

**Figure 2.** The Titchener/Ebbinghaus circles illusion. The target circles in the center of the two arrays appear to be different sizes although they are physically equivalent. The target surrounded by the annulus of smaller circles (A) appears to be larger than the circle in the annulus of larger circles (B).
The distinction between dorsal and ventral streams can be further delineated based on the temporal scale they operate. Because goal-directed actions unfold with dynamic changes in limb-to-target position, it is necessary for the dorsal visuomotor networks to operate in real-time. Indeed, consider the classic double-step paradigm wherein a target location ‘jumps’ unexpectedly at movement onset (Bridgeman, et al., 1979; Goodale et al., 1986). The work in this area has shown that participants amend their reaching trajectory to the new target position automatically in the absence of awareness of the target jump. Further, during a target jump individuals with chronic or transient (i.e., via transcranial magnetic stimulation: TMS) lesions to the posterior parietal cortex do not demonstrate real-time corrections to their reach trajectory (Gréa et al., 2002; Pisella et al., 2000) – a pattern of results indicating that intact dorsal networks are necessary for online limb corrections. In addition, Westwood and Goodale (2003) used a size-contrast illusion to compare perceptual estimates and grasps in conditions with and without target vision between response cuing and movement onset. Results showed that perceptual estimates were sensitive to size-contrast displays; however, grasping responses were refractory to the illusion as long as vision was available during movement planning. In contrast, when vision was removed at any point prior to movement onset grasps were influenced by the contextual cues surrounding the illusion. These results suggest that real-time visuomotor mechanisms are engaged in the control of action only after the response is cued and only if the target is visible, otherwise such actions are guided by a stored cognitive representation laid down and maintained by the ventral visual pathway. Moreover, Rosetti et al. (2005) investigated the visually guided

**Figure 3.** The Müller-Lyer illusion. The central lines are perceived to be of different size even though they are physically identical. The central line flanked by the outward facing arrows (A) is perceived as being shorter than the line flanked by inward facing arrows (B).
reaching behaviour of patients with bilateral lesions to the PPC (i.e., optic ataxia) in tasks with delayed and immediate pointing responses. In the immediate reaching task, the target was presented with a cue to respond after a 2s preview period, whereas in the delayed task, the target was presented for 2s, after which it was removed and the response was cued 5s after its offset. In the immediate pointing task, patients demonstrated greater variable and constant error than control participants; however, the converse pattern was true in the delayed task wherein patients exhibited reduced error and variability compared to the control participants. In a subsequent experiment, a 5s preview period of the target was given prior to a delay period after which the target reappeared prior to movement onset. Importantly, however, on some trials, the target would reappear in a location incongruent with its preview location. In this task, patients failed to detect the change in target location and aimed towards the previous location, whereas control subjects completed their responses to the new target location. Given these findings Rosetti et al. proposed that optic ataxic patients’ inability to make rapid online adjustments reflects the use of ventral visual inputs that provide for a “slow-mode” of cognitive-mode that does not permit rapid online corrections.

A slow mode of cognitive control is not limited to clinical or TMS studies and has been observed in studies involving a deliberate motor response. For example, Day and Lyon (2000) (see also: Johnson, Van Beers, & Haggard, 2002) had participants complete a target jump task (i.e., when target displacement was perceptible) in conditions wherein participants implemented an online correction to the jump (i.e., pro-correction) and when required to implement a correction mirror-symmetrical to the target jump (i.e., anti-correction). Results showed that latencies for pro-corrections occurred between 100-160 ms following target perturbation (Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991; Prablanc & Martin, 1992) whereas anti-corrections were significantly delayed (i.e., >160 ms). These increased latencies were attributed to the cognitive processing demands of inhibiting a stimulus-driven response and computing a mirror-symmetrical motor plan (i.e., vector inversion). Accordingly, anti-corrections are thought to be a top-down task and thus mediated via the slow visuoperceptual networks of the ventral visual pathway.

In addition to target perturbation paradigms, work involving stationary targets have reported that antipointing (i.e., mirror-symmetrical to a target; a 180° spatial transformation) responses are
mediated via a slow mode of cognitive control. Heath et al. (2009a) reported that antipointing responses in the left and right visual fields exhibit a pattern of endpoint bias consistent with perceptual responses. In particular, antipointing in the left and right visual fields exhibited an under- and overshooting bias consistent with the reported under- and overestimation of perceptual properties (i.e., brightness, numerosity, distance) in the left and right visual fields (Charles, Sahra, & Mcgeorge, 2007; Nicholls, Bradshaw, & Mattingley, 1999). Accordingly, Heath et al. proposed that the visual-field specific endpoint bias demonstrates that the volitional demands of decoupling stimulus-response spatial relations renders a slow-mode of cognitive control supported via the visuoperceptual networks of the ventral visual pathway. In further demonstration of this point, Maraj and Heath (2010) employed a regression analysis (for review see Heath, Neely, Krigolson, & Binsted, 2010) to determine the extent that pro- and antipointing movements employed online trajectory modifications. The analysis entailed computing the proportion of variance (i.e., $R^2$ values) relating limb position at a particular stage in the reaching response (e.g., at 75% of movement time, or at the time of peak velocity/deceleration) to the response’s ultimate movement endpoint. The basis for this technique is that smaller $R^2$ values reflect a response implemented via online control mechanisms; that is, the spatial position of the limb at any stage in the trajectory does not predict a response’s ultimate movement endpoint due to feedback-based amendments. In contrast, robust $R^2$ values indicate a response controlled primarily offline via central planning mechanisms (see also Elliott, Binsted, & Heath, 1999; Messier & Kalaska, 1999). Maraj and Heath showed that antipointing exhibited less accurate and more variable endpoints and larger $R^2$ values than their propointing counterparts and was a result taken to evince that the cognitive (and hence perception-based) demands of antipointing renders a slow mode of cognitive control (Heath et al., 2009a; Rossit et al., 2011; for antisaccades see Heath et al, 2010).

Another approach to investigating whether distinct visual information supports pro- and antipointing is to examine the extent to which they adhere to lawful speed-accuracy relations. Fitts (Fitts, 1954; see also Fitts & Peterson, 1964) proposed that movement time (MT) for reciprocal and discrete reaching responses (i.e., propointing) is determined by a task’s index of difficulty (ID, henceforth referred to as $ID_{\text{Fitts}}$) that is reflected in the equation $\log_2(2A/W)$: where $A$ represents movement amplitude and $W$ the width associated with the target object. Fitts found that increasing $ID_{\text{Fitts}}$ resulted in a linear increase in movement time (MT) and found that
MT remained equivalent across different A and W values given a constant ID_{Fitts} ratio. It is, however, important to recognize that more contemporary research has found that although A and W manipulations of ID_{Fitts} give rise to robust linear MT/ID relations, the slope of MT/ID is non-unitary (de Grosbois, Heath, & Tremblay, 2015; Heath, Weiler, Marriott, Elliott, & Binsted, 2011; MacKenzie & Graham, 1997). In demonstrating this point, Heath et al. (2011) had participants complete discrete reaches to visual targets in an amplitude manipulation wherein a constant target width of 3 cm was combined with target amplitudes of 15.5, 19, 25.5 and 38 cm, thus resulting in ID_{Fitts} of 3.36, 3.67, 4.08 and 4.67 bits. In turn, participants completed reaches in a width manipulation wherein a constant movement amplitude of 25.5 was combined with the targets widths of 2, 3, 4 and 5 cm to produce the same ID_{Fitts} as the amplitude condition. As expected, amplitude and width manipulations produced linear ID_{Fitts}/MT relations; however, the slope of the relation was steeper in the amplitude (i.e., b=96) compared to the width (i.e., b=13) manipulation. Thus, the constituent elements of ID_{Fitts} are dissociable rather than a unitary fixed parameter. To that end, a number of investigators have discovered that the lengthening of MT in response to decreased target width typically arises from online corrections to limb position during the later portion of the movement trajectory (Elliott et al., 1995; Langolf, Chaffin, & Foulke, 1976; Mackenzie et al., 1987). More specifically, increasing the demands of a reaching movement (i.e., decreasing target size) results in participants achieving peak velocities earlier in the movement to implement online trajectory corrections during the deceleration phase of the response (i.e., time after peak velocity: TAPV) (see Elliott et al., 1999). Because evidence has shown that ID_{Fitts}/MT relations can be attributed to online feedback corrections, it is possible that the slow cognitive control associated with antipointing will result in actions that do not adhere to speed-accuracy relations.

To my knowledge no previous work has examined whether antipointing adheres to lawful speed-accuracy relations. This represents an important question because if Fitts’ equation has not yet been applied to movements that are, in part, supported via the ventral visual stream, then it is unclear whether this movement principle is specific to dorsally driven actions or rather a generalized index underlying human performance. Accordingly, the present investigation manipulated target widths at distinct target amplitudes to achieve equivalent between-condition ID_{Fitts} values. Such a manipulation provided a framework for determining whether antipointing to
targets of equivalent $ID_{\text{Fitts}}$ with varying target properties differentially adhere to – or violate – lawful speed-accuracy relations as defined by Fitts (1954).

As a secondary research objective, I investigated whether the presence or absence of online limb vision influences the nature of antipointing control. A myriad of work involving propointing has shown that limb vision during a response optimizes reaching accuracy (Chua & Elliott, 1993; Elliott et al., 1999; Elliott, Hanson, Grierson, & Lyons, 2010; Heath, Hodges, Chua, & Elliott, 1998; Thaler & Goodale, 2011). For example, Chua and Elliott (1993) had subjects perform video-based aiming movements (i.e., via a computer mouse and graphics tablet) to a stationary target under conditions with and without vision of the aiming cursor. Results showed that participants were more accurate in conditions with visual feedback and exhibited reduced endpoint variability compared to conditions without vision. Further, with online vision participants’ movement endpoints became more variable with increasing target size, whereas such an effect was not apparent under conditions when vision was unavailable. On that account, vision is thought to be an important determinant in the use of feedback-based trajectory corrections. Indeed, even when provided with only brief or intermittent visual samples of the limb and reaching environment it has been shown that trajectory profiles change with target $ID_{\text{Fitts}}$ in line with their full vision counterparts (Elliott, Pollock, Lyons, & Chua, 1995). Thus, visually guided reaching allows the performer to structure his/her movement in a way that maximizes the use of that visual information (Heath, 2005). Accordingly, if antipointing is mediated via a slow mode of cognitive control then the manipulation of limb vision should have a reduced impact of the spatiotemporal properties of the response compared to their propointing counterparts.

In terms of research predictions, if antipointing responses do not show a linear relationship between MT and $ID_{\text{Fitts}}$ then results would indicate that such actions are not governed by lawful speed-accuracy relations. Further, such results would provide evidence that the top-down demands of decoupling stimulus-response spatial relations renders a slow-mode of cognitive control. In other words, results would suggest that antipointing is supported via ventrally based visuoperceptual networks.
2 Methods

2.1 Participants

Fourteen Western University students with a mean age of 23.9 years volunteered to participate in this study (range = 22-27 years: 10 female). All participants were right handed as determined by a modified version of the Waterloo Handedness Questionnaire (Bryden 1977), had normal or corrected-to-normal vision, and self-reported that they had not been diagnosed with a current or previous neurological or neuropsychiatric disorder. Prior to data collection, participants read a letter of information and signed a consent form approved by the Non-Medical Research Ethics Board, University of Western Ontario, and this work was conducted in accord with the Declaration of Helsinki.

2.2 Apparatus

Participants were seated in a height adjustable chair in front of a reaching apparatus that consisted of a rectangular frame containing three shelves. The top shelf supported a computer monitor (30-inch, 16 ms response time, 60 Hz, Dell 3007WFP, Round Rock, TX, USA) that was used to project images onto the middle shelf which contained a half-silvered mirror. A solid reaching surface comprised the bottom shelf and was the area wherein participants completed reaching movements. The distance between each shelf was 34 cm and the optical geometry of this setup created a situation wherein participants perceived visual stimuli displayed by the computer monitor as appearing on the reaching surface (see Figure 4 for apparatus). To maintain a constant optical geometry, participants' head was placed in a head/cheek rest (Applied Sciences Laboratory: Model 819-2155, Bedford, MA, USA). In combination with extinguishing the lights in the experimental suite, the one-way mirror served to occlude direct vision of the reaching limb. In the place of direct limb vision, a red light emitting diode (LED) was placed on the fingernail of each participants' right index finger to provide information about limb position. A switch located 37 cm from the front edge of the reaching surface and placed at midline served as the start location for each trial. MATLAB (7.9.0: The MathWorks, Natick, MA, USA) and the Psychophysics Toolbox extension (ver 3.0) (Brainard, 1997) controlled all experimental events.
2.3 Stimuli and Procedure

Visual stimuli were presented on a white background (136 cd/m²) and included a black central fixation cross (i.e., 1.5 cm by 1.5 cm: 0 cd/m²) and black target squares (0 cd/m²). The fixation cross was overlaid with the start location (i.e., a microswitch) and target squares were located in the same horizontal axis 20 cm (i.e., proximal amplitude) and 30 cm (distal amplitude) to the left and right of the start location. This produced visual eccentricities of ~18° and ~26° to the proximal and distal target amplitudes, respectively. For the proximal amplitude, target stimuli were 0.5, 2, 3.5 and 5 cm in width, whereas for the distal amplitude target stimuli were 0.75, 3, 5.2 and 7.5 cm in width. The target widths for each target amplitude were selected because they produced equivalent ID_{Fitts} values (i.e., 6.3, 4.3, 3.5, and 3.0 bits). For each trial, the target amplitude and width combinations identified above were randomly presented on a trial-by-trial basis.
At the start of each trial, participants were prompted to press the start location with their right index finger (i.e., the reaching limb) which initiated a trial sequence. A sequence began with the illumination of the LED attached to the reaching finger and the presentation of the central fixation cross for a randomized foreperiod between 1,000 to 2,000 ms. Participants were asked to maintain their gaze on the start location/fixation cross throughout a trial, and the constant gaze instruction was used to maintain equate extraretinal feedback across the pro- and antipointing (see details below) (van Donkelaar, Lee, & Gellman, 1994). Following the foreperiod, a target square appeared and its onset cued participants to pro- or antipoint as “quickly and accurately as possible”. Propointing required that participants reach to the veridical target location, whereas antipointing required that participants reach mirror symmetrical to the target location. Pro- and antipointing trials were completed with (i.e. limb visible [LV] trials) and without (i.e., limb occluded [LO] trials) limb vision. For LV trials, the LED remained visible throughout a trial and thereby provided online limb vision during movement planning and execution. For LO trials, the LED was extinguished coincident with release of pressure from the home location, and as a result vision was available during response planning but not movement execution (see Figure 5 for schematic of stimuli). Pro and antipointing trials to each limb vision condition were performed in separate and randomly ordered blocks, and within each block participants completed ten trials to each visual space (i.e., left and right of fixation) by target amplitude (i.e., proximal, distal) by IDFitts (3.0, 3.5, 4.3, 6.3 bits) combination for a total of 640 experimental trials.

**Figure 5.** Schematic of visual and motor events in the LV (A) and LO (B) conditions. In LV trials, the LED remained illuminated throughout the duration of the trial, whereas in LO trials the LED was extinguished once the participant released pressure from home position switch.
2.4 Data Collection and Reduction

An IRED secured to the nail of participants’ right index finger was used to track the position of the reaching limb via an OPTOTRAK Certus (Northern Digital Inc., Waterloo, ON, Canada) sampling at 400 Hz for 1.5 seconds following target onset. Position data were filtered offline using a second-order dual-pass Butterworth filter with a low-pass cutoff frequency of 15 Hz. A five-point central finite difference algorithm was used to calculate instantaneous velocities. Movement onset and offset were determined when resultant limb velocity exceeded and fell below 50 mm/s for ten consecutive frames, respectively.

2.5 Dependent Variables and Statistical Analyses

Dependent variables included reaction time (RT: time from target onset to movement onset), movement time (MT: time from movement onset to movement offset), peak velocity (PV: maximum resultant velocity between movement onset and offset), percent time after peak velocity (%TAPV: time from PV to movement offset as a percentage of total MT) and constant error in the primary (CE_P) and secondary (CE_S) movement directions and their associated variable error measures (i.e., VE_P, VE_S). Positive and negative CE_P and CE_S values represent over- and undershooting bias, respectively.

Dependent variables were examined via 2 (task: propointing, antipointing) by 2 (limb vision: LV, LO), by 2 (target amplitude: proximal, distal) by 4 (ID_Fitts: 3.0, 3.5, 4.3, 6.3 bits) fully-repeated measures ANOVA. Prior to data analyses, trials were removed if RT or MT measures were 2.5 standard deviations above or below participant-specific means for task and ID_Fitts manipulations. This resulted in less than 3% of trials removed for any participant. Significant effects/interactions were decomposed via simple effects and/or power-polynomials (Pedhazur 1997).
3 Results

3.1 Performance Measures

RT revealed main effects of task, $F(1,13)=32.04$, $p<.001$, $\eta^2_p=0.71$, limb vision, $F(1,13)=11.23$, $p=.005$, $\eta^2_p=.46$, target amplitude, $F(1,13)=9.05$, $p=.010$, $\eta^2_p=.41$, and $ID_{Fitts}$, $F(3,39)=41.57$, $p<.001$, $\eta^2_p=.76$. RTs were shorter for pro- (382 ms, SD=90) than antipointing (453 ms, SD=106), were shorter for LV (414 ms, SD=105) than LO (422 ms, SD=106) trials, and were shorter for the proximal (412 ms, SD=106) than the distal (423 ms, SD=105) target. As well, Figure 6 shows that RT increased in relation to increasing $ID_{Fitts}$ (significant linear effect: $F(1,13)=71.55$, $p=.001$, $\eta^2_p=.85$).

**Figure 6.** Reaction time for pro- and antipointing limb visible (LV) and limb occluded (LO) trials as a function of $ID_{Fitts}$. Error bars represent 95% within-participant confidence intervals and linear regression equations and associated proportion of explained variance are shown for each limb vision by $ID_{Fitts}$ combination.
MT produced main effects for target amplitude, $F(1,13)=184.42$, $p<.001$, $\eta^2_p=.93$, $\text{ID}_{\text{Fitts}}$, $F(3,39)=4.25$, $p=.011$, $\eta^2_p=.25$, and a three-way interaction involving task by target amplitude by $\text{ID}_{\text{Fitts}}$, $F(3,39)=4.89$, $p=.006$, $\eta^2_p=.27$. To decompose the interaction, for each task and target amplitude combination I computed simple effects (i.e., one-way ANOVA involving $\text{ID}_{\text{Fitts}}$) and then determined the best-fitting polynomial for any analysis yielding a significant effect. Figure 7 shows that propointing to the proximal and distal target amplitudes as well as antipointing to the proximal target amplitude produced a linear increase in MT with increasing $\text{ID}_{\text{Fitts}}$ (only linear effects significant: all $F(1,13)=4.19$, 9.20 and 7.18, ps=.051, .010, and .019, $\eta^2_p=.24$, .42, and .36). In contrast, antipointing MTs to the distal target amplitude did not reliably vary with $\text{ID}_{\text{Fitts}}$, ($F(1,13)=0.38$, $p=.55$, $\eta^2_p=.03$).

**Figure 7.** Movement time for pro- and antipointing limb visible (LV) and limb occluded (LO) trials as a function of $\text{ID}_{\text{Fitts}}$. Error bars represent 95% within-participant confidence intervals and linear regression equations and associated proportion of explained variance are shown for each limb vision by $\text{ID}_{\text{Fitts}}$ combination.
PV produced main effects for task, $F(1,13)=12.82$, $p=.003$, $\eta^2_p=.49$, target amplitude, $F(1,13)=85.90$, $p<.001$, $\eta^2_p=.87$, ID$_{Fitts}$, $F(3,39)=6.59$, $p=.001$, $\eta^2_p=.34$, and a three-way interaction involving task by target amplitude by ID$_{Fitts}$. $F(3,39)=4.02$, $p=.014$, $\eta^2_p=.24$. Figure 8 shows that antipointing to the proximal and distal target eccentricities produced PVs that increased linearly with decreasing ID$_{Fitts}$ (only linear effects significant: all $F(1,13)=5.69$ and 6.14, $p=.033$ and .027, $\eta^2_p=.31$ and .32), whereas propointing to the distal target amplitude decreased from the 3 to 4.3 bits ID$_{Fitts}$ targets and then increased at the 6.3 bits ID$_{Fitts}$ targets (significant quadratic effect: $F(1,13)=5.59$, $p=.034$, $\eta^2_p=.30$). In turn, propointing to the proximal target amplitude did not reliably vary with ID$_{Fitts}$, $F(1,13)=3.25$, $p=.095$, $\eta^2_p=.20$.

**Figure 8.** Peak velocity for pro- and antipointing limb visible (LV) and limb occluded (LO) trials as a function of ID$_{Fitts}$. Error bars represent 95% within-participant confidence intervals and linear regression equations and associated proportion of explained variance are shown for each limb vision by ID$_{Fitts}$ combination.
%TAPV produced main effects for limb vision, F(1,13)=5.01, p=.043, \( \eta_p^2=.28 \), ID\textsubscript{Fitts}, F(3,39)=7.17, p<.001, \( \eta_p^2=.36 \), and three-way interactions involving task by target amplitude by ID\textsubscript{Fitts}, F(3,39)=4.02, p=.014, \( \eta_p^2=.24 \), and limb vision by target amplitude by ID\textsubscript{Fitts}, F(3,39)=3.10, p=.037, \( \eta_p^2=.19 \). The task by target amplitude by ID\textsubscript{Fitts} interaction indicated that propointing to the proximal and distal target amplitudes produced %TAPV values that increased linearly with increasing ID\textsubscript{Fitts} (only linear effects significant: F(1,13)=6.33 and 35.06, p=.026 and p<.001, \( \eta_p^2=.33 \) and 0.73, whereas antipointing to proximal and distal target amplitudes did not systematically vary with ID\textsubscript{Fitts}, F(3,39)=1.02 and 3.81, ps=.331 and .073, \( \eta_p^2=.07 \) and .23. In terms of the limb vision by target amplitude by ID\textsubscript{Fitts} interaction, results showed that limb visible trials to proximal and distal target amplitudes, and limb occluded trials to the distal target amplitude, yielded %TAPV values that increased linearly with increasing ID\textsubscript{Fitts} (only linear effects significant: F(1,13)=8.71, 4.60, and 53.44, ps=.011, .051, and .001, \( \eta_p^2=.40, .01, \) and .80. In contrast, limb occluded trials to the proximal target amplitude did not significantly vary with ID\textsubscript{Fitts}, F(3,39)=1.89, p=.192, \( \eta_p^2=.13 \) (See Figure 9).

**Figure 9.** The percentage of time after peak velocity (i.e., %TAPV) for pro- and antipointing limb visible (LV) and limb occluded (LO) trials as a function of ID\textsubscript{Fitts}. Error bars represent 95% within-participant confidence intervals and linear regression equations and associated proportion of explained variance are shown for each limb vision by ID\textsubscript{Fitts} combination.
3.2 Constant Error

CE$_P$ yielded main effects for task, F(1,13)=25.37, p<.001, $\eta_p^2$=.66, limb vision, F(1,13)=28.63, p<.001, $\eta_p^2$=.69, target amplitude, F(1,13)=10.99, p=.006, $\eta_p^2$=.46, ID$_{\text{Fitts}}$, F(3,39)=8.38, p<.001, $\eta_p^2$=.39, and produced interactions involving task by limb vision, F(1,13)=9.76, p=.008, $\eta_p^2$=.43, and task by target amplitude by ID$_{\text{Fitts}}$, F(3,39)=14.23, p<.001, $\eta_p^2$=0.5. The task by limb vision interaction indicated that CE$_P$ for propointing LV (-18.6 mm, SD=10.9) and LO (-15.8 mm, SD=14.1) trials did not reliably differ ($t$(13)=1.91, p=.078), whereas CE$_P$ for antipointing LV trials (-35.3 mm, SD=17.4) was greater than their LO trial counterparts (-25.6 mm, SD=19.6) ($t$(13)=5.69, p=.001). In terms of the three-way interaction, Figure 10 shows that propointing to the proximal target amplitude did not reliably differ across ID$_{\text{Fitts}}$, F(3,39)=0.46, p=.714, $\eta_p^2$=.03, whereas propointing to the distal target amplitude resulted in comparable CE$_P$ values across the 3.0 to 4.3 bits ID$_{\text{Fitts}}$ targets and then decreased at the 6.3 bit ID$_{\text{Fitts}}$ target (significant quadratic effect: F(3,39)=7.33, p=.018, $\eta_p^2$=.36). Antipointing to the proximal and distal target amplitudes produced a linear increase in CE$_P$ with decreasing ID$_{\text{Fitts}}$, F(3,39)=34.08 and 9.58, p=.001 and .009, $\eta_p^2$=.72 and .42.

The analysis of CEs yielded a main effect for target amplitude, F(1,13)=16.16, p=.001, $\eta_p^2$=.55: CE$_S$ was smaller for the proximal target amplitude (0.3 mm, SD=16.4) than for the distal target amplitude (-2.1 mm, SD=18.0).

Figure 10. Constant error in the primary movement direction (i.e., CE$_P$) for pro- and antipointing limb visible (LV) and limb occluded (LO) trials as a function of ID$_{\text{Fitts}}$. Error bars represent 95% within-participant confidence intervals and linear regression equations and associated proportion of explained variance are shown for each limb vision by ID$_{\text{Fitts}}$ combination.
3.3 Variable Error

VE_P produced main effects for task, F(1,13)=24.04, p<.001, \( \eta_p^2 = .65 \), limb vision, F(1,13)=14.86, p=.002, \( \eta_p^2 = .53 \), target amplitude, F(1,13)=4.71, p=.049, \( \eta_p^2 = .23 \), and an interaction involving limb vision by target amplitude, F(1,13)=5.70, p=.033, \( \eta_p^2 = .31 \). VE_P was smaller for propointing (14.9 mm, SD=5.2) than antipointing (20.3 mm, SD=5.7). Figure 11 depicts the limb vision by target amplitude interaction and demonstrates that LO trials were more variable than their LV trial counterparts at both proximal and distal target amplitudes (t(13)=-2.17 and -3.72, ps=.049, .003).

The VEs analysis produced main effects for limb vision, F(1,13)=9.06, p=.010, \( \eta_p^2 = .41 \), and target amplitude, F(1,13)=71.62, p<.001, \( \eta_p^2 = .85 \). VEs was smaller for LV trials (12.7 mm, SD=4.9) than LO trials (15.3 mm, SD=6.0) and was smaller for the proximal (11.5 mm, SD=4.0) than the distal (16.5 mm, SD=5.9) target amplitude.

Figure 11. Variable error in the primary movement direction (i.e., VE_P) for pro- and antipointing limb visible (LV) and limb occluded (LO) trials as a function of ID_Fitts. Error bars represent 95% within-participant confidence intervals and linear regression equations and associated proportion of explained variance are shown for each limb vision by ID_Fitts combination.
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**Table 2.** Experimental means and between-participant standard deviations for reaction time (RT: ms), movement time (MT: ms), peak velocity (PV: mm/s), percent time after peak velocity (%TAPV), constant (CEp: mm) and variable (VEp: mm) error for antipointing limb visible and limb occluded trials as a function of ID\textsubscript{Fitts} condition. Means are reported for both proximal (Prox) and distal target amplitudes.
4 Discussion

Previous work proposed that distinct neural networks support pro- and antipointing (Heath, Maraj, Gradkowski, et al., 2009). Neuroimaging and electroencephalographic evidence suggests that propointing is supported by the visuomotor networks of the dorsal visual pathway, whereas antipointing is mediated via the visuoperceptual networks of the ventral visual pathway (Connolly et al., 2000; Heath et al., 2012). The activation of the ventral visual pathway is thought to reflect that the constituent elements of antipointing (i.e., response suppression and vector inversion) are top-down and visuoperceptual processes. The primary goal of my investigation was to determine whether antipointing adheres to Fitts' equation in line with their propointing (i.e., visuomotor task) counterparts, and therefore further understand the extent to which each task is mediated via a distinct visual network. To accomplish that objective, participants performed pro- and antipointing responses to targets of varying $ID_{Fitts}$ values in conditions with (i.e., LV) and without (i.e., LO) online limb vision. The manipulation of target $ID_{Fitts}$ in conjunction with the availability of online limb vision provided a framework for identifying the constituent planning and control characteristics of antipointing.

4.1 Response planning: reaction time influenced by $ID_{Fitts}$

Antipointing produced longer RTs and lower PVs than propointing as well as decreased endpoint accuracy (i.e., larger $CE_p$) and increased endpoint variability (i.e., $VE_p$). The RT results are in line with the extant antisaccade (for review see Munoz & Everling, 2004) and antipointing (Chua, Carson, Goodman, & Elliott, 1992; Heath et al., 2009; Heath, Maraj, Maddigan, & Binsted, 2009) literature’s demonstration that response suppression and vector inversion required for directionally correct antipointing are cognitively demanding and time-consuming processes that increase movement planning times. Additionally, the antipointing differences in PV, $CE_p$, and $VE_p$ have been attributed to the fact that the top-down demands of decoupling stimulus-response spatial relations renders the specification of movement endpoints via relative visual information – an information source that provides increased uncertainty about target location (Edelman, Valenzuela, & Barton, 2006; Heath et al., 2009; Neely, Binsted, & Heath, 2008).
In terms of the impact of $\text{ID}_{\text{Fitts}}$, RTs for pro- and antipointing across proximal and distal target amplitudes showed a linear increase with increasing $\text{ID}_{\text{Fitts}}$ – a finding that is consistent with some other research (Goggin & Christina, 1979; Klapp, 1975). It is, however, important to recognize that Fitts and Peterson (1964) found that a change in RT was specific to amplitude-based, but not width-based, changes to $\text{ID}_{\text{Fitts}}$ (see also Mohagheghi & Anson, 2002; Semjen & Requin, 1976; Siegel, 1977), whereas Heath et al. (2011) found that RT did not reliably vary with $\text{ID}_{\text{Fitts}}$. The basis for the discrepancy is thought to reflect that veridical target width and movement amplitudes have dissociable precision constraints, rather than a fixed unitary $\text{ID}_{\text{Fitts}}$ value (Mohagheghi & Anson, 2002). Thus, results may vary due to the changing target widths and amplitudes used across multiple studies with each posing varying precision constraints. Further, Klapp (1975) suggested that target widths have no effect on RT when presented at large amplitudes because of the increased time for feedback during the movement, whereas shorter target amplitudes require increased preparation time to account for the increased planning demands for smaller targets. In terms of my research, I propose that the RT/$\text{ID}_{\text{Fitts}}$ relationship is due to the need to lengthen response planning to account for the increased precision demands of the small target widths used here. Moreover, that both pro- and antipointing showed a linear RT/$\text{ID}_{\text{Fitts}}$ relation suggests that movement planning processes are, in part, mediated via an interaction between dorsal and ventral visual pathways (Glover, 2004).

4.2 Propointing and $\text{ID}_{\text{Fitts}}$

MTs for propointing increased linearly with $\text{ID}_{\text{Fitts}}$ across proximal and distal target amplitudes. This is an entirely predicted finding in keeping with Fitts’ original research and the extensive body of subsequent research on speed-accuracy relations for spatially compatible reaches (Chua & Elliott, 1993; Elliott, Binsted, & Heath, 1999; Heath et al., 2009, 2011; for extensive review see Plamondon & Alimi, 1997). In particular, the increase in MT with $\text{ID}_{\text{Fitts}}$ is frequently taken to reflect the additional time required to make online corrections to the trajectory in order to meet the increased precision demands associated with a target of greater $\text{ID}_{\text{Fitts}}$ (Fitts, 1954; Fitts & Peterson, 1964). These online trajectory modifications are attributed to the control of the dorsal visuomotor network that operates on a moment-to-moment basis and allows information regarding limb position to be updated in real-time. In support of this view, $\text{CE}_p$ and $\text{VE}_p$ values did not vary with $\text{ID}_{\text{Fitts}}$ targets across proximal and distal target amplitudes – a pattern of results
indicating that participants increased the duration of their response to maintain endpoint accuracy. Furthermore, results for %TAPV showed a linear increase with increasing ID_{Fitts}. As indicated in the Introduction, %TAPV is the stage of the response attributed to the evocation of online and error-reducing trajectory amendments provided via proprioceptive and/or visual feedback (Carlton, 1981; Chua & Elliott, 1993; Elliott, Binsted, & Heath, 1999). Hence, that %TAPV showed a linear relation with ID_{Fitts} indicates the evocation of discrete and/or continuous feedback-based trajectory corrections to maintain speed-accuracy relations.

4.3 Antipointing and ID_{Fitts}

Antipointing results showed that MTs increased linearly with ID_{Fitts} for the proximal target amplitude; however, MT did not reliably vary with ID_{Fitts} for the distal target amplitude. Moreover, antipointing produced CE_{p} values that decreased with increasing ID_{Fitts}, showing greater accuracy to smaller targets at both proximal and distal target amplitudes. The presence of the MT/ID_{Fitts} relationship at the proximal – but not distal – target amplitude suggests that the response mechanisms governing antipointing are amplitude-dependent. In accounting for this finding, I propose that targets presented at a more eccentric location (i.e., further in the peripheral visual field) are more reliant on allocentric visual information than their proximal amplitude counterparts. According to van Donkelaar, Lee and Gellman (1994), when a stationary target appears in the peripheral field, retinal and extraretinal signals provide the performer with information about its eccentricity. This information is then used to calculate the appropriate saccade to bring the target’s image onto the fovea to ensure a more accurate reaching movement (Bock, 1986; Robinson, 1981). Further, Paillard and Amblard (1985) have demonstrated that two distinct visual subsystems exist for static and kinetic vision. The former codes stable stimulus features in central vision and has high spatial acuity, whereas the latter dominates the peripheral retina and is tuned primarily for velocity and direction sensitivity (Paillard & Amblard, 1985). In the present study, however, participants were required to maintain their gaze on a central fixation point throughout the duration of the response rather than look directly at the target, limiting targets to peripheral vision. This presents an interesting constraint on reaching because there is evidence to suggest that reaching to targets in central and peripheral space rely on different neural substrates. To illustrate this dichotomy, Pisella et al., (2009) showed that patients with optic ataxia exhibit a performance deficit under conditions in which a stimulus is presented in
peripheral vision in both perceptual and motor tasks, whereas performance to stimuli presented in central vision is unaffected. Further, Prado et al., (2005) used event-related fMRI to measure brain activity when participants reached toward central versus peripheral targets. Their results indicated that reaches to the peripheral field engaged a more extensive network of cortical activation than when reaching to the central visual field. In addition, when visual feedback is unreliable the visuomotor system relies increasingly on relative visual cues (Neely et al., 2007). Accordingly, I propose that antipointing responses in the peripheral visual field engage both dorsal and ventral stream pathways in response evocation – a mode of control that decreases the extent to which such actions are constrained by lawful speed-accuracy relations.

### 4.4 Antipointing governed by offline mode of control

In contrast to propointing, %TAPV for antipointing did not vary with ID\textsubscript{Fitts} for either proximal or distal target amplitudes. This result is taken as \textit{prima facie} evidence that antipointing responses are controlled via a mode of control that is distinct from their propointing counterparts. In particular, I propose that propointing is controlled via a feedback-based mode of control, whereas antipointing is controlled offline via a slow mode of cognitive control. Accordingly, it is possible that the MT/ID\textsubscript{Fitts} relationship achieved in antipointing at the proximal amplitude may be based on motor plans pre-programmed prior to movement onset. That is, veridical target features are parameterized during movement planning and the ensuant response unfolds with minimal online error corrections. Indeed, evidence suggests that the planning and control of action exist in two distinct stages (Glover, 2002, 2004; Woodworth, 1899). Glover (2004) reported that the planning system selects the appropriate motor program based on the reaching environment and the goals of the performer. This selection considers a variety of visual information including the size, shape, and orientation of a target. Importantly, Glover proposed movement planning engages both visuoperceptual and visuomotor networks. As such, it is possible that for an antipointing response to a proximal target eccentricity a degree of interactivity between visuoperceptual and visuomotor networks permits response planning to adhere to speed-accuracy relations. In turn, I propose that for a more eccentric target (i.e., the distal eccentricity used here) that the response is planned using a process that relies more heavily on a visual percept that does not adhere to speed-accuracy relations.
4.5 The role of limb vision

Propointing trials with limb vision had greater %TAPV at both target amplitudes than their limb occluded counterparts. As well, limb visible propointing trials led to less variable endpoints (i.e., VE_p) than limb occluded trials. These findings are consistent with research showing that the presence of an ego-motion cue (i.e., the limb) renders an online mode of control in which the unfolding trajectory is shaped via feedback-based corrections (Carlton, 1979; Carson, Goodman, & Elliott, 1992; Chua & Elliott, 1993; Elliott, Carson, Goodman, & Chua, 1991). Further, it has been shown that these trajectory corrections lead to the lengthening of time in the deceleration phase of a response and produce decreased endpoint variability (Elliott, Binsted, & Heath, 1999).

In terms of antipointing, my results showed that MT, %TAPV, and VE_p did not vary as a function of the availability of limb vision. These results are taken to evince that antipointing is controlled offline and is therefore not influenced by the presence or absence of a salient ego-motion cue. Indeed, research indicates that responses implemented without online limb vision elicit temporally symmetrical velocity profiles as well as increased endpoint variability with minimal (if any) corrections to the reach trajectory (Carlton, 1981; Elliott, 1988; Heath, 2005; Langolf et al., 1976; Westwood, Heath, & Roy, 2001, 2003).

A surprising finding from the present work was that antipointing CE_p for limb occluded trials was less than their limb visible counterparts. In accounting for this finding it is known that advanced knowledge of the availability of limb vision influences the manner a response is planned (Neely et al., 2007; Zelaznik et al., 1983). In particular, advanced knowledge that vision will be occluded results in a cognitive strategy of enhanced storage of target information, whereas knowledge that vision will be available has been shown to decrease target-based encoding (Elliott & Madalena, 1987; Heath, 2005). It is therefore possible that increased target-based encoding during limb occluded trials produced more accurate endpoints, whereas the decreased encoding during limb visible trials combined with a slow-mode’ of cognitive control contributed to increased endpoint error.
4.6 Study limitations

One limitation of the study is that participants were unable to physically touch the target object, as stimuli were presented as virtual renderings. Thus, when reaches were nearing the target area, participants were uncertain whether they were within the target’s boundary—a sensorimotor environment that decreases the potential for offline error detection and correction (Khan et al. 2002). Indeed, de Grosbois et al. (2015) noted that in Fitts’ original research participants had access to tactile cues (i.e., augmented terminal feedback) at reaching endpoints which may have contributed to the lawful speed-accuracy relations. Another limitation which is discrepant from Fitts’ original work is that the smallest target widths (i.e., 0.5 and 0.75 cm) used in my investigation were smaller than the width of the effector used to complete pointing responses. Fitts proposed that the variability associated with a response is, in part, determined by the permissible tolerance of that response (i.e., the difference between the diameters of the target and the effector). However, in my experiment, the width of the pointing finger was larger than the width of two target sizes used here, creating a negative tolerance, which may have an effect on the way in which a response adheres to speed-accuracy relations. A third limitation of this study is that I did not independently manipulate target width and amplitude similar to Heath et al. (2011). Such a manipulation may provide a more beneficial opportunity to observe the separate effects of target width and movement amplitude on lawful speed-accuracy relations. Finally, target vision was not manipulated in my study. Accordingly, the manipulation of target vision independent of limb vision may provide further insight to the extent to which pro- and antipointing actions adhere to Fitts’ equation.
5 Conclusions

My results indicate that speed-accuracy relations in antipointing is amplitude-dependent. Moreover, my findings demonstrate that antipointing is governed by a slow mode of cognitive control supported via relative visual information mediated via the ventral visual pathway. In accounting for the amplitude-dependency of antipointing, I propose that responses to proximal targets are planned using both visuoperceptual and visuomotor networks, which allows for response planning that adheres to speed-accuracy relations. Conversely, for a more eccentric target, central processing mechanisms rely entirely on a visual percept that does not support speed-accuracy relations. In addition, limb vision provided no advantage for antipointing movements to make online trajectory corrections, further demonstrating the offline control of the ventral visual pathway.
References


Thaler, L., & Goodale, M. A. (2011). The Role of Online Visual Feedback for the Control of


7 Appendices

7.1 Ethics approval

Date: 26 April 2018
To: Dr. Matthew Heath
Project ID: 111571
Study Title: The Role of Vision in Online Lure Control for Proportioning versus Antipropotion
Application Type: NIMREB Initial Application
Review Type: Delegated
Full Board Reporting Date: June 1, 2018
Date Approval Issued: 26/4/2018
RRE Approval Expiry Date: 26/4/2019

Dear Dr. Matthew Heath

The Western University Non-Medical Research Ethics Board (NIMREB) has reviewed and approved the WREM application form for the above mentioned study as of the date noted above. NIMREB approval for this study remains valid until the expiry date noted above, conditional to timely submission and acceptance of NIMREB Continuing Ethics Review.

This research study is to be conducted by the investigator noted above. All other required institutional approvals must also be obtained prior to the conduct of the study.

Documents Approved:

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No deviations from, or changes to, the protocol should be initiated without prior written approval from the NIMREB, except when necessary to eliminate immediate hazards to study participants or when the change(s) involves only administrative or logistical aspects of the trial.

The Western University NIMREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the Ontario Personal Health Information Protection Act (PHIPA, 2004), and the applicable laws and regulations of Ontario. Members of the NIMREB who are named as Investigators in research studies do not participate in discussions related to, nor review such studies unless they are unrelated to the REB. The NIMREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB00000941.

Please do not hesitate to contact us if you have any questions.

Sincerely,

Kelly Paterson, Research Ethics Officer on behalf of Dr. Randolph Gobioff, NIMREB Chair

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).
# Curriculum Vitae

<table>
<thead>
<tr>
<th>Name:</th>
<th>Marlowe Pecora</th>
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<tbody>
<tr>
<td><strong>Post-secondary</strong></td>
<td>Western University</td>
</tr>
<tr>
<td><strong>Education and</strong></td>
<td>London, Ontario, Canada</td>
</tr>
<tr>
<td><strong>Degrees:</strong></td>
<td>2012-2016, B.A. (Honors), School of Kinesiology</td>
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<td><strong>Honours and Awards:</strong></td>
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<td></td>
<td>2015, 2016</td>
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<td>Athletic Financial Award</td>
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<td>Western University</td>
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<td>2012, 2016</td>
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<td></td>
<td>CIS Academic All-Canadian</td>
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<tr>
<td><strong>Related Work Experience:</strong></td>
<td>Teaching Assistant</td>
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<td></td>
<td>Western University</td>
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<td>2016-2018</td>
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<td><strong>Conference Abstracts:</strong></td>
<td>Pecora, M., Heath, M. (2017). Antipointing requires conscious visual percept to support motor output. (Poster Presentation)</td>
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