# I spy with my dominant eye

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I spy with my dominant eye

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Abstract

The current study investigated how visual information from the non-dominant and dominant eyes are utilized to control ongoing dominant hand movements. Across two experiments, participants performed upper-limb pointing movements to a stationary target or an imperceptibly shifted target under monocular dominant, monocular non-dominant and binocular viewing conditions. Under monocular dominant viewing conditions, participants exhibited better endpoint precision and accuracy. On target jump trials, participants spent more time after peak limb velocity and significantly altered their trajectories toward the new target location only when visual information from the dominant eye was available. Overall, the results suggest that the online visuomotor control processes that typically take place under binocular viewing conditions are significantly influenced by input from the dominant eye.
Introduction

Empirical studies have shown that visual feedback gathered during limb trajectories significantly contribute to the successful completion of voluntary movements (e.g., Woodworth, 1899; Keele & Posner, 1968; Zelaznik, Hawkins, & Kisselburgh, 1983). Most of these studies investigated the use of visual information gathered under binocular viewing conditions. While a wide array of literature has investigated and reviewed hand dominance (e.g., Tapley & Bryden, 1985) as well as manual asymmetries for visuomotor control (Elliott & Chua, 1996), much less work has been done on eye dominance and visual asymmetries (Porac & Coren, 1976; see below). The current study sought to further investigate how visual information from the non-dominant and dominant eyes can be used to plan and control dominant hand movements.

The dominant hand’s functional significance for visuomotor control is well documented (e.g., Sainburg & Kalakanis, 2000). In contrast, the functional significance of the dominant and non-dominant eyes has been relatively overlooked. Eye dominance can refer to: the eye favoured under monocular viewing conditions, the eye preferred when monocular views are discrepant, or the eye displaying physiological or refractive superiority (see Porac & Coren, 1976 for a review). Empirical work has shown that the dominant eye is advantageous over the non-dominant eye to accurately strike a target (Coren, 1999; Lund, 1932) and perform a shooting task (Banister, 1935; Crider, 1943). Given that most hand movements are performed under binocular viewing conditions, however, it is no surprise that empirical work has revealed a functional advantage of seeing with both eyes.

Binocular vision of a moving limb facilitates the accurate execution of upper-limb movements. In general, binocular viewing conditions lead to greater endpoint precision in reach
and grasp movements (e.g., Bradshaw et al., 2004; Loftus et al., 2004; Melmoth & Grant, 2006: see also Coull, Weir, Tremblay, Weeks, & Elliott, 2000). Within the context of pointing movements tested in the current study, previous work has consistently shown that binocular viewing of the limb trajectory is necessary to engage in limb-target regulation processes (e.g., Elliott et al., 2010). For example, Chua and Elliott (1993) found that on trials performed under binocular vision, participants spent more time after peak limb velocity (TaPV) compared to when no vision of the limb trajectory was available. In general, this finding has been interpreted as evidence for online visuomotor control. That is, greater TaPV values reflect more time spent initiating limb-target regulation processes that lead to an increase in endpoint accuracy. Further, additional behavioural measures have been used to quantify online control and probe limb-target regulation processes.

In a study conducted by Heath, Neely, and Krigolson (2008), participants completed reaching movements under four vision conditions in which either monocular or binocular vision was given during the planning and/or the control phase of the movement. During the trajectory, the limb was either occluded or remained visible via the use of liquid-crystal goggles. The main dependent variable was a measure of trajectory scaling, which correlates the position of the limb at a given movement proportion with the end position of the limb. If the limb position early in the trajectory predicts the limb position at movement end, then it is presumed that few amendments took place and that the movement execution was predominantly based on what was planned (i.e., high $R^2$ values: see also Heath, 2005). In contrast, if the limb positions achieved early in the trajectory are weakly correlated with limb positions at movement end, then it is presumed that amendments were implemented during the trajectory (i.e., low $R^2$ values). Heath et al. (2008) reported that participants exhibited the lowest $R^2$ values when binocular vision was
provided throughout the movement. In contrast, when monocular vision was provided throughout the movement, $R^2$ values were comparable to those observed for movements performed without vision. As a result, Heath et al. (2008) suggested that participants engaged in a more offline mode of control under monocular viewing conditions. Thus these authors provided evidence for kinematic differences between reaches performed while vision was available to both eyes or to one eye, or when vision was not available. However, to our knowledge, the contribution of the dominant and non-dominant eye for online control mechanisms has never been investigated.

While there is a known advantage of the dominant eye over the non-dominant eye when performing a target strike or shooting task, it is not known if this advantage is due to better motor planning and/or online control mechanisms. The current study sought to further probe the contribution of visual information gathered by the non-dominant and dominant eye to online control mechanisms. In the first experiment, participants performed upper-limb pointing movements to a stationary target under monocular dominant, monocular non-dominant and binocular viewing conditions. Experiment 2 employed a target jump to directly test online control. One hypothesis was that online control requires visual input from both eyes. In such a case, evidence of online control should be found when viewing the movement’s trajectory binocularly but not in any of the monocular vision conditions. Such a result would fall in line with literature reporting an advantage of binocular over monocular vision for online control (e.g., Heath et al., 2008). Alternatively, because monocular vision investigations have often avoided testing both monocular vision conditions, online control may be possible when vision is available from one particular eye. Because a dominant right hand is more often visible to the dominant right eye than the non-dominant left eye (see discussion), it was hypothesized that evidence of
online control would be observed with vision from the dominant but not the non-dominant eye. If such a hypothesis is correct, only reaches performed under the monocular dominant viewing condition should yield comparable performance to binocular viewing, while both should be different from the non-dominant viewing condition. Such a result would support empirical evidence of the advantage of the dominant eye for the control of voluntary actions (Banister, 1935; Coren, 1999; Crider, 1943; Lund, 1932).

**Experiment 1**

**Methods**

Twelve right-hand and right-eye dominant participants (4 female, 8 male; $M = 22$ years, $SD = 4.3$) with self-reported normal to corrected-to-normal vision and hearing were recruited from the University of Toronto community. Participants had no self-reported history of neurological impairment. Hand dominance was assessed using a handedness inventory questionnaire adapted from Oldfield (1971). Eye dominance was assessed with a simple eye-target alignment test adapted from Miles (1930). Written informed consent was obtained prior to the experiment and the protocol was approved by the University of Toronto Research Ethics Board. The experimental protocol lasted approximately 30 minutes and compensation for participating was $5.

**Apparatus**

Participants were seated on an adjustable kneeling chair at a desk with a custom built aiming console (width: 27.5 cm, length: 50 cm, height: 8 cm) positioned on the desk along the participant’s mid-saggital axis. The top of the aiming console was covered with a translucent
polymer sheet (width: 25 cm, length: 50 cm) while a 0.7 mm x 0.7 mm strip of Velcro™ served as the home position (see Figure 1). Beneath the surface of the aiming console was a 5 mm diameter green light emitting diode (LED), which when lit and visible served as the aiming target for participants. The target LED was located 30 cm away from the home position and both were aligned with the participant’s mid-saggital axis. Participants were cued to begin their movement via an auditory beep from a piezo-electric buzzer (2900 Hz: Sonalert SC416; Mallory Inc., Indianapolis, IN, USA).

Participants were required to wear liquid-crystal occlusion spectacles (Translucent Technologies Inc., Toronto, ON, Canada; see Milgram, 1987) for the entire duration of the experiment, allowing the experimenter to manipulate the availability of vision to each eye independently. An infra-red light emitting diode (IRED) sampled at 250 Hz for 2 seconds (Optotrak Certus, Northern Digital Inc., Waterloo, ON, Canada) was taped to the dorsal side of the participant’s index finger and used to track limb position data. A custom Matlab (The MathWorks Inc., Natick, MA, USA) script was used to control the Optotrak, aiming console and liquid crystal goggles via a data acquisition board (PCI-6024e, National Instruments Inc., Austin, TX, USA).

**Procedure**

The experiment consisted of a familiarization phase and an experimental phase. During both phases participants wore the liquid-crystal occlusion spectacles. The main purpose of the familiarization phase was to ensure that participants become familiar with the movement time bandwidth of 250 ms to 400 ms, which was employed to minimize speed accuracy trade-offs (Fitts, 1954; Fitts & Peterson, 1964). Also, such a movement time bandwidth follows other work
from our laboratory (e.g., Kennedy et al., 2015; Tremblay et al., 2017) and allows us to probe the ability of the CNS to implement rapid trajectory amendments, which are necessary in many real-life scenarios (e.g., sports, driving). Participants were instructed to reach to the target as accurately as possible while completing their movement within the movement time bandwidth.

The familiarization phase consisted of 10 trials in which participants were instructed to aim to the target (i.e., located 30 cm away from the home position) with the index finger of their right dominant hand. Ten out of the twelve participants were able to complete the movement within the movement time bandwidth at the end of 10 trials. For two participants, no more than 5 familiarization trials were conducted to ensure proper completion of the movement. The participant’s movements fell outside the movement time bandwidth an average of 10.2 trials during the experimental phase and these trials were included in the analyses. For each trial, an auditory beep (i.e., GO signal) prompted the participant to begin the movement. Once the reaching movement was completed, participants were asked to stay at the target position until 2 auditory beeps presented in quick succession, which prompted them to move back to the home position. Movement start was defined as two consecutive samples where the limb first exceeded a velocity of 0.03 m/s. Movement end occurred when the velocity of the limb first went below 0.03 m/s for two consecutive samples.

The experimental phase included three vision conditions (binocular, monocular non-dominant and monocular dominant) performed in a blocked and counterbalanced fashion (i.e., 30 trials per vision condition). In total, participants completed 100 trials in experiment 1. During each vision condition, participants received a preview of the environment (i.e., goggles transparent) for 3000 ms without presentation of the target. The preview of the environment was consistent with the viewing condition during the upper-limb reaching movement (i.e., monocular
dominant viewing in the preview and monocular dominant viewing during the reach) and the onset of the GO signal coincided with the appearance of the target. Both lenses became translucent after movement termination so the participant returned their limb to the home position without the use of vision. Such removal of terminal vision was employed to minimize offline feedback processing and mechanisms (see Salmoni, Schmidt & Walter, 1984). Consistent with the familiarization phase, participants were instructed to aim to the target with the index finger of their right hand as accurately as possible within the movement time bandwidth.

Data Analysis

To contrast the performance across the 3 vision conditions (binocular, monocular non-dominant or monocular-dominant), repeated measures ANOVAs were conducted on the following dependent variables: movement time (MT), time to peak limb velocity (TtoPV), time after peak limb velocity (TaPV), endpoint position in the primary axis (END$_{\text{prim}}$), endpoint position in the secondary axis (END$_{\text{sec}}$), variable error in the primary axis (VE$_{\text{prim}}$) and variable error in the secondary axis (VE$_{\text{sec}}$).

To test the extent of online visuomotor control processes, correlational analysis were performed in which limb positions at various points in the trajectory (25%, 50% and 75% of movement time) were correlated with the positions at movement end (see Heath, 2005). These values were squared and were submitted to a 3 vision condition (binocular, monocular non-dominant or monocular-dominant) x 3 movement proportion (25%, 50% or 75%) repeated measures ANOVA.

In all analyses, a Greenhouse-Geisser correction was used to correct the degrees of freedom, reported to two decimal places when sphericity was violated. When significance was
reached, post-hoc comparisons were made using a Tukey’s HSD test. Alpha was set at 0.05 for all contrasts and all significant effects are reported.

Results

Data from all dependent variables can be found in Table 1. In addition, the average movement velocities are shown in Figure 2. Analysis of MT ($F(2, 22) = 1.04, p = .371, n_p^2 = .086$), TtoPV ($F(2, 22) = 1.02, p = .377, n_p^2 = .085$) and TaPV ($F(2, 22) = 1.23, p = .296, n_p^2 = .105$) failed to yield a main effect of vision condition.

Movement trajectories along the primary axis are shown in Figure 3. Analysis of END prim ($F(2, 22) = 1.48, p = .249, n_p^2 = .119$) also failed to yield a main effect of vision condition whereas analysis of END sec yielded a main effect of vision condition, $F(1.27, 13.99) = 6.25, p = .020, n_p^2 = .362$ (see Figure 4). Post-hoc comparisons (HSD = 1.1 mm) revealed a significant difference between the monocular dominant and both the monocular non-dominant and binocular vision conditions in which monocular dominant viewing resulted in the largest leftward bias.

Analysis of VE prim yielded a main effect of vision condition, $F(2, 22) = 5.41, p = .012, n_p^2 = .330$ (see Figure 5). Post-hoc comparisons (HSD = 1.3 mm) revealed significant differences between the binocular and monocular non-dominant vision condition but not with the monocular dominant condition. Analysis of VE sec ($F(1.37, 15.04) = 2.11, p = .164, n_p^2 = .161$) however, failed to yield a main effect of vision condition.

Correlational analyses failed to yield a main effect of vision condition, $F(2, 22) = 2.57, p = .099, n_p^2 = .189$. However, these analyses yielded a main effect of movement proportion, $F(1.10, 12.11) = 93.2, p < .001, n_p^2 = .894$, as well as a significant interaction between vision.
condition and movement proportion, $F (4, 44) = 2.89, p = .033, n_p^2 = .208$. Post-hoc comparisons ($HSD = .09$) revealed significant lower $R^2$ values at 75% of the movement in the binocular than in both the monocular dominant and non-dominant vision conditions (see Table 1).

**Discussion**

Experiment 1 was designed to investigate the relative contribution of visual information available to the dominant and non-dominant eyes for the online control of upper-limb reaching movements. To this end, participants performed 30 cm reaches while visual information was available to both eyes (i.e., binocular condition), the left eye (i.e., monocular non-dominant condition) or the right eye (i.e., monocular dominant condition). The results first revealed that in all three viewing conditions, no differences were found in terms of movement time and endpoint position in the primary movement axis. This suggests that speed-accuracy trade-offs unlikely took place (Fitts, 1954). In contrast, endpoint position along the secondary axis and variable error along the primary axis did yield main effects of vision.

The results for endpoint position along the secondary movement axis suggests that the non-dominant eye is advantageous for planning a consistent movement endpoint along the medio-lateral axis. Pointing with vision from the dominant eye alone yielded a significant leftward bias, compared to the non-dominant and binocular viewing conditions. It is critical to note here that endpoint position (i.e., endpoint accuracy) is not as closely linked to online control as endpoint precision (i.e., variable error: see Tremblay et al., 2013). That is, if the variability of the trajectory increases as the movement unfolds, online visual feedback would be required to amend the ongoing trajectory, thus yielding a reduction in endpoint distribution irrespective of bias (Khan et al., 2006). Thus, the observed differences in endpoint position found for the
medio-lateral axis may reflect the enhanced ability of the non-dominant eye to perform target encoding during the preview of the environment provided prior to each trial, but not online control per se.

In contrast, the results for variable error along the primary axis suggest that having visual feedback from the dominant eye may be more associated with online control mechanisms than the non-dominant eye. That is, reaching endpoint distributions were larger in the monocular non-dominant compared to the binocular condition, which did not differ from the monocular dominant condition. Although the difference between binocular and non-dominant viewing was quite small (1.7 mm), the results suggest that for such rapid movements employed in experiment 1, this difference may reflect error reduction that occurs specifically during the trajectories (e.g., Elliott et al., 2010; Hansen et al., 2008; Khan et al., 2006; Tremblay et al., 2013). Indeed, while the average endpoint location may have been better in the non-dominant than in the dominant vision condition, this smaller, albeit non-significant endpoint distribution for the dominant vision condition may suggest a differential role for online control between the two eyes.

The correlational analyses between the amplitudes observed during the trajectory and the amplitudes observed at movement end yielded evidence of more online control processes in the binocular than in both monocular vision conditions. Perhaps the different patterns of results for the constant and variable error for the monocular dominant and non-dominant vision conditions were related to variations in movement planning. Recall that participants were given a preview of the environment consistent with the viewing condition during the upper-limb reaching movement (i.e., monocular dominant viewing in the preview and monocular dominant viewing during the reach). Because of the nature of the preview, it may not be possible to dissociate whether the advantage in endpoint precision is due to the contribution in the planning and/or
online control stages of the movement. In addition to movement variability (i.e., variable error), an additional method used to probe online control is the utilization of a target jump (e.g., Desmurget, Epstein, Turner, Prablanc, & Grafton, 1999; Kiernan et al., 2016). To further uncover the relative contribution of each eye during the online control phase of the movement, a second experiment was designed and conducted that utilized a target jump.

**Experiment 2**

In experiment 2, participants consistently received a binocular preview prior to each trial. During the movement, vision was restricted such that participants only received a 20 ms window of vision (e.g., Cullen et al., 2001) under binocular, monocular non-dominant or monocular dominant viewing conditions. To isolate the use of visual information during the online control stages of the movement, a target jump was also employed. That is, following movement initiation, the target could shift from 30 to 27 cm (i.e., unconscious target jump: see Goodale, Péligson & Prablanc, 1986). As such, experiment 2 assessed specifically how a brief visual cue provided to the non-dominant or dominant eye can be used to correct movements online. These brief visual samples were specifically selected to draw high demands on the visuomotor system while avoiding awareness of the target jumps.

**Methods**

Sixteen right-handed and right-eye dominant participants with self-reported normal to corrected-to-normal vision and hearing were recruited from the University of Toronto community. One participant reported seeing the target jump and was therefore excluded from formal data analysis. As a result, final data analysis was conducted on fifteen right-hand and right-eye dominant participants (9 female, 6 male; $M = 22$ years, $SD = 3.7$). As in experiment 1,
hand and eye dominance were assessed for each participant prior to participation. Written informed consent was obtained prior to the experiment and the protocol was approved by the University of Toronto Research Ethics Board. The protocol lasted approximately 30 minutes and compensation for participating was $5.

Apparatus

The apparatus used in experiment 2 was identical to the apparatus used in experiment 1 aside from an additional 5 mm diameter green LED beneath the surface of the aiming console serving as an additional target. The additional target was positioned 27 cm away from the home position along the participant’s mid-saggital axis and used for the target jump condition (see Figure 1).

Procedure

The participant’s task was to perform fast and accurate reaching movements to the LED target. To this end, participants first completed 20 familiarization trials under the four vision conditions (i.e., full vision, binocular, monocular non-dominant and monocular dominant). During these trials, participants performed reaching movements to the 30 cm target. Prior to movement initiation, participants were provided with a 20 ms binocular preview of the environment, with the 30 cm target illuminated. Following this very brief binocular preview, the goggles became translucent (i.e., without vision of the environment) and, following a beep from the piezo-electric buzzer, the participant initiated their movement.

In the experimental trials performed under full vision, participants were able to see their entire movement. As in the familiarization trials, a 20 ms binocular preview of the environment
was provided. During this preview, participants viewed the 30 cm target. Following the preview, the piezo-electric buzzer cued the participant to begin the movement towards the 30 cm target while both lenses remained transparent. Following completion of the movement (i.e., limb velocity below 0.03 m/s) the goggles once again became translucent and participants returned to the home position without visual feedback of the environment. When performing movements in the monocular dominant, monocular non-dominant or binocular viewing conditions, participants were again provided with a 20 ms binocular preview of the environment. Upon completion of this preview, the goggles became translucent, and the piezo-electric buzzer sounded. When the participant’s limb reached a velocity of 1.0 m/s, a 20 ms window of vision was provided. This velocity criterion was chosen specifically to isolate the contribution of visual feedback gathered by each eye to online visual control. That is, a limb velocity of 1.0 m/s has previously been shown to be associated with limb-target regulation processes (Tremblay, Hansen, Kennedy & Cheng, 2013; Tremblay et al., 2017). Based on Matlab processing and hardware transmission delays, the time taken to change the state of the liquid crystal goggles (i.e., transparent or translucent) was less than 10 ms, which was deemed to be taking place in real-time. Depending on the monocular vision condition, the right or left lens of the goggles became transparent while the other remained translucent. In the binocular condition, both lenses became transparent. Following this 20 ms window of vision, the goggles once again became translucent. When performing movements in the window viewing conditions, the target could jump following the preview of the environment. On target jump trials, the 30 cm target was extinguished and the 27 cm target illuminated following movement initiation (i.e., while the goggles remained translucent). Target jumps occurred on 33% of trials within each block. Participants completed 30 trials per condition (i.e., full vision, monocular dominant, monocular non-dominant, and
binocular) in a blocked and counter-balanced order. In total, participants completed 140 trials in the experiment.

**Data Analysis**

All dependent variables were the same as in experiment 1 (i.e., MT, TtoPV, TaPV, END prim, END sec, VE prim and VE sec). To determine the effects of experimental manipulations, separate 3 vision condition (binocular, monocular non-dominant or monocular dominant) x 2 jump condition (no jump or jump) repeated measures ANOVAs were conducted on all dependent variables. The distributions were tested for violation of sphericity although such violations were not observed. G*Power Version 3.17 (University of Düsseldorf, Düsseldorf, North Rhine-Westphalia, Germany) was used to compute achieved post-hoc power (e.g., Faul, Erdfelder, Buchner, & Lang, 2009; Faul, Erdfelder, Lang, & Buchner, 2007). Also, Tukey HSD contrasts were performed on all main effects and interactions involving more than 2 means. Because of the hypothesized differences between jump and no jump conditions (see above), the comparisons between jump conditions (i.e., within each vision condition) were carried out for each dependent variable. As well, because the jump condition was expected to elicit significant online control processes, comparisons between vision conditions were made for each dependent variable for the jump trials only. To contrast jump versus no jump trials, Tukey HSD values were computed for the inferential statistics associated with the interaction between vision and jump conditions. As in experiment 1, the extent of visuomotor control processes was analyzed via an R² correlational analysis. This analysis correlated limb position at various points in the trajectory (25%, 50% and 75% of movement time) with the position at movement end (see Heath, 2005). Because these analyses are typically conducted with 20 trials or more, only the no-jump trials were analyzed. As a result, the R² values were submitted to a 3 vision condition (binocular, monocular non-
dominant and monocular dominant) x 3 movement proportion (25%, 50% and 75) repeated measures ANOVA.

**Results**

Means and standard deviations for all dependent variables can be found in Table 2. Velocity profiles for all movement conditions are also shown in Figure 2. When participants completed the reaching movement to the 30 cm target in the full vision condition, the average movement endpoint was 314 cm (SD = 23.2 mm). Within the window viewing conditions, analyses of MT failed to yield a main effect of vision condition, \( F(2, 28) = .044, p = .957, n_p^2 = .003 \), post-hoc power = .05, but did yield a main effect of jump condition, \( F(1, 14) = 12.3, p = .003, n_p^2 = .468 \), post-hoc power = .97. In addition, the interaction between vision and jump failed to reach significance, \( F(2, 28) = .540, p = .589, n_p^2 = .037 \), post-hoc power = .06. As expected, reaches made to the jumped target location yielded shorter movement times (\( M = 346 \) ms; \( SD = 30.5 \)) than those made towards the original target location (\( M = 353 \) ms; \( SD = 32.2 \)). The HSD contrasts of the MT values across vision conditions failed to reveal significant differences in the jump conditions (\( HSD = 22 \) ms).

The analysis of TtoPV revealed no significant effects of vision condition, \( F(2, 28) = 1.92, p = .164, n_p^2 = .121 \), post-hoc power = .15, jump condition, \( F(1, 14) = 1.27, p = .279, n_p^2 = .083 \), post-hoc power = .09, or vision by jump interaction, \( F(2, 28) = .177, p = .839, n_p^2 = .012 \), post-hoc power = .05. Preplanned contrasts between the vision conditions on jump trials revealed shorter times to peak limb velocity in the monocular dominant than the monocular non-dominant and binocular viewing conditions (\( HSD = 8 \) ms).
The analysis of TaPV yielded no main effects of vision condition, $F(2, 28) = 2.31, p = .118, n_p^2 = .142$, post-hoc power = .19, or vision by jump interaction, $F(2, 28) = .128, p = .880, n_p^2 = .009$, post-hoc power = .12. However, a main effect of jump condition was found, $F(1, 14) = 11.9, p = .004, n_p^2 = .460$, post-hoc power = .99. Again, as expected, the times taken after peak limb velocity were shorter for the jump ($M = 197$ ms; $SD = 30.0$) than for the no-jump condition ($M = 204$ ms; $SD = 29.4$). Preplanned comparisons between the vision conditions showed that, on jump trials, participants spent more time after peak limb velocity in the monocular dominant than monocular non-dominant condition and binocular conditions ($HSD = 9$ ms: see Figure 6).

The ANOVA conducted for VE$prim$ failed to yield a main effect of vision condition, $F(2, 28) = 1.47, p = .246, n_p^2 = .095$, post-hoc power = .11, or a significant vision by jump interaction, $F(2, 28) = .427, p = .657, n_p^2 = .030$, post-hoc power = .06, but did yield an effect of jump condition, $F(1, 14) = 5.18, p = .039, n_p^2 = .270$, post-hoc power = .98. Post-hoc tests performed for the main effect of jump revealed that participants’ endpoint distributions were more variable on jump trials ($M = 17.8$ mm; $SD = 7.1$) than no jump trials ($M = 16.4$; $SD = 5.5$). Preplanned contrasts ($HSD = 3.0$ mm) performed for the jump trials showed that participants’ endpoint distributions were less variable in the monocular dominant than in the monocular non-dominant condition (see Table 2).

The ANOVA conducted for VE$sec$ yielded a significant effect of vision condition, $F(2, 28) = 5.38, p = .011, n_p^2 = .278$, post-hoc power = .60, but no significant effect of jump condition, $F(1, 14) = .516, p = .484, n_p^2 = .036$, post-hoc power = .06, or vision by jump interaction, $F(2, 28) = .287, p = .753, n_p^2 = .020$, post-hoc power = .05. Post-hoc tests ($HSD = 2.1$ mm) conducted for the main effect of vision revealed that participant’s endpoint distributions
were smaller in the monocular dominant and binocular conditions than the monocular non-
dominant condition (see Table 2). The preplanned comparisons within vision conditions and
between jump conditions revealed participants’ endpoint variability was smaller in the
monocular dominant and binocular than in the monocular non-dominant condition (HSD = 1.4
mm: see Figure 7).

Average movement trajectories for all vision conditions can be found in Figure 8. The
ANOVA conducted on the END prim yielded a main effect of vision condition, $F(2, 28) = 5.72,$
$p = .008, \eta_p^2 = .290$, post-hoc power = .99, and a main effect for jump condition, $F(1, 14) = 9.62,$
$p = .008, \eta_p^2 = .407$, post-hoc power = .99. These lower order effects were superseded by a
significant vision by jump conditions interaction, $F(2, 28) = 4.91, p = .015, \eta_p^2 = .260$, post-hoc
power = .99. Tukey HSD contrasts performed for the interaction revealed that participant’s
endpoints on jump trials shifted towards the new target location only in the dominant and
binocular vision conditions (HSD = 8.37 mm: see Figure 9). To further probe the magnitude of
the correction, the percentage of correction was computed between the jump and no jump trials
for the dominant and binocular conditions. This analysis showed that participants corrected for
31% and 30% of the 30 mm target jump in the dominant and binocular condition respectively.
This correction occurred despite the participant only seeing 6% of the movement duration.

Finally, the ANOVA conducted for END sec failed to yield significant effects of vision
condition, $F(2, 28) = 2.48, p = .101, \eta_p^2 = .151$, post-hoc power = .28, jump condition, $F(1, 14) = 4.39, p = .339, \eta_p^2 = .066$, post-hoc power = .08, or vision by jump interaction, $F(2, 28) = 2.89,$
$p = .072, \eta_p^2 = .171$, post-hoc power = .35. Lastly, contrasting the jump conditions (HSD = 2.2
mm), revealed that participant’s endpoints in the monocular dominant and binocular conditions
were significantly more to the right as compared to the monocular non-dominant condition (see Table 2).

The 3 vision condition (binocular, monocular non-dominant, and monocular dominant) by 3 movement proportion (25, 50 and 75) analysis failed to yield a main effect of vision, \( F(2, 28) = 1.49, p = .244, \eta_p^2 = .096 \), post-hoc power = .13, or vision by proportion interaction, \( F(4, 56) = 1.36, p = .257, \eta_p^2 = .089 \), post-hoc power = .12. However, a significant main effect of proportion, \( F(2, 28) = 190.5, p < .001, \eta_p^2 = .932 \) was found, post-hoc power = 1.0. Post-hoc contrast (HSD = .13) conducted for proportion revealed significantly higher \( R^2 \) values at 50 and 75 percent of the movement compared to at 25 percent. In addition, larger \( R^2 \) values were also found at 75 percent of the movement than at 50 percent (see Table 2).

**Discussion**

Experiment 2 more directly assessed the contribution of visual information from the dominant and non-dominant eye to the online control of reaching movements. Participants were first provided with a very brief binocular preview of the environment. Following the preview, visual information was withdrawn and participants began their movements towards the target. On one third of trials, the target (i.e., 30 cm) presented during the preview was extinguished and a 27 cm target was illuminated (i.e., target jump). Visual feedback was provided for 20 ms to either the non-dominant eye, the dominant eye, or both eyes, when the limb reached a velocity of 1.0 m/s. As expected, none of the participants were able to notice the target jump. Notably, the results indicated that despite modest differences in the average movement endpoint distributions between vision conditions, reaching movements were more accurate and precise in the presence of target jumps when visual information was available to the dominant eye (i.e., dominant and
binocular viewing conditions). Critically, the analysis of TaPV revealed that on jump trials, participants spent more time after peak limb velocity in the dominant than in the non-dominant and binocular viewing conditions. These results suggest that visual information from the dominant eye significantly contributes to online visuomotor control processes.

One issue that required further explanation was the lack of effects for the $R^2$ analyses. Indeed, it was predicted that evidence of online control would be greater with binocular and monocular dominant vision than with monocular non-dominant vision. However, no differences in $R^2$ values were found in experiment 2. Because of the corrections for the target jump presented after movement onset in experiment 2 in both conditions with vision provided to the dominant eye for 20 ms, it is clear that significant online control processes can be implemented with that eye alone. As such, the absence of effects for the $R^2$ analyses in experiment 2 could be due to the very brief visual input and that such type of analyses require more visual information to yield differences.

Overall, the advantages of viewing a limb’s trajectory binocularly may thus be significantly driven by input from the dominant eye. Previous work on this topic has shown that continuous visual feedback during the trajectory yields greater accuracy during reaching movements (e.g., Carlton, 1981; Beaubaton & Hay, 1986). In these experiments (e.g., Carlton, 1981; Beaubaton & Hay, 1986), movements were performed under binocular viewing conditions. In the current study, movements terminated closer to the targets under viewing conditions where vision was available to the dominant eye (i.e., dominant and binocular viewing conditions). When viewed in conjunction with the results of Carlton (1981) and Beaubaton and Hay (1986), the current study provides novel evidence that online control processes are significantly influenced by visual feedback gathered by the dominant eye.
General Discussion

The results of both experiments emphasize the importance of visual information gathered by the dominant eye for accuracy and precision of upper limb movements. Aside from the advantage of the non-dominant eye for the medio-lateral end point control, which cannot be explained by online control mechanisms, experiment 1 found increased precision when visual information was available to the dominant eye. The results of experiment 2 emphasized the critical role of the dominant eye when engaging in online visuomotor control processes. Evidence for this claim can be found in the significant shift in endpoints towards the new target location on target jump trials in the dominant and binocular viewing conditions, as well as the increase in time after peak limb velocity on target jump trials relative to the non-dominant and binocular viewing conditions.

This study highlights the important role of visual information gathered by the dominant eye for online visuomotor control. Empirical work has shown that online control occurs during the limb deceleration phase, as the limb approaches the target (e.g., Chua & Elliott, 1993). In their study, Chua and Elliot (1993) found that participants spent more time after peak limb velocity when binocular visual information was available compared to when visual information was absent. This led the authors to conclude that visual information acquired after peak limb velocity was crucial to accurately control the movement. The results of the current study suggest that visual information gathered specifically by the dominant eye after peak limb velocity is critical to accurately control a movement online.

The hypothesis that online control is driven by input from the dominant eye can be consistent with the model put forward by Elliott et al. (2010). In their multiple-processes model,
online control is accomplished via visual and proprioceptive feedback gathered during the trajectory. This sensory information is then utilized to engage in limb-target regulation processes (i.e., online control of the limb), which must take place following a target jump implemented after movement onset. The results of the current study suggest that such online control processes may be driven by input from the dominant eye. When information from the dominant eye was available, participants also spent more time after peak limb velocity (e.g., Chua & Elliott, 1993), which led to enhanced accuracy and precision in comparison to when input from the non-dominant eye was available. As such, at least for the rapid reaching movements performed in the current study, visual input from the dominant eye seems sufficient to enable the online visuomotor control processes that typically occur under binocular viewing conditions.

One possible explanation for the advantage of the dominant over the non-dominant eye for the online control of voluntary reaches stems from the typical occlusion of the dominant limb prior to movement initiation. That is, movements typically begin with the dominant limb (i.e., the right limb) resting on the ipsilateral side of the body relative to the dominant eye. As the limb begins the trajectory towards a target object, the earliest visual cues are initially available to the ipsilateral eye (i.e., the dominant eye; see Spector, 1976). Indeed, because of the bridge of the nose, the dominant hand is not always visible to the non-dominant eye. As a result, humans may develop stronger visuomotor pathways for the control of hand movements via the dominant than the non-dominant eye. However, such an explanation remains speculative at this point and requires further investigations.

 Nonetheless, the current study emphasizes the significant role of the dominant eye when engaging in goal-directed reaching movements. In two experiments reported here, it was found that reaches performed when vision was available to the dominant eye facilitated endpoint
precision (i.e., experiment 1 & 2) and accuracy (i.e., experiment 2). Further, when directly probing online control via a target jump (i.e., experiment 2), it was found that participants significantly corrected their trajectories, and spent more time after peak limb velocity when visual information was available to the dominant eye. As such, the results of the current study suggest that having visual feedback available from the dominant eye is necessary to accurately control the moving limb, and enables online visuomotor control processes.
Acknowledgements

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References


**Figure 1.** Depiction of aiming console and stimuli for Experiment 1 & 2. A. The participant's point of view of the aiming console depicting the home position as well as the target location. In Experiment 1 only the 30 cm target was used whereas in Experiment 2 both the 30 cm and 27 cm targets were used. B. Depiction of the experimental setup for Experiments 1 & 2. In Experiment 1, participants executed reaching movements to the 30 cm target. In Experiment 2, the displayed target could switch from 30 to 27 cm following movement start (i.e., target jump).
Figure 2. The average movement velocities are shown for all vision conditions in Experiment 1 and 2. A. the average velocity achieved for all vision conditions in Experiment 1. B. The average velocity for the vision conditions when aiming to the 30 cm target of Experiment 2. C. The average velocity per vision condition when aiming to the 27 cm target in Experiment 2. The grey dashed line in Panel B and C indicates when the 20 ms window of vision was provided.
Figure 3. Average movement trajectories along the primary movement axis for all vision conditions of Experiment 1 are shown.
Figure 4. Movement end position along the secondary movement axis (i.e., medial-lateral axis) is shown.
Figure 5. Variable error along the primary movement axis.
Figure 6. Results for time after peak limb velocity. Post-hoc tests showed that participants spent more time after peak limb velocity during target jump trials in the monocular dominant condition compared to the monocular non-dominant and binocular viewing conditions.
Figure 7. Variability in endpoint along the secondary axis on target jump trials, across vision conditions. Participants were less variable in the monocular dominant and binocular viewing conditions than the monocular non-dominant condition.
Figure 8. Movement trajectories to the 30 cm and 27 cm targets are shown for the three window viewing conditions. In addition, the average endpoint position for both targets are shown.
Figure 9. Results for end position along the primary axis. Post-hoc testing of the significant vision x jump interaction revealed that participant's endpoints shifted towards the new target location only when visual information was available to the dominant eye (i.e., monocular dominant and binocular viewing conditions).
Table 1: Means and Between-Participants Standard Deviations for Movement Time (MT; ms), Time to peak limb velocity (TtoPV; ms), Time after peak limb velocity (TaPV; ms), End position (END; mm) and Variable error (VE; mm) in the Primary (prim) and Secondary (sec) movement axes and correlation values ($R^2$) for 25%, 50% and 75% of the movement are shown.

<table>
<thead>
<tr>
<th>Vision Condition</th>
<th>Monocular non-dominant</th>
<th>Monocular-dominant</th>
<th>Binocular</th>
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<tbody>
<tr>
<td></td>
<td>$M (SD)$</td>
<td>$M (SD)$</td>
<td>$M (SD)$</td>
</tr>
<tr>
<td>MT</td>
<td>349.7 (27.9)</td>
<td>357.0 (26.9)</td>
<td>350.1 (21.8)</td>
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<tr>
<td>TtoPV</td>
<td>135.1 (12.3)</td>
<td>136.9 (14.9)</td>
<td>140.0 (12.1)</td>
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<tr>
<td>TaPV</td>
<td>214.6 (29.0)</td>
<td>220.2 (25.4)</td>
<td>210.5 (18.3)</td>
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<tr>
<td>END</td>
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</tr>
<tr>
<td>prim</td>
<td>302.7 (6.1)</td>
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<td>303.2 (4.9)</td>
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<tr>
<td>sec</td>
<td>- 1.2 (2.3)</td>
<td>- 2.6 (2.7)</td>
<td>- 1.4 (2.5)</td>
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<tr>
<td>VE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>prim</td>
<td>8.1 (2.0)</td>
<td>7.6 (2.0)</td>
<td>6.4 (1.3)</td>
</tr>
<tr>
<td>sec</td>
<td>5.0 (1.0)</td>
<td>4.9 (1.3)</td>
<td>4.4 (0.8)</td>
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<td>$R^2$</td>
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<tr>
<td>25%</td>
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<td>0.05 (0.05)</td>
<td>0.04 (0.04)</td>
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<tr>
<td>50%</td>
<td>0.09 (0.13)</td>
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<td>0.04 (0.07)</td>
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<td>75%</td>
<td>0.50 (0.19)</td>
<td>0.50 (0.19)</td>
<td>0.37 (0.20)</td>
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Table 2: Means and Between-Participants Standard Deviations for Movement Time (MT; ms), Time to peak limb velocity (TtoPV; ms), Time after peak limb velocity (TaPV; ms), End position (END; mm) and Variable error (VE; mm) in the Primary (prim) and Secondary (sec) axis and correlation values ($R^2$) for 25%, 50% and 75% of the movement are shown.

<table>
<thead>
<tr>
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<tr>
<td></td>
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<td>Monocular-dominant</td>
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<td></td>
<td>$M$ (SD)</td>
<td>$M$ (SD)</td>
</tr>
<tr>
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<td>354.8 (31.2)</td>
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<tr>
<td>TtoPV</td>
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<td>141.2 (20.4)</td>
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<tr>
<td>TaPV</td>
<td>203.2 (31.2)</td>
<td>213.6 (35.4)</td>
</tr>
<tr>
<td>END prim sec</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>369.5 (32.3)</td>
<td>357.9 (37.7)</td>
</tr>
<tr>
<td></td>
<td>11.4 (15.7)</td>
<td>14.6 (18.9)</td>
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<td>15.4 (4.9)</td>
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<td></td>
<td>10.2 (2.3)</td>
<td>7.8 (2.4)</td>
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<tr>
<td>$R^2$</td>
<td></td>
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</tr>
<tr>
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<td>0.11 (0.15)</td>
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<tr>
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<td>0.28 (0.21)</td>
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<tr>
<td>75%</td>
<td>0.61 (0.21)</td>
<td>0.75 (0.15)</td>
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