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Eye movement accuracy determines natural interception strategies

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Eye movements aid visual perception and guide actions such as reaching or grasping. Most previous work on eye-hand coordination has focused on saccadic eye movements. Here we show that smooth pursuit eye movement accuracy strongly predicts both interception accuracy and the strategy used to intercept a moving object. We developed a naturalistic task in which participants (n = 42 varsity baseball players) intercepted a moving dot (a “2D fly ball”) with their index finger in a designated “hit zone.” Participants were instructed to track the ball with their eyes, but were only shown its initial launch (100–300 ms). Better smooth pursuit resulted in more accurate interceptions and determined the strategy used for interception, i.e., whether interception was early or late in the hit zone. Even though early and late interceptors showed equally accurate interceptions, they may have relied on distinct tactics: early interceptors used cognitive heuristics, whereas late interceptors’ performance was best predicted by pursuit accuracy. Late interception may be beneficial in real-world tasks as it provides more time for decision and adjustment. Supporting this view, baseball players who were more senior were more likely to be late interceptors. Our findings suggest that interception strategies are optimally adapted to the proficiency of the pursuit system.

Introduction

It is well known that eye movements aid visual perception and guide actions such as reaching or grasping. An important goal of movement is accurate interception of moving objects, both for evolutionary advantage (e.g.,...
prey capture) and in everyday activities such as sports. Interception requires estimation of an object’s trajectory from a brief glance at its motion, and a decision when to intercept it (Brenner & Smeets, 2015). This requires a fundamental tradeoff, related to “optimal stopping” in decision theory. An early interception strategy could allow the animal to quickly seize an opportunity but at the risk of an inaccurate strike, whereas a late interception strategy allows more time to extract visual information and make a decision. Perhaps for this reason, athletes are instructed to “keep their eyes on the ball.”

Indeed, there is a tight coupling between motion perception and smooth pursuit eye movements—continuous, slow movements that keep the eyes close to a moving visual target (Kowler, 2011; Lisberger, 2015; Spering & Montagnini, 2011). These movements enable better motion perception and improved ability to predict object trajectories in space (Spering, Schütz, Braun, & Gegenfurtner, 2011) and time (Bennett, Baures, Hecht, & Benguigui, 2010). Most previous studies on interception, however, have focused on saccadic eye movements. It is not known how smooth pursuit accuracy affects interception accuracy and strategy.

There is also a close link between eye and hand movements. Many studies show that eye movements occur naturally when observers engage in reaching, grasping, pointing, or hitting (Diaz, Cooper, Rothkopf, & Hayhoe, 2013; Hayhoe & Ballard, 2005; Hayhoe, McKinney, Chajka, & Pelz, 2012; Land, 2006; Land & McLeod, 2000; Mrotek & Soechting, 2007; Ripoll, Bard, & Paillard, 1986; Soechting & Flanders, 2008). Professional athletes and other task experts show more accurate and less variable eye movements in the field. For instance, expert cricket batsmen make a saccade to the predicted bounce location of a consistently bowled ball; experts’ saccades are more accurate and occur earlier than novices’ saccades (Land & Furneaux, 1997; Land & McLeod, 2000). Moreover, eye and hand movements are spatially and temporally coordinated. Gaze leads the hand by up to 1 s (Ballard, Hayhoe, Li, & Whitehead, 1992; Land, 2006; Sailer, Flanagan, & Johansson, 2005; Smeets, Hayhoe, & Ballard, 1996) and gaze locations depend on task requirements during object manipulation (Belardinelli, Stepper, & Butz, 2016; Johansson, Westling, Bäckström, & Flanagan, 2001). Gaze is anchored on the target in pointing tasks (Gribble, Everling, Ford, & Mattar, 2002; Neggers & Bekkering, 2000) and when hitting, catching or tracking moving objects with the hand (Brenner & Smeets, 2011; Cesqui, Mezzetti, Lacquaniti, & d’Avella, 2015; van Donkelaar, Lee, & Getman, 1994), presumably because of the beneficial effects of smooth pursuit on motion prediction (Bennett et al., 2010; Spering et al., 2011).

This behavioral evidence, however, is mostly based on observational and descriptive studies indicating a link between eye movements and the subject’s expertise or skill level, and most of these studies are on saccades. We developed a novel paradigm to directly assess the functional importance of smooth pursuit for manual interception accuracy and strategy in a task manipulating eye movement quality. Observers had to track a small moving dot (the ball) with smooth pursuit eye movements and manually intercept (hit) it as accurately as possible after it entered a designated “hit zone.” Critically, the ball disappeared briefly after its launch, requiring trajectory extrapolation akin to a real-life baseball scenario, where hitters have less than 300 milliseconds to decode a ball’s trajectory (Adair, 2002). It is well known that tracking can be temporarily maintained after disappearance of a moving target, using a combination of saccades and smooth pursuit (Becker & Fuchs, 1985; Bennett & Barnes, 2005; Bennett, Orban de Xivry, Barnes, & Lefèvre, 2007). Motion trajectory information can be extracted from brief initial exposure and used to predictively drive pursuit (Bennett et al., 2007).

On one hand, we might expect beneficial effects of smooth pursuit on interception accuracy, based on the close link between pursuit and motion prediction, and pursuit’s natural occurrence in interception tasks (Brenner & Smeets, 2011; Hayhoe & Ballard, 2005; Land, 2006; Soechting & Flanders, 2008). On the other hand, perception-pursuit dissociations have been reported frequently (Spering & Carrasco, 2015) and pursuit quality and catching performance have been reported to be uncorrelated on a trial-by-trial basis (Cesqui et al., 2015). Our data allow us to directly link spatio-temporal properties of smooth pursuit eye movements to interception accuracy and strategy, revealing distinct tactics used to intercept either early or late.

Material and methods

Observers

Observers were 42 males (mean age 19.4 ± 1.4 years), members of the UBC varsity baseball team, with normal or corrected-to-normal visual acuity; 37 were right-handed, five were left-handed (dominant hand was defined as hand used for writing). We included 32 participants in the main experiment and the remaining ten observers, who completed the same experiment, in testing a neural network model. All observers were unaware of the purpose of the experiment. The experimental protocol adheres to the Declaration of Helsinki and was approved by the UBC Behavioral Research Ethics Board; participants gave written informed consent prior to participation.
Visual stimuli and apparatus

The pursuit target was a black ball (Gaussian dot, $SD = 0.38^\circ$) with luminance 5.4 cd/m$^2$, moving across a gray background equally divided into a lighter (35.9 cd/m$^2$) and darker (31.5 cd/m$^2$) zone, the “hit zone” (Figure 1a). The physical trajectory of the ball was simulated to be the natural flight of a batted baseball. In the following equations, $\ddot{x}$ and $\ddot{y}$ are the horizontal and vertical acceleration components, taking into account ball mass ($m$), gravitational acceleration ($g$), aerodynamic drag force ($F_D$), and Magnus force ($F_M$) as induced by the baseball’s spin; $\theta$ is the angle between the velocity vector and the horizontal (for conditions and constants used in the simulation see Table 1).

$$\ddot{x} = -\frac{1}{m} \left( F_D \cos(\theta) + F_M \sin(\theta) \right)$$

(1)

$$\ddot{y} = -g - \frac{1}{m} \left( F_D \sin(\theta) - F_M \cos(\theta) \right)$$

(2)

The drag force ($F_D$) and the Magnus force ($F_M$) are defined as

$$F_D = (C_D A \rho v^2)/2,$$

(3)

$$F_M = \gamma f v C_D,$$

(4)

in which $A$ is the cross sectional area of the baseball, $\rho$ the air density, $\gamma$ is an empirical constant determined by measurements of a spinning baseball in a wind tunnel by Watts and Ferrer (1987), $f$ refers to the frequency with which the simulated ball spins, $v$ denotes the ball’s velocity, and $C_D$ is the drag coefficient. The launch angle was constant ($\theta = 35^\circ$).

Stimuli were back-projected onto a translucent screen (Figure 1b) with nondistorting projection screen material (Twin White Rosco screen, Rosco Laboratories, Markham, ON, Canada) clamped onto a solid glass plate and fixed in an aluminum frame with a Vivid LX20 LCD projector [Christie Digital Systems Inc., Cypress, CA; refresh rate 60 Hz, resolution 1280 (H) × 1024 (V) pixels]. The displayed window was 48.5 (H) × 38.8 (V) cm or 60 × 48 in size. Stimulus display and data collection were controlled by a PC (NVIDIA GeForce GT 430 graphics card), and the experiment was programmed in Matlab 7.1 using Psychtoolbox 3.0.8. Observers were seated in a dimly lit room at 46 cm distance from the screen with their head supported by a combined chin- and forehead-rest, and they viewed stimuli binocularly.

Procedure and design

We tested each observer’s right-handed and left-handed interception in separate blocks of trials: In right-handed interception blocks, stimulus motion was from left to right (see example trial in Figure 1a); in left-handed blocks, stimulus motion was from right to left. Each trial started with fixation on a stationary ball presented 14° to the left or right from the screen center. During fixation, the eye had to be within a 1.4° radius of the fixation target (drift correction). We introduced a set of conditions to increase task difficulty, varying only stimulus speed and presentation duration. The ball moved at one of three speeds (24°/s, 29°/s, or 34°/s) and disappeared after one of three visible durations (100, 200, 300 ms, denoted with solid symbols in Figure 1c); conditions were randomly interleaved within each block of trials.
Table 1. Conditions and constants used in the baseball trajectory simulation. Notes: 1 International Civil Aviation Organization, manual of the ICAO standard atmosphere; 2 Bahill, Baldwin, and Venkateswaran (2005); 3 NASA research; 4 Adair (2002); 5 International system of units; 6 Watts and Ferrer (1987); and 7 Experimental design.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air density (20°C, sea level)</td>
<td>( \rho = 1.204 \text{ kg/m}^3 )</td>
</tr>
<tr>
<td>Baseball cross section</td>
<td>( A = 2\pi \cdot 0.0365 \text{ m}^2 )</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>( C_D = 0.3 )</td>
</tr>
<tr>
<td>Mass of baseball</td>
<td>( m = 0.145 \text{ kg} )</td>
</tr>
<tr>
<td>Initial angle of flight</td>
<td>( \theta = 35^\circ )</td>
</tr>
<tr>
<td>Gravitational acceleration</td>
<td>( g = 9.81 \text{ m/s}^2 )</td>
</tr>
<tr>
<td>Frequency of ball spin</td>
<td>( f = 50 \text{ Hz} )</td>
</tr>
<tr>
<td>Empirical constant</td>
<td>( c = 1.2 \times 10^{-3} \text{ kg} )</td>
</tr>
<tr>
<td>Initial x-y position</td>
<td>([-14.1^\circ, 0^\circ])</td>
</tr>
<tr>
<td>Initial absolute velocities</td>
<td>([24^\circ, 29^\circ, 34^\circ]/s)</td>
</tr>
</tbody>
</table>

We instructed observers to track the ball with their eyes and to continue to track it to the best of their abilities after it had disappeared. Observers then had to intercept the ball with their index finger in the hit zone as accurately as possible. Prior to each experimental block, observers completed a brief baseline pursuit block (27 trials) and nine practice interception trials, both with the entire trajectory visible. If interception occurred after the trajectory (including the visible and invisible part) had ended (trajectory durations 1.2, 1.4, and 1.6 s for fast, medium, and slow speed), observers received a “time out” message. However, trajectory durations were sufficiently long to complete the task without feeling rushed, and time outs only occurred during the first practice trials, but not during the experiment. Observers placed their hand on a table-fixed resting pad after each interception. At the end of each trial, observers received visual performance feedback: Interception location was shown as a red disk; true target position at time of interception was indicated by a black disk (Figure 1a). Each observer completed two blocks of 99 trials with each hand, resulting in a total of 198 trials per hand (11 trials per hand, per condition).

Eye and hand movement data analyses

Smooth pursuit in response to a moving target can be initiated reliably, even for targets which disappear after a brief presentation (Figure 2). Smooth pursuit is commonly separated into an initiation or open-loop phase (the first 140 ms after pursuit onset), where pursuit is usually driven by retinal image motion alone (Lisberger & Westbrook, 1985), and the maintenance or closed-loop phase (from 140 ms after pursuit onset to interception), where pursuit is driven by a combination of retinal image motion and feedback signals. Note that one implication of the limited stimulus duration in our study is that in some trials the target had already disappeared by the time pursuit was initiated. Hence, open-loop pursuit in our study must have been driven by a combination of retinal and velocity memory signals. We analyzed pursuit latency, initial pursuit peak velocity (0–140 ms after pursuit onset) and closed-loop velocity gain. We also analyzed the invisible tracking time, defined as the duration of continued smooth tracking after stimulus disappearance until the next catch-up saccade was made. Tracking error, defined as root mean square deviation of eye position relative to target position, was analyzed across the entire trial (from pursuit onset to interception). In 33% of all trials tracking was initiated with a saccade and no pursuit onset was detected prior to the first saccade. In those trials, tracking error was calculated for the time interval from first-saccade offset to interception. To assess the temporal evolution of tracking error in relation to interception performance, we also analyzed tracking error in separate 150-ms time bins aligned to interception. Finally, catch-up saccades were detected based on a combined velocity and acceleration criterion: Five consecutive frames had to exceed a fixed velocity criterion of 50°/s; saccade on- and offsets were then determined as acceleration minima and maxima, respectively, and saccades were excluded from pursuit analysis. Pursuit onset was detected in individual traces using a piecewise linear function fit to the filtered position trace. Each trial was manually inspected, and we excluded trials with blinks (0.85%) and those in which observers moved their hand before stimulus onset (0.2%).

Index finger position was recorded with a magnetic tracker (3D Guidance trakSTAR, Ascension Technology Corp., Shelburne, VT) at a sampling rate of 240 Hz; a lightweight sensor was attached to the observer’s fingertip with a small Velcro strap. The 2D finger interception position was recorded in x- and y-screen-centered coordinates for each trial. Trials in which the point of interception was not detected were excluded (1.6% trials across all observers).

Eye and hand movement recordings and preprocessing

Monocular eye position signals were recorded with a video-based eye tracker (Figure 1b; Eyelink 1000 tower mount; SR Research Ltd., Ottawa, ON, Canada) and sampled at 1000 Hz. Eye movements were analyzed offline using custom-made routines in Matlab. Eye velocity profiles were filtered using a low-pass, second-order Butterworth filter with cutoff frequencies of 15 Hz (position) and 30 Hz (velocity). Saccades were
are an important and integral part of the pursuit response and occur when the eye falls behind the target (de Brouwer, Yüksel, Blohm, Missal, & Lefèvre, 2002; Ego, Orban de Xivry, Nassogne, Yüksel, & Lefèvre, 2013; Orban de Xivry & Lefèvre, 2007). We analyzed the amplitude of the first catch-up saccade and the cumulative catch-up saccade amplitude for the time interval from pursuit onset to interception.
Each observer completed the task with both left and right hand (two blocks of trials each), regardless of handedness. We analyzed finger latency, finger peak velocity, and interception accuracy, defined as interception error and calculated as the Euclidean distance between finger position and target position at time of interception. We found no difference in interception error between interception with the dominant hand and interception with the nondominant hand, \(t(31) = 1.07, p = 0.29\); paired-sample, two-tailed \(t\) test, and averaged across data from right and left hand.

A standard score (\(z\) score) analysis was performed on all eye and finger measures across all trials and observers; individual observers’ values that deviated from the respective measure’s group mean by more than three standard deviations were flagged as outliers and excluded from further analysis (0.8%–3.5% per measure across all trials and observers); these were mostly due to small undetected saccades. To investigate the relation between eye movement error and interception error, we ran a multiple linear regression model with predictors: pursuit latency, open-loop peak velocity, initial saccade amplitude, overall peak velocity, velocity gain, eye position error, cumulative catch-up saccade sum, and invisible tracking time. We also included in the regression model the effect of feedback about the true position of the target and the point of interception (Figure 1a), calculated as the Euclidean distance between position of the feedback disk in the present trial and averaged feedback position across all previous trials per speed. We refer to this variable as feedback memory. Next, we conducted a feature selection to confirm the regression results using a random forest algorithm for classification and regression (Liaw & Wiener, 2002) on the same input variables as in the multiple linear regression model. The random forest algorithm is a simple machine learning model that constructs multiple decision trees using bootstrapping and then estimates the importance of each input attribute (between 0%–100%) by assessing how much the prediction error increases when the respective attribute is neglected. Selected parameter settings were \(mtry = 3\) (number of variables randomly sampled as candidates in each split), and \(ntree = 500\) (number of trees to grow).

To investigate interception timing we conducted a hazard analysis in Matlab to identify each observer’s preferred interception time, i.e., the probability of intercepting at a particular point in time. The time interval from stimulus motion onset to offset was divided into 50-ms bins to achieve distinct hazard peaks (highest likelihood of interception) at high temporal accuracy; in every time bin the number of executed interceptions was counted across all trials for each observer. Next we computed the hazard level \(H_t\), which is defined as the conditional probability of an interception occurring at time \(t\), given that it has not occurred before, as follows:

\[
H_t = \frac{I_t}{N - \sum_{i=1}^{t-1} I_i},
\]

where \(I_t\) is the number of interceptions counted within time interval \(i\), \(N\) the total number of interceptions across all trials, and \(\sum_{i=1}^{t-1} I_i\) the number of interceptions that occurred prior to time \(t\); hazard levels close to 0 indicate a low probability of interception at time \(t\), levels close to 1 indicate a high probability of interception. Hazard peaks across all observers were then analyzed with a k-means clustering algorithm to investigate if the data fell into distinct groups of observers intercepting at particular times.

A single-hidden-layer neural network (R CRAN package \texttt{caret}) was trained on trial-by-trial eye movement parameters (same as in the regression model defined above) of all 32 participants with respect to their interception groups. Subsequently, eye movement data of ten new participants were classified into early or late interception using the trained neural network. Neural network predictions were then compared to results from the hazard analysis.

### Results

#### Eye movement quality and interception error

Figure 2 shows typical eye position traces for individual trials (Figure 2a, b), eye position traces averaged across trials within condition (Figure 2c, d), and averaged eye velocity (Figure 2e, f), for two representative observers. It is evident that there is a close relation between where subjects look and where they point to. Even though observers spent most of the trial fixating or tracking the target with pursuit eye movements (73% of total time per trial on average, \(SD = 9.4\); solid lines in Figure 2a, b), considerable distance was covered by catch-up saccades (dotted lines in Figure 2a, b). Across all observers, the ability to accurately intercept a predicted target trajectory scaled with pursuit quality: A multiple linear regression model yielded a highly significant relationship between tracking error (2D eye position error calculated across the entire trial) and interception error, \(R^2 = 0.24, F(9, 7814) = 281.1, p < 0.001\). Regression model results indicate that tracking error is the largest contributor to interception error (Table 2). This finding was confirmed by a random forest algorithm, which also selected tracking error as the most important contributor (68%, Figure 2a).
Note that for the regression model analysis, tracking error was averaged across the entire trial from pursuit onset to interception (or, if no pursuit onset was found, from offset of the first saccade to interception) and includes the part of the trial where the ball was invisible. The second most important parameter according to this model is cumulative saccade amplitude (Figure 3a). Catch-up saccades likely have a strong influence on tracking error as well. To control for the effect of the first saccade, we recalculated tracking error from offset of the first saccade to interception for all trials, but the model results for this version of tracking error were almost identical (coefficient = 0.74, T = 38.18, p < 0.001; compare with tracking error in Table 2) and the order of predictors in the random-forest analysis was unchanged. It is interesting that open-loop pursuit parameters, the eyes’ immediate response to visual target motion, were least predictive of interception performance, possibly due to strong anticipatory pursuit (Figure 2e, f).

Table 2. Multiple linear regression model results. Notes: Shown are slope coefficients and their standard error, as well as t statistic and significance level for each predictor.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>SE coefficient</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pursuit latency</td>
<td>−0.0042</td>
<td>0.0003</td>
<td>−15.13</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Open-loop peak velocity</td>
<td>0.0035</td>
<td>0.0018</td>
<td>1.87</td>
<td>0.06</td>
</tr>
<tr>
<td>Initial saccade amplitude</td>
<td>−0.051</td>
<td>0.0064</td>
<td>−8.01</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Closed-loop gain</td>
<td>−0.042</td>
<td>0.061</td>
<td>−0.69</td>
<td>0.49</td>
</tr>
<tr>
<td>Eye peak velocity</td>
<td>0.0067</td>
<td>0.0017</td>
<td>4.04</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Tracking error</td>
<td>0.82</td>
<td>0.02</td>
<td>38.56</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Cumulative saccade amplitude</td>
<td>0.036</td>
<td>0.0045</td>
<td>7.96</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Invisible tracking time</td>
<td>0.0018</td>
<td>0.0002</td>
<td>8.56</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Feedback memory</td>
<td>0.10</td>
<td>0.0095</td>
<td>10.74</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

Figure 3b through e shows the temporal development of the relation between tracking error (calculated in 150-ms time bins, aligned with time of interception) and interception error from hand movement onset (mean movement duration: 588 ± 12.4 ms) to interception. Regardless of speed and presentation durations (variations not shown), the eye-hand link increased over time, reaching a maximum close to the time of interception (Figure 3e). Congruently, the Euclidean distance between eye and finger at time of interception is relatively small, 1.36 (SD = 0.44), indicating that observers intercept close to their current eye position (see also Figure 2a, b). These findings extend the close relation between saccades and hand movements in manual interception tasks to smooth pursuit and show temporally linked behavior, relying on common trajectory estimation and planning mechanisms. Moreover, eye tracking error initially increases but then decreases (data points are shifted to the left along the x axis), from an average of 2.9° (SD = 1.32) at 600–450 ms before interception (Figure 3b) to 2.5° (SD = 1.32) at 150 ms before interception (Figure 3e).
0.53) close to interception (Figure 3e; mean tracking engagement of the hand. This improvement close to the time of interception happens despite increasing duration of target invisibility over time, and hence might be linked to the engagement of the hand.

### Eye movement quality and interception strategy

Humans can continue to track a moving object that has disappeared based on internal target velocity memory (Orban de Xivry, Coppe, Blohm, & Lefèvre, 2013; Orban de Xivry, Missal, & Lefèvre, 2008), but this memory signal decays over time. Thus, the longer the ball is invisible the greater the uncertainty about its current position. Given this constraint, it seems that intercepting as soon as the ball enters the strike zone would be the most effective strategy. Note that we did not provide a “go” signal; observers were free to intercept the ball at any time while it was in the hit zone. We observed different but stable interception timing strategies: Some participants tended to always intercept early in the hit zone; others intercepted late.

Figure 4a shows 2D interception positions for two representative observers and illustrates that across all levels of stimulus speed one observer intercepts early, and the other observer intercepts late. To quantitatively investigate observers’ preferred interception strategy, we conducted a Hazard analysis based on each individual observer’s interception times. Splitting our data into two groups using a k-means cluster analysis of individual Hazard peaks (Figure 4b) reduced within-group variability (within-cluster sum of squares) of interception times by 80% and 86% for the two groups; increasing the cluster number to three or beyond led to only marginal further reductions in variability. We thus compared performance between two clusters: a group of “early” interceptors (n = 17; mean interception time 865 ± 79 ms) and a group of “late” interceptors (n = 15), who hit the target on average 129 ms later (994 ± 93 ms; \( t = -14.23, p < 0.001 \); see Figure 4c). We conducted this analysis across presentation durations and speeds. Although both factors significantly affect interception time [main effect of presentation duration: \( F(2, 60) = 4.02, p = 0.02 \); speed: \( F(2, 60) = 23.88, p = 0.001 \); Presentation Duration × Speed interaction: \( F(2, 60) = 3.41, p = 0.01 \); see Figure 4d], there were no differential effects of duration or speed on the two groups [Duration × Group: \( F < 1 \); Speed × Group: \( F(2, 60) = 1.73, p = 0.19 \)].

Even though late interceptions followed a longer period of invisible ball flight, thus creating larger spatio-temporal uncertainty, spatial interception performance was similar between early versus late interceptors. These results are reflected in a repeated-measures ANOVA for interception error with within-subjects factors presentation duration and speed and between-subjects factor group; ANOVA results can be visualized using Figure 5a, which shows interception position within the strike zone for all early versus late interceptors. The ANOVA showed expected significant main effects of presentation duration, \( F(2, 60) = 131.71, p < 0.001 \); (compare symbol types in Figure 5a) and speed, \( F(2, 60) = 12.07, p < 0.001 \), but no main effect of group, \( F(1, 30) = 0.99, p = 0.34 \); (compare open vs. closed symbols in Figure 5a), indicating similar magnitude of interception error across groups. We next computed interception error in separate time bins, aligned with time of interception (Figure 5b). Results reveal similar interception errors for early and late interceptors across time; however, there is a trend for late interceptors to hit more accurately if their interception occurs in the last time bin, relative to early interceptors: two-sample \( t \) test, \( t(89.9) = 1.87, p = 0.06 \). The finding that late interceptors are at least as accurate as early interceptors indicates an actual performance advantage in late interceptors, as we
expect higher errors with uncertainty accumulating over time.

Figure 5a also reveals an interesting tendency to intercept close to the medium-speed trajectory, thus remaining inside the range of space covered by the three possible trajectories: Interception locations for the slowest speed showed positive-sign vertical position errors ($M = 1.16, SD = 0.72$); interception locations for the fastest speed showed negative-sign vertical position errors ($M = -0.92, SD = 0.52$). This spatial averaging effect scaled with presentation duration: Averaging was strongest for the shortest presentation duration. This finding is reflected in a highly significant Speed × Presentation Duration interaction on vertical position error, $F(4, 120) = 119.44, p < 0.001$, regardless of group (no three-way interaction with group, $F < 1$).

Notwithstanding between-group similarities in interception error, the two groups differ in the type of information used, as well as in their eye movement quality, hand movement dynamics, hand movement path, and speed. We evaluated differences between early and late interceptors by fitting multiple linear regressions to eye and hand movement data determining which parameters best predict early versus late interception error. We included finger latency and peak velocity in this model to investigate the extent to which hand movement speed affects accuracy in early versus late. Interception error in both groups is best predicted by tracking error (early: coefficient $= 0.86, t = 27.8, p < 0.001$; late: coefficient $= 0.86, t = 28.0, p < 0.001$), and this result was confirmed with a random forest model run separately for each group (early: 43%, late: 64%). However, the second most important variable in the early group is memorized position of the interception feedback from previous trials within the same speed condition (coefficient $= 0.18, t = 12.6, p < 0.001$; random forest 30%). By contrast, feedback memory does not play a major role in predicting late interceptors’ performance (coefficient $= 0.03, t = 2.30, p = 0.02$; random forest: 16%). In accordance with the model, early interceptors hit significantly closer to the memorized feedback position across previous trials within the same speed condition, mean distance $2.5° ± 1.6°$, than late interceptors, mean distance $3.2° ± 1.9°$, significant main effect of group, $F(1, 30) = 17.25, p < 0.001$.

These results indicate that the two groups of observers use different tactics to intercept accurately: early interceptors rely on a combination of accurate eye movements and cognitive heuristics, whereas late interceptors rely on accurate eye movements only. In line with these regression results, we found superior pursuit quality in late versus early interceptors. Figure 6a shows mean eye velocity traces for each group (early vs. late interceptors) for the fastest speed and all presentation durations, revealing faster pursuit (13% increase in overall peak velocity across all conditions) in late as compared to early interceptors. These group differences can also be seen in individual observer’s velocity profiles (representative early interceptor in Figure 2c; representative late interceptor in Figure 2f). A significant main effect of group on peak velocity, $F(1, 30) = 4.29, p = 0.04$) supports this observation. Late interceptors also initiated pursuit earlier than late interceptors with a 30% decrease in latency. Late interceptors’ initial saccade amplitude was smaller ($M = 6.4, SD = 1.0$) than in early interceptors ($M = 6.8, SD = 1.3$). However, these differences in latency and initial saccade were nonsignificant ($F < 1, ns$).

Hand movements (finger latency and peak velocity) were less predictive of interception error in either group (<15% in either random forest model), but early and late interceptors show different hand movement strat-
Strategies (Figure 6b, c). Early interceptors start moving their hand earlier (12% lower finger latency across all conditions), confirmed by a main effect of group on finger latency, $F(1, 30) = 3.8, p = 0.05$, and they move their hand faster (10% increase in peak velocity; $F(1, 30) = 4.76, p = 0.03$, and in a more direct path (see Figure 6c). By contrast, late interceptors move more slowly and seem to perform online corrections to the target position until late in the trajectory. Similar to eye movement data, finger peak velocity also shows expected significant main effects of speed, $F(2, 60) = 180.96, p < 0.001$, but was unaffected by presentation duration, ($F < 1, \text{ns}$).

In sum, these findings reveal striking differences between early and late interceptors’ eye and hand movements. Interception strategy is intricately linked to eye movement quality: Hand movements are initiated when uncertainty increases and tracking quality declines; this limit may be reached earlier in early interceptors due to lower eye movement quality, whereas late interceptors can afford to track invisible balls longer. This strategy allows more time to extract important ball trajectory information, thus enabling late interceptors to remain temporally and spatially accurate for late interceptions (Figure 5b). Remarkably, our data reveal a close relation between early versus late interception strategy and level of experience in our cohort of varsity baseball players. A larger proportion of senior players chose to intercept late (Figure 7), indicating a strong link between experience and interception strategy.

Next, trial-by-trial eye movement data of all observers were used to train a neural network with respect to interception strategy. We then used the model to classify 10 new observers into early versus late interceptors based on only their eye movement quality (the same parameters as in multiple linear regressions, Table 2). The model classified nine out of 10 observers correctly, i.e., in accordance with a hazard analysis of the respective hand movement data, solely based on their eye movement quality. Only one late interceptor was falsely assigned to the early group. When the neural net was trained with a single parameter, tracking error, we were still able to classify seven out of 10 observers correctly. These classification results emphasize the importance of smooth pursuit eye movements for manual interception; however, they are not proof of causality between eye movements and interception error. They indicate that attributes of smooth pursuit

Figure 6. Vectorial eye and finger velocity traces across all observers for early (magenta) versus late interceptors (gray) for the fastest speed ($34^\circ/s$) and all presentation durations (indicated by line type). Saccades were replaced by linear interpolation. (A) Eye velocity ($^\circ/s$) aligned to 200 ms before stimulus motion onset. (B) Finger velocity (cm/s) in 3D aligned to stimulus onset. (C) Bird’s eye view of interception hand path (finger position in cm) aligned to stimulus motion onset, averaged across presentation durations.

Figure 7. Proportion of late interceptors out of 32 observers who were freshmen, sophomore, junior, or senior. All were members of the UBC varsity baseball team.
Eye movements may be sufficient to predict, with up to 90% accuracy, the preferred interception strategy.

**Discussion**

Eye and hand movements are closely linked in space and time in visually guided reaching, grasping, pointing, or interception tasks. Most behavioral and neurophysiological studies on the relation between eye and hand movements have focused on saccades to stationary or moving objects. Knowledge about the role of smooth pursuit for the control of hand movements is sparse. Because of the known advantages of pursuit for motion prediction (Bennett et al., 2010; Spering et al., 2011) and the importance of prediction for manual interception (Flanagan, Bowman, & Johansson, 2006; Soechting, Juveli, & Rao, 2009), we assume that accurate pursuit is critical for the ability to predictively intercept a moving visual object. Here we used a novel naturalistic task to directly test this assumption and report the following key findings:

First, a position-dependent variable, 2D eye position error (tracking error calculated across the entire trial), is the most important predictor of interception error. This finding might be due to the overall low quality of smooth tracking in a task that included only brief periods of target visibility; keeping the target close to the fovea by any means possible determines the ability to intercept. The close relation between tracking error and interception error increases over time: Eye movement quality is most informative for hand movement control just before the hand intercepts the target, and interception occurs close to the location of the eye (within <1.4°; see Figure 2a, b, and Figure 3e). This temporal evolution of the link between pursuit and interception error extends earlier findings that the eye guides the hand (Ballard et al., 1992; Johansson et al., 2001; Land, 2006; Sailer et al., 2005; Smeets et al., 1996). Previous studies focused on patterns of fixations and saccades, ballistic eye movements of short duration, which arrive at the target long (up to 1 s) before the hand, indicating that gaze supports hand movement planning. We assessed a continuous eye-movement response and show that the link between smooth pursuit and hand movement is closest at the time of interception, indicating joint mechanisms of trajectory prediction and movement planning. Indeed, common prediction has been shown to be useful in synthesizing eye and hand movements in a computational model of interception (Yeo, Lesmana, Neog, & Pai, 2012).

The temporal evolution of the eye-hand link (Figure 3b through e) also reveals that eye tracking error is smallest at the time of interception. This is noteworthy, given that the target has long disappeared at the time of interception. These findings indicate that an ongoing hand movement may boost eye movement accuracy, as has previously been shown for saccades (Dean, Marti, Tsui, Rinzel, & Pesaran, 2011; Epelboim et al., 1997; Lünendenburger, Kutz, & Hoffmann, 2000; Snyder, Calton, Dickinson, & Lawrence, 2002) and smooth pursuit during manual tracking (Niehorster, Siu, & Li, 2015) or when visual target motion is controlled by observers’ own finger movements (Chen, Valsecchi, & Gegenfurtner, 2016).

Second, our task involves a considerable amount of uncertainty, given that the target always disappears after its initial launch. We found that observers tend to intercept close to the spatial average of all potential target trajectories, i.e., the trajectory of the target moving at medium speed. The extent to which observers intercept close to the spatial average increased for shorter target presentation (i.e., with larger uncertainty). These findings indicate that observers learn the statistics of the trajectory to increase the likelihood of an interception within the range of target motion. Such use of a Bayesian prior, in combination with sensory information, has been shown with tasks involving uncertainty due to low stimulus contrast (Stocke, Simoncelli, & Adelson, 2006) or ambiguous motion information (Weiss, Simoncelli, & Adelson, 2002).

Third, we found that eye movement quality predicts observers’ preference to intercept early versus late with greater than 90% accuracy. Interception error in the early group was best predicted by a combination of accurate smooth pursuit eye movements (tracking error) and cognitive heuristics, whereas late interceptors’ hitting error was best predicted by accurate pursuit only. In line with these results, obtained from a random-forest regression model, late interceptors have better pursuit, move their hand more slowly, and continuously correct their hand movement near the point of interception. Remarkably, group membership was closely linked to experience in a real-world task, baseball. More senior varsity athletes had a higher probability of intercepting late. In baseball, hitters have to extract visual trajectory information about the ball in limited time. Late interceptions allow more time for information accrual and decision making. Different strategies used by the two groups of early versus late interceptors could thus point to different capabilities in motion perception, and to differences in how motion information is used in an internal model for trajectory estimation. As an alternative, later interception, indicating better trajectory estimation, could be a direct consequence of better pursuit. To investigate the direct effect of pursuit on trajectory estimation, we developed an experimental paradigm in which observers had to judge whether a linearly moving target (the “ball”) would hit or miss a stationary vertical line segment (the
Our results verify a strong relationship between eye movements and hand movements and show, for the first time, which aspects of smooth pursuit eye movement quality determine interception accuracy and strategy. Interception strategy is optimally adapted to the constraints of the eye movement system: Good pursuit enables later interceptions, thus extending the
time interval available for sensory information accrual and decision making. We directly link this novel finding to experience, revealing a stronger tendency for senior varsity baseball players to be late interceptors. In addition to obvious advantages in sports, late interception may have conferred an evolutionary advantage to predators deciding to strike at their prey or their prey deciding on an evasive maneuver.

Keywords: eye movements, smooth pursuit, saccades, motion prediction, interception, eye-hand coordination, timing

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