

# Saccade dynamics during an online updating task change with healthy aging

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Goal-directed movements rely on the integration of both visual and motor information, especially during the online control of movement, to fluidly and flexibly control coordinated action. Eye–hand coordination typically plays an important role in goal-directed movements. As people age, various aspects of motor control and visual performance decline (Haegerstrom-Portnoy, Schneck, & Brabyn, 1999; Seidler et al., 2010), including an increase in saccade latencies (Munoz, Broughton, Goldring, & Armstrong, 1998). However, there is limited insight into how age-related changes in saccadic performance impact eye–hand coordination during online control. We investigated this question through the use of a target perturbation paradigm. Older and younger participants completed a perturbation task where target perturbations could occur either early (0 ms) or later (200 ms) after reach onset. We analyzed reach correction latencies and the frequency of the reach correction, coupled with analyses of saccades across all stages of movement. Older participants had slower correction latencies and initiated corrections less frequently compared to younger participants, with this trend being exacerbated in the later (200 ms) target perturbation condition. Older participants also produced slower saccade latencies toward both the initial target and the perturbed target. For trials in which a correction occurred to a late perturbation, touch responses were more accurate when there was more time between the saccade landing and the touch. Altogether, our results suggest that these age-related effects may be due to the delayed acquisition of visual and oculomotor information used to inform the reaching movement, stemming from the increase in saccade latencies before and after target perturbation.

reaction times increase with age (Haegerstrom-Portnoy, Schneck, & Brabyn, 1999) as do reach durations (Seidler et al., 2010), as well as saccade latencies (e.g., Munoz, Broughton, Goldring, & Armstrong, 1998). Although each of these movements has been studied extensively independently, the goal-directed movements critical for daily living rely on coordinated eye and hand movements. Online control, which refers to the capacity to update goal-directed movements during the execution process using visual and proprioceptive information, is also an essential part of fluid and flexible control of actions. Changes in performance for goal-directed movements with healthy aging may be due to changes in control of an individual effector or changes in the sensorimotor integration required to update and integrate new information during movements. Online control paradigms, in which it is possible to quantify the outcome of the reach and responses to change during the movements, offer a valuable opportunity to quantify changes in performance with healthy aging and understand its impact on sensorimotor control.

Goal-directed movements such as reaches have been modeled using control theory (e.g., Desmurget & Grafton, 2000; van Beers, Baraduc, & Wolpert, 2002). These models contain feedforward and feedback components that rely on visual and proprioceptive information. A movement plan is made to a target, and the movement can be refined during the movement based on comparisons between the movement plan and the visual and proprioceptive information gathered during the movement. The double-step paradigm has been used to investigate how visual feedback after the movement has commenced can be used to update a movement online. The double-step paradigm typically involves a participant reaching to a target and perturbation of the target after the hand is in flight. The participant must adapt their movement while the hand is still in flight, and performance is quantified in terms of correction latency and accuracy (e.g., Elliot, Hansen, Grierson, Lyons, Bennett, & Hayes, 2010;

## Introduction

Age-related decline in visual perception and motor performance has been well documented. For example,

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Liu & Todorov, 2007; Paulignan, Mackenzie, Marteniuk, & Jeannerod, 1991). This paradigm has been used with a healthy younger population to increase understanding of how visual and proprioceptive information is used during online control (Sarlegna, Blouin, Bresciani, Bourdin, Vercher, & Gauthier, 2003) and to estimate the duration of the sensorimotor feedback loop (Paulignan et al., 1991).

However, the impact of healthy aging on online control has received less attention. Specifically, we have only limited insight into how age-related changes in saccade latencies impact eye–hand coordination during online control and little evidence describing how the online control process in general changes with age. In addition, there is currently no formal account for how the multiple visual and motor processes impacted by aging impact the sensorimotor control process in such a way that would elicit testable predictions of behavior. One of the first steps toward developing a model of sensorimotor control that can predict performance across ages is to obtain quantitative data about the effect of aging on the online control of visually guided movement.

Sarlegna (2006) compared reaching trajectories of older and younger participants when pointing to a target that was perturbed upon initiation of the movement. This meant that the participant had the entire reach movement to correct their trajectory. However, the corrections made by older participants were proportionally less complete (72%) compared with the younger controls (95%), even though the older participants generally took significantly longer to initiate a corrective reach movement. Sarlegna (2006) argued these results highlight the impairment of older adults to monitor the online control of movement through visual feedback. Kimura, Kadota, and Kinoshita (2015) also compared the reach trajectory of older and younger participants in response to a target perturbation that occurred close to reach onset. They quantified the kinematic properties of the reaching movement across participants and, like Sarlegna (2006), found a significant increase in the time to initiate a corrective movement for older participants; however, contrary to the findings of Sarlegna (2006), there was no age-related impact on endpoint error. The key to this discrepancy may lie in participant reach durations. The results of Kimura et al. (2015) showed that the older participants were considerably slower than the younger ones. This suggests that older participants had more time overall to account for the change in target position and, despite the age-related increase in time to initiate a reach correction, were able to maintain a level of accuracy comparable to that of the younger participants. This is not without precedent, as older participants have been known to slow down their movements in order to preserve accuracy

(Rabbitt, 1979; Ratcliff, Thapar, & McKoon, 2006). Kimura et al. (2015) speculated that the effects seen within their study may be attributed to age-related changes in oculomotor function. They argued that participants are likely to make a saccade toward the displaced target location. Given the well-known effects of age on saccade dynamics (Munoz et al., 1998), it is possible that this may adversely affect the visual updating of visuomotor information regarding the target location; however, Kimura et al. (2015) were unable to test this empirically, as eye position information was not recorded within their study.

Older individuals may rely more heavily on visual information during a goal-directed reach to compensate for any age-related impacts to movement planning and execution (e.g., Welsh, Higgings, & Elliot, 2007); however, aspects of saccade dynamics, such as saccade latency, accuracy, and velocity, are known to change as a function of age (Irving, Steinbach, Lillakas, Babu, & Hutchings, 2006; Rand & Stelmach, 2012). Indeed, Abel, Troost, and Dell’Osso (1983) compared eye movement metrics across individuals ranging from 18 to 87 years of age. Participants made saccades toward targets presented  $\pm 1^\circ$  to  $30^\circ$  from fixation. Their results showed that older participants had significantly slower saccade latencies and velocities compared to younger participants. Although some variation across individuals has been observed, the age effects on saccade latencies have been found to be within the range of 100 to 150 ms (Munoz et al., 1998) and have been shown across sequences and multiple movements (Rand & Stelmach, 2011). These results, in conjunction with the strong link between the eye and the hand during coordinated movement, suggest that it is important to consider changes in saccade behavior to understand how eye–hand coordination during the online control of movement is impacted by healthy aging.

There has been little investigation into the dynamics of eye–hand coordination during the online control of movement (Abekawa, Inui, & Gomi, 2014), especially within an aging population. Abekawa et al. (2014) investigated eye–hand coordination during the online control of goal-directed movement within a younger cohort. Specifically, they investigated whether the initial component of the corrective movement is coupled with or independent of the saccade toward the perturbed target. To address this, Abekawa et al. (2014) examined corrections to a target perturbation under two gaze conditions: saccade or fixation. Participants made reaching movements to a centralized target that could be perturbed  $9^\circ$  left or right of fixation, close to reaching onset. They showed that the latency of the correction was faster within the condition containing an accompanying saccade than in the fixation condition. Furthermore, the latency of the correction was often faster than that of the saccade initiation. This suggests that the corrective adjustments were modulated

by whether or not they were accompanied by a saccade, regardless of when the saccade occurred. This observation highlights how eye position information, in addition to new visual information, contributes to online control, and, considering the well-established age-related delays in oculomotor movements (e.g., saccade latency), may have significant implications for how eye–hand coordination during online control is impacted during healthy aging.

The aim of this study was to provide insight into coordinated eye and hand behavior during an online updating task across older and younger participants. We used a target perturbation paradigm and manipulated the time at which the target perturbation could occur after reach onset. Target perturbations were presented early (0 ms after reach onset) and at an intermediate time in the reach (200 ms after reach onset), with a reach duration time pressure of 550 ms. These times were selected to determine how older and younger participants’ eye–hand performance changed in response to a target perturbation at reach onset or well into the reach. Given the variability in performance across older participants, we chose to initiate target perturbations relative to reach onset and provide feedback on reach duration in an attempt to equate perturbation time across participants. This approach is often used with younger participants (Song & Nakayama, 2007) to reduce variability in movement times. We measured eye position and hand position throughout the trial to quantify eye–hand coordination and how this changes with age and perturbation time. If it is the case that age-related changes in eye movements impact online control of a visually guided movement, then the saccade behavior should be associated with characteristics of the hand movement at the beginning, during (e.g., reach correction latency), and at the end of the reach.

We expected that there would be a significant difference between groups and that there would also be a significant effect of the different perturbation time conditions on eye–hand coordinated behavior. Based on previous research (e.g., Munoz et al., 1998), our first hypothesis was that older participants would have significantly longer reach correction latencies, longer saccade latencies (in relation to the initial and perturbed target), longer reach latencies, and longer eye–hand latencies. These measures tell us about the dynamics of eye–hand coordination at reach initiation and how potential age-related changes in such may impact the execution of the reach as a whole. Saccade landing position and touch position have also been found to be spatially correlated for reaching movements, so we also hypothesized that there would be a relationship between eye position and touch location at completion of the movements (e.g., eye–hand distance) and that this would differ between groups and across perturbation conditions and perturbation times.

## Method

### Participants

Sixteen older participants (mean age, 70 years; range, 62–78; eight females) and 16 younger participants (mean age, 26 years; range, 20–30; 10 females) were recruited from within and around the University of Adelaide. This study was approved by the Human Ethics Committee of the School of Psychology at the University of Adelaide (14/90) and was conducted according to the principles expressed in the tenets of the Declaration of Helsinki. All participants gave written, informed consent and were free to withdraw from the experiment at any time without penalty.

To ensure normal cognitive and physical functioning relative to age, all participants completed a series of screening measures. These included the Mini-Mental State Exam (Folstein, Folstein, & McHugh, 1975), Activities of Daily Living Scale (Sheikh, Smith, Meade, Golderenberg, Brennan, & Kimella, 1979), Pelli–Robson Contrast Sensitivity Chart (Pelli, Robson, & Wilkins, 1988), Snellen visual acuity chart (Snellen, 1862), and the Randot Stereotest (Stereo Optical Company, Chicago, IL). All scores were within the age-related norms of functioning, as specified by the test standards. Handedness was assessed with the Edinburgh Handedness Inventory (Oldfield, 1971). Two older participants and four younger participants were identified as left handed.

### Apparatus

A custom-designed system unit with an Intel i7 core (Intel Corporation, Mountain View, CA) and processor speed of 3.07 GHz was used to execute program functions. The unit running Windows XP Enterprise (Microsoft Corporation, Redmond, WA) contained 12.0 GB of RAM. An Elo 17-inch standard format touchscreen monitor (Elo Touch Solutions, Milpitas, CA) was used to display the stimuli and collect the touch responses. The monitor operated at a resolution of  $1280 \times 1024$  pixels with a refresh rate of 60 Hz. A computer mouse was secured to the desk with Velcro, 30 cm from the monitor and in line with the participant’s midline. A headrest with a chin cup was used to ensure that the viewing distance of 40 cm was maintained throughout the experiment and to minimize head movements. An EyeLink 1000 eye tracker (SR Research, Ottawa, Ontario, Canada) was used to sample eye position at a rate of 1000 Hz. Calibration was carried out at the beginning of each block of trials. A Liberty electromagnetic motion tracking system (Polhemus, Colchester, VT) at a sampling rate of 240 Hz was used to record the reach trajectory.

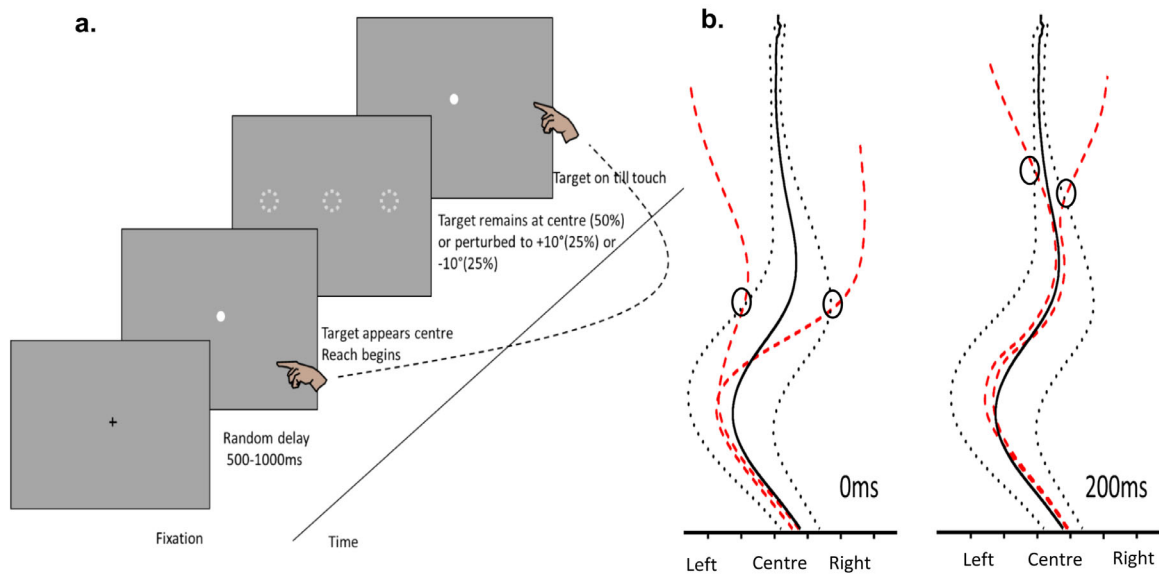


Figure 1. Diagram of a single trial. The participant fixates on a cross presented on the screen. (a) After a random delay, the initial target appears. The participant begins their reach, and the target either remains stationary (50%) or is perturbed to  $10^\circ$  eccentricity left or right (25%) of the initial target at such time designated by the perturbation time condition (0 ms, 200 ms) after reach initiation. Target remains visible until touch. (b) Identification of the latency of the corrective movements. Trajectories toward the non-perturbed target position in a single block were averaged for each participant (solid black line) and  $\pm 1.5$  SDs around each average trajectory were calculated (dashed black line). The point in time when the trajectory describing a single target perturbation trial (dashed red line) exceeded the boundary designated by the 1.5 SD was defined as the onset of corrective movement (indicated by a circle). Data from a single younger exemplar depicting a left and right perturbation trial is presented. Adapted from O’Rielly and Ma-Wyatt (2019).

A Polhemus sensor was attached to the forefinger of the participant’s dominant hand with a Velcro glove. Custom software to run the experiment was written in MATLAB (MathWorks, Natick, MA), using extensions from the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997).

## Stimuli

A black fixation cross, approximately  $1^\circ$ , was presented on the computer screen that maintained a stable gray background (luminance of  $44 \text{ cd/m}^2$ ). The reaching target was a suprathreshold, high-contrast (60%) white dot that subtended  $0.5^\circ$  in diameter at a viewing distance of 40 cm.

## Task procedure

Participants were seated at a reaching distance (40 cm) from the monitor in a slightly darkened room. Before participating in the experimental trials, participants completed 10 to 20 practice trials to ensure each participant’s comfort with the experimental setup and task requirements. A double-step paradigm was used to investigate differences in online updating between age groups. At the beginning of each trial,

the participant was instructed to fixate on the screen while holding down the left mouse button with the pointer finger of their dominant hand. After a random delay of 500 to 1000 ms, the stimulus was presented, and the participants made a saccade and reach toward the target. When the participant’s finger made contact with the monitor, the trial ended, and the participant returned their finger to the set-up position in their own time in preparation for the next trial (Figure 1).

The target initially appeared at a central location  $4.5^\circ$  above the fixation point. Participants initiated a reaching movement toward this target, and after a variable amount of time (0 or 200 ms), it either remained at the same location (50%) or disappeared and reappeared at a second location. On these perturbation trials, the target was shifted laterally to the right (25%) to an eccentricity of  $10^\circ$  from the central location or left (25%) to an eccentricity of  $-10^\circ$ . Target perturbation trials were randomly interweaved with static trials. The target remained visible until touch. The time of perturbation was relative to the participant’s initiation of a pointing trial by the release of the mouse button and could occur at either 0 ms or 200 ms after release of the mouse button.

Participants were given feedback regarding their reach duration but not accuracy. This was done to ensure consistency in reach duration across trials. Participants were provided with feedback in the form of

a tone if their reach duration was greater than 550 ms, and the text “too slow” appeared on the monitor. The text “too fast” accompanied by a tone was provided if participant movement time was less than 450 ms. Feedback limits were informed by previous work within our lab (O’Rielly & Ma-Wyatt, 2018).

Testing was conducted over the course of a single day, with no testing session lasting longer than 1 hour. Each block within the testing session took about 5 minutes to complete and consisted of 80 trials. Regular breaks were used throughout the session to prevent fatigue. All participants completed all experimental conditions across six blocks of trials. This provided a total of 480 trials per participant.

## Data analysis

Custom analysis software was developed by the authors in MATLAB to extract relevant dependent variables from the gaze position, hand position, and touch point data recorded by the experimental system. Data were initially visually inspected for completeness. Trials in which there was an apparatus recording error were identified and removed from analysis; such errors included the touch screen not being touched with enough pressure to register a touch response or the eye tracker failing to maintain a stable eye trace across the entire trial. Identifying such data resulted in 24% of trials being removed from further analysis within the younger group and 53% of trials within the older group. This may seem like a large number of trials; however, due to difficulties in establishing a stable corneal reflection among older participants and the inexperience of all participants with eye tracking, this is not uncommon (O’Rielly & Ma-Wyatt, 2018). From the remaining dataset, trials in which the participant failed to initially fixate on the fixation cross were also removed, as participants failed to follow task instructions. This resulted in a further 16% of trials being removed from analysis within the younger group and 15% of trials within the older group. Trials in which the saccade latency was less than 100 ms were also removed from the remaining dataset as anticipatory saccades (4% for the younger group and 3% for the older group).

Finally, individual participant data were then processed according to perturbation time and direction, and outliers to performance were detected and removed using the median absolute deviation (MAD) method (Leys, Ley, Klein, Bernard, & Licata, 2013). We followed a moderately conservative approach, recommended by Leys et al. (2013), where we removed scores that deviated  $\pm 2.5$  times the MAD from the median. From the remaining dataset, an additional 9% of trials were removed from the younger group and 12% of trials from the older group. As this overall process resulted in a disproportionate number of trials

being removed across participants, participant mean scores across conditions (i.e., no perturbation, 0 ms left/0 ms right and 200 ms left/200 ms right) were used for analysis of dependent variables. Other analyses of the hand movement data have been published elsewhere (O’Rielly & Ma-Wyatt, 2019).<sup>1</sup>

## Dependent variables

Our analysis focuses on the comparative eye and hand movement performance across age groups. Custom software was developed by the authors to identify and classify saccades, using a velocity criterion of 80 cm/s and acceleration criterion of 9500 cm/s<sup>2</sup>. The end of the saccade was determined when velocity fell below 35 cm/s. A 100-ms time period was necessary between the end of the previous saccade and start of the next saccade in order for them to be classified as distinct eye movements (He & Kowler, 1989). The dependent variables quantified in this way included saccade latency (time between initial stimulus presentation and initiation of the saccade), eye–hand latency (time between saccade initiation and reach initiation signified by release of the mouse button), post-perturbation saccade latency (time between perturbed stimulus presentation and initiation of the saccade), and eye–hand distance (Euclidian distance between the final eye position and the touch location). Touch accuracy was calculated as the Euclidian distance (absolute value) in degrees of visual angle between the touch location and the final target location. The correction response to a target perturbation was determined in line with Song and Nakayama (2007) and Rossit and Harvey (2008) and as described in detail within O’Rielly and Ma-Wyatt (2019). This process is briefly described in Figure 1b. On the advice of a reviewer, we also calculated the time between landing the post-target perturbation saccade and the touch response.

We assessed whether there was a directional effect based on direction of target perturbation on the dependent variables. Given the range of movement within this experiment ( $\pm 10^\circ$ ) and previous work conducted within our lab over these smaller eccentricities (Ma-Wyatt & McKee, 2007) we did not hypothesize there to be a directional effect of perturbation direction. Although it is common practice within similar areas of investigation (Song & Nakayama, 2007; Wilson & Hyde, 2013) to collapse across direction within these eccentricities, we tested an effect of perturbation direction (left or right) for each of our dependent variables in the interest of being thorough. Where the effect of perturbation direction was not statistically significant, data were collapsed across perturbation direction, and where preliminary analysis determined there to be a significant effect of

perturbation direction, this term was included in the statistical analysis.

Dependent variables were analyzed using a linear mixed model (LMM) procedure run in SPSS Statistics 21 (IBM, Armonk, NY). This was done by using the LMM procedure with age group (older and younger), target final position (center, left, and right), and perturbation time (0 ms and 200 ms) as fixed effects and participant as a random effect, with the variance structure modeled as variance components. We used a Type III  $F$  tests to test the significance of the main effects. We have reported the  $F$  test results and results of post hoc pairwise comparisons for the sake of space, consistent with other examples of reporting of LMM analyses for repeated measures designs (e.g., Cheterikov & Filippova, 2014). This analysis was used to test each of our hypotheses, for each dependent variable. Where a significant main effect was detected, post hoc pairwise analysis was performed, and a Bonferroni adjustment for multiple comparisons was used. At present, there is no generally agreed-upon measure of effect size that can be calculated for linear mixed models (e.g., Snijders & Bosker, 1999). To date, there is also no generally agreed-upon method for calculating power for LMM analyses with fixed and random effects (for further discussion of this topic, see Brysbaert & Stevens, 2018). For exploratory studies like this one, where few comparable data are available in the literature, it can be difficult to estimate effect size in advance, and this is an additional difficulty for calculating power. However, it is important to understand what proportion of the variance is explained by our statistical analyses. To give insight into the proportion of the variance explained by the fixed and random effects specified in our LMM analyses, we calculated a pseudo- $R^2$  measure first proposed by Nakagawa and Schielzeth (2013) and further developed by Johnson (2014).  $R^2$  marginal ( $R^2_{\text{GLMM}(m)}$ ) describes the variance explained by the fixed effects relative to the expected variance of the dependent variable (values 0–1), whereas  $R^2$  conditional ( $R^2_{\text{GLMM}(c)}$ ) can be considered the variance explained by the fixed and the random effects relative to the expected variance of the dependent variable (values 0–1). This analysis was implemented in Jamovi using the GAMLj: General Analyses for the Linear Model in Jamovi package (Jamovi Project, 2020).

## Results

### Initial saccade latency

The relationship between the eye and the hand is well documented. Given this, we were interested in how the dynamics of eye–hand behavior changed

across age groups. We investigated whether there was a significant effect of age and perturbation time on initial saccade latency. There was a significant group effect,  $F(1, 34.63) = 5.26, p = 0.03$ , with post hoc pairwise analysis, indicating that older participants executed a saccade an average of 25.50 ms slower than their younger counterparts. Perturbation time did not have a significant effect on initial saccade latency,  $F(2, 136.48) = 0.94, p = 0.39$ , and the interaction between group and perturbation time was not significant,  $F(2, 136.48) = 0.84, p = 0.62$ . Values for the  $R^2$  marginal and  $R^2$  conditional measures were  $R^2_{\text{GLMM}(m)} = 0.12$  and  $R^2_{\text{GLMM}(c)} = 0.81$ . Older participants also had greater variability in their saccade latencies, as can be seen in the greater whisker length in Figure 2 (top, left) and captured in the greater proportion of variance accounted for by the  $R^2$  conditional measure.

### Reach latency

We next investigated whether there was a significant effect of age and perturbation time on reach latency. There was no significant group effect,  $F(1, 34.28) = 3.59, p = 0.07$ . Perturbation time did not have a significant effect on reach latency,  $F(2, 136.18) = 0.734, p = 0.48$ , and the interaction between group and perturbation time was not significant,  $F(2, 136.18) = 0.78, p = 0.46$ . This is not surprising, as the target perturbation occurred relative to the reach onset and should not have had an affect on reach latency. Values for the  $R^2$  marginal and  $R^2$  conditional measures were  $R^2_{\text{GLMM}(m)} = 0.09$  and  $R^2_{\text{GLMM}(c)} = 0.85$ . Older participants also had greater variability in their reach latencies as can be seen in the greater whisker length in Figure 2 (bottom, left) and captured in the greater proportion of variance accounted for by the  $R^2$  conditional measure.

### Eye–hand latency

Following from this, we considered the relationship between the initiation of the initial saccade and hand movement—that is, the eye–hand latency (Figure 3, top right). There was no significant group effect,  $F(1, 34.594) = 0.17, p = 0.89$ . Perturbation time did not have a significant effect on eye–hand latency,  $F(2, 136.44) = 0.05, p = 0.95$ , and the interaction between group and perturbation time was not significant,  $F(2, 136.44) = 0.08, p = 0.92$ . Values for the  $R^2$  marginal and the  $R^2$  conditional measure were  $R^2_{\text{GLMM}(m)} = 7.68\text{e-}4$  and  $R^2_{\text{GLMM}(c)} = 0.78$ .

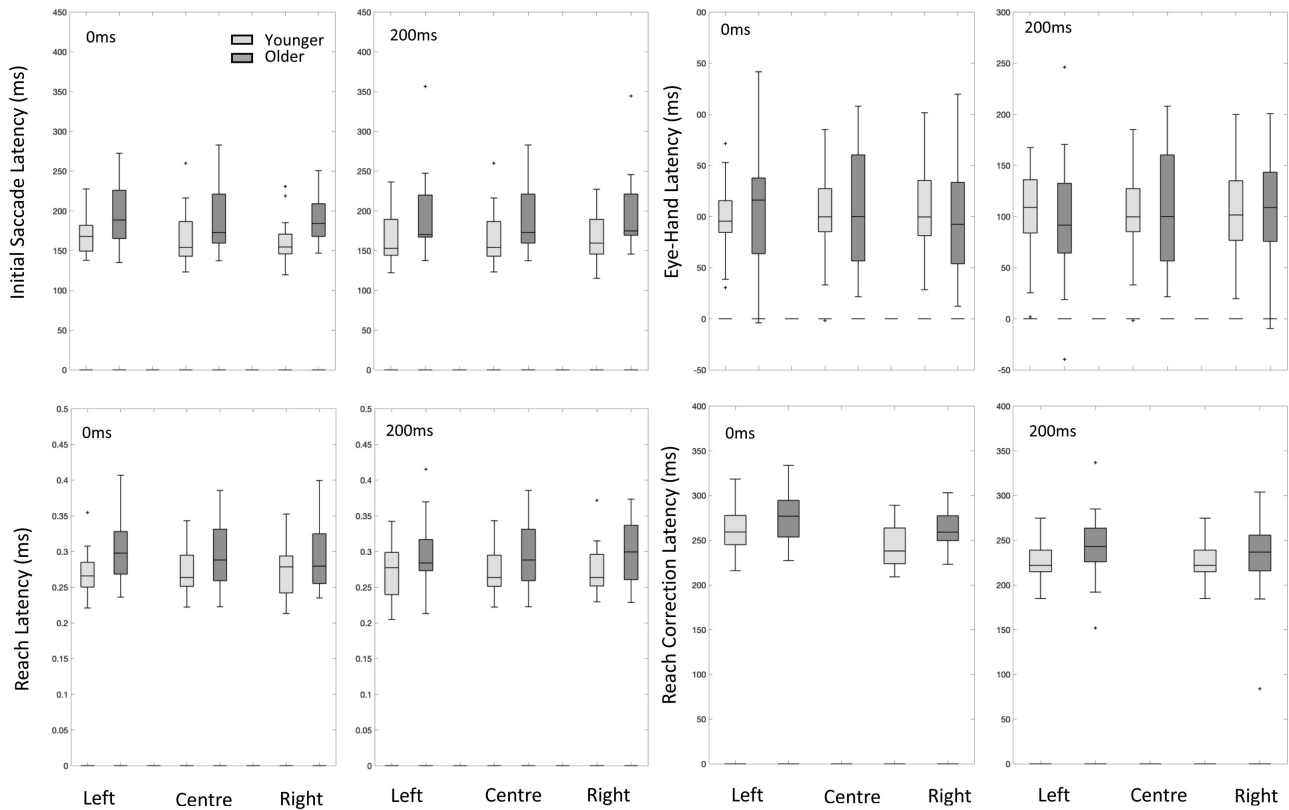


Figure 2. Initial saccade latency (top, left), reach latency (bottom, left), eye–hand latency (top, right), and reach correction latency (bottom, right). Box-and-whisker plots for dependent variables for older and younger participants are plotted as a function of the perturbation time condition and target perturbation. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points, and the outliers are plotted individually and represented as +.

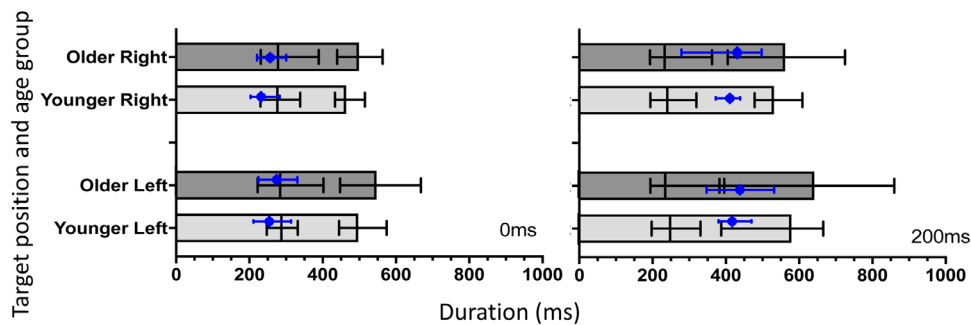


Figure 3. Reach correction latency (blue) calculated relative to reaching onset overlaid mean acceleration (first partition) and deceleration (second partition) phases of the reaching movement plotted as a function of target final position and age group. Error bars signify maximum and minimum responses.

### Reach correction latency

To understand the impact of age on the online correction of visually guided reaching movements, we next investigated whether there was a significant effect of age and perturbation time on reach correction latency. There was a significant group effect,  $F(1, 32.68) = 5.53, p = 0.02$ , with older participants

across conditions executing a correction an average of 16.80 ms slower than their younger counterparts. Older participants also performed a correction much less often than their younger counterparts,  $\chi(1) = 97.26, p = 0.000$  (Table 1).

There was also a significant effect of perturbation time condition on correction latency,  $F(1, 97.07) = 52.28, p = 0.00$ , with post hoc pairwise analysis

Group	0-ms trial		200-ms trial	
	Left	Right	Left	Right
Younger	99%	99%	75%	68%
Older	93%	92%	61%	42%

Table 1. Percentage of trials that elicited a correction in response to a target perturbation.

indicating a significant difference between perturbation conditions; on average, the 200-ms condition produced a 30.27-ms faster correction latency compared to the 0-ms condition (Figure 2, bottom right). There was a significant effect of perturbation side,  $F(1, 97.08) = 7.20, p = 0.01$ , with post hoc pairwise analysis indicating that corrections to the left were on average 11.23 ms slower. This effect should perhaps be interpreted with caution, however, given the differences in the number of trials that elicited a corrective response in that direction (Table 1). There was also considerable variability in correction latency across participants, as evidenced by the additional variance explained by the  $R^2$  conditional measure beyond that of the  $R^2$  marginal. Values were  $R^2_{\text{GLMM}(m)} = 0.28$  and  $R^2_{\text{GLMM}(c)} = 0.52$ .

To gain insight into the timing of the reach correction as it occurred during the reaching movement, we overlaid a breakdown of the reach duration with the reach correction latency (Figure 3). Figure 3 provides a visualization of the reach duration defined by peak velocity and partitioned into the acceleration (first partition) and deceleration (second partition) phases of the reach movement. This is plotted as a function of age group, final target position, and perturbation time condition. The reach correction latency, calculated relative to the reaching onset (indicated in blue in the figure), is overlaid on the reach acceleration/deceleration breakdown. Figure 3 shows that corrections to target perturbations that occur later in the reach (e.g., 200-ms condition) occur proportionally later and after peak velocity in the deceleration phase of the reaching movement. Furthermore, older participants had extended deceleration times. This may perhaps be a compensation mechanism given the delay in the initial saccade latencies for older participants. As such, we will next consider the eye position following the target perturbation.

### Saccade latency after perturbation

We next investigated whether there was a significant effect of age and perturbation time on the latency of saccadic eye movements in response to a target perturbation. There was a significant group effect,  $F(1, 31.69) = 14.25, p = 0.00$ , with older participants

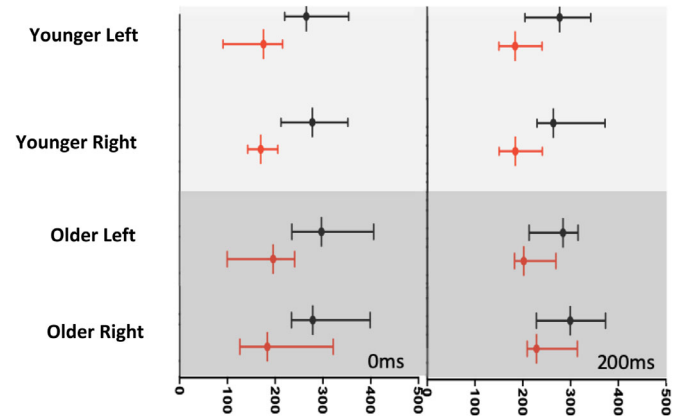


Figure 4. Post-perturbation saccade latency (red) plotted alongside reach correction latency (black) relative to the target perturbation and plotted as a function of perturbation condition, side, and age group. The center mark denotes the mean with maximum and minimum values alongside.

eliciting a saccade after target perturbation that was 26.28 ms slower than that of the younger participants. There was also a significant effect of perturbation time,  $F(1, 92.98) = 42.28, p = 0.00$ , with saccades to later target perturbations (200-ms conditions) being an average of 24.90 ms slower than those to earlier target perturbations. The interaction between group and perturbation time was significant,  $F(1, 92.96) = 10.74, p = 0.001$ , as well as the interaction between perturbation time and perturbation side,  $F(1, 90.89) = 6.26, p = 0.01$ . There were no other significant main effects or interactions, although older participants had greater variability in their saccade latencies, as captured in the greater proportion of variance accounted by the  $R^2$  conditional measure ( $R^2_{\text{GLMM}(m)} = 0.33$  and  $R^2_{\text{GLMM}(c)} = 0.59$ ).

To explore the interaction between the production of a corrective reach response and a saccadic eye movement after the target perturbation occurred, we plotted the reach corrective latency alongside the latency of the saccade after target perturbation (Figure 4). Generally, for both younger and older participants, within the early target perturbation (0 ms) condition the saccade following the target perturbation occurred before initiation of the reach correction (plotted in red in Figure 4). However, in the later (200 ms) target perturbation condition, there was considerable overlap between initiation of a corrective response (depicted in black in Figure 4) and initiation of a saccadic response after target perturbation. This was especially true for the older participants. Given this, it is possible that this overlap may mean that there was less time to collect visual information about the updated location of the target, after target perturbation, and to use this information effectively to refine the reach trajectory. As such, and on advice from a reviewer, we considered the



Trial	Mean (SE)	
	Younger group	Older group
0 ms	288.72 (4.93)	300.28 (8.19)
200 ms	153.83 (6.65)	177.59 (11.53)

Table 2. Mean (SE) time between landing of the post-perturbation saccade and time of touch (ms).

time between landing this post-perturbation saccade on the updated target location and time of touch.

### Time between landing the post-perturbation saccade and time of touch

The time between landing the post-perturbation saccade on the updated target location and the time of touch provides insight into how much time before completion of the reaching movement that foveal visual information was available to influence the reaching outcome through online control. Table 2 provides the mean time (and standard error of the mean) between landing the post-perturbation saccade on the updated target location and the time of touch for younger and older participants across perturbation conditions.

Across both younger and older participants, there was much less time between landing the post-perturbation saccade and when the hand touched the screen for the later target perturbation condition (200 ms) compared to the earlier (0 ms) perturbation condition,  $t(2947) = 33.41$ ,  $p = 0.00$ . It is worth noting that older participants had comparatively more time between landing the final saccade and the touch,  $t(2947) = 2.70$ ,  $p = 0.01$ . Given this, we were next interested in seeing how this impacted eye–hand performance across these conditions and groups, especially given the extended deceleration profiles of older participants reaching movement.

To further understand the relationship between the eye and the hand during a target perturbation task, we quantified the distance between the eye position and the hand position at the time of touch as a function of saccade landing time. Table 3 shows Pearson’s correlations between the eye–hand distance (Euclidian distance in degrees of visual angle) and the time between when the eye arrived at the perturbed target and touch for all participant trials. For younger participants, there was a significant negative correlation between the eye–hand distance and the time between when the eye arrived at the perturbed target and touch. This was the case for both the 0-ms and 200-ms conditions; however, this correlation was not significant for the older participants.

We considered these correlations alongside scatterplots depicting the eye–hand distance and the

time between when the eye arrived at the perturbed target and touch (ms). Figure 5 shows that the pattern of responses was consistent across groups and target perturbation times. Interestingly, for trials in which a correction to a target perturbation was not produced (depicted in red in Figure 5), the distance between the eye and the hand was small and the time between when the eye arrived at the perturbed target and touch was short. As such, we next considered the impact of this on the accuracy of the touch.

To understand the impact on the functional consequences of the reaching movement (i.e., Euclidian touch accuracy), we correlated for all participants’ trials the time between when the eye arrived at the perturbed target and when the touch occurred with the accuracy of the touch response (Table 4). There was a strong negative correlation for the later (200 ms) perturbation time condition for both younger and older participants. This indicates that the greater the time between when the saccade landed and the touch, the more accurate the touch was for this condition. We considered these correlations alongside scatterplots depicting the eye position accuracy (Euclidean degrees of visual angle between the eye position and final target position) and the time between when the eye arrived at the perturbed target and touch (ms). Figure 6 clearly shows that the greater the time between when the saccade landed and the touch, the more accurate the touch was for this condition. Furthermore, when there was no reach correction in response to a target perturbation (trials depicted in red in Figure 6), there was little time between when the eye arrived at the perturbed target and touch, so the touch was also inaccurate.

## Discussion

We investigated how eye–hand coordination during the online control of movement is impacted by healthy aging. Eye position and hand position were measured throughout the trial to quantify how eye–hand coordination is impacted by age and perturbation time. We used an analysis of the reach correction latency coupled with analysis of saccadic eye movement behavior across all stages of movement. Consistent with previous work, older participants produced longer saccade latencies before and after target perturbation. They also initiated movement corrections later and much less often than younger participants, for both perturbation times. This effect was exacerbated during the later perturbation for older participants. These results suggest that the age-related changes in oculomotor function may adversely affect eye–hand coordination during the online control of movement.

Pearson’s correlation

Trial	Younger group	Older group
0 ms	-0.11 ( $df = 913, p = 0.00, R^2 = 0.01$ )	-0.02 ( $df = 548, p = 0.57, R^2 = 0.00$ )
200 ms	-0.18 ( $df = 870, p = 0.00, R^2 = 0.03$ )	0.02 ( $df = 614, p = 0.58, R^2 = 0.00$ )

Table 3. Pearson’s correlation between the eye–hand distance and the time between when the eye arrived at the perturbed target and touch.

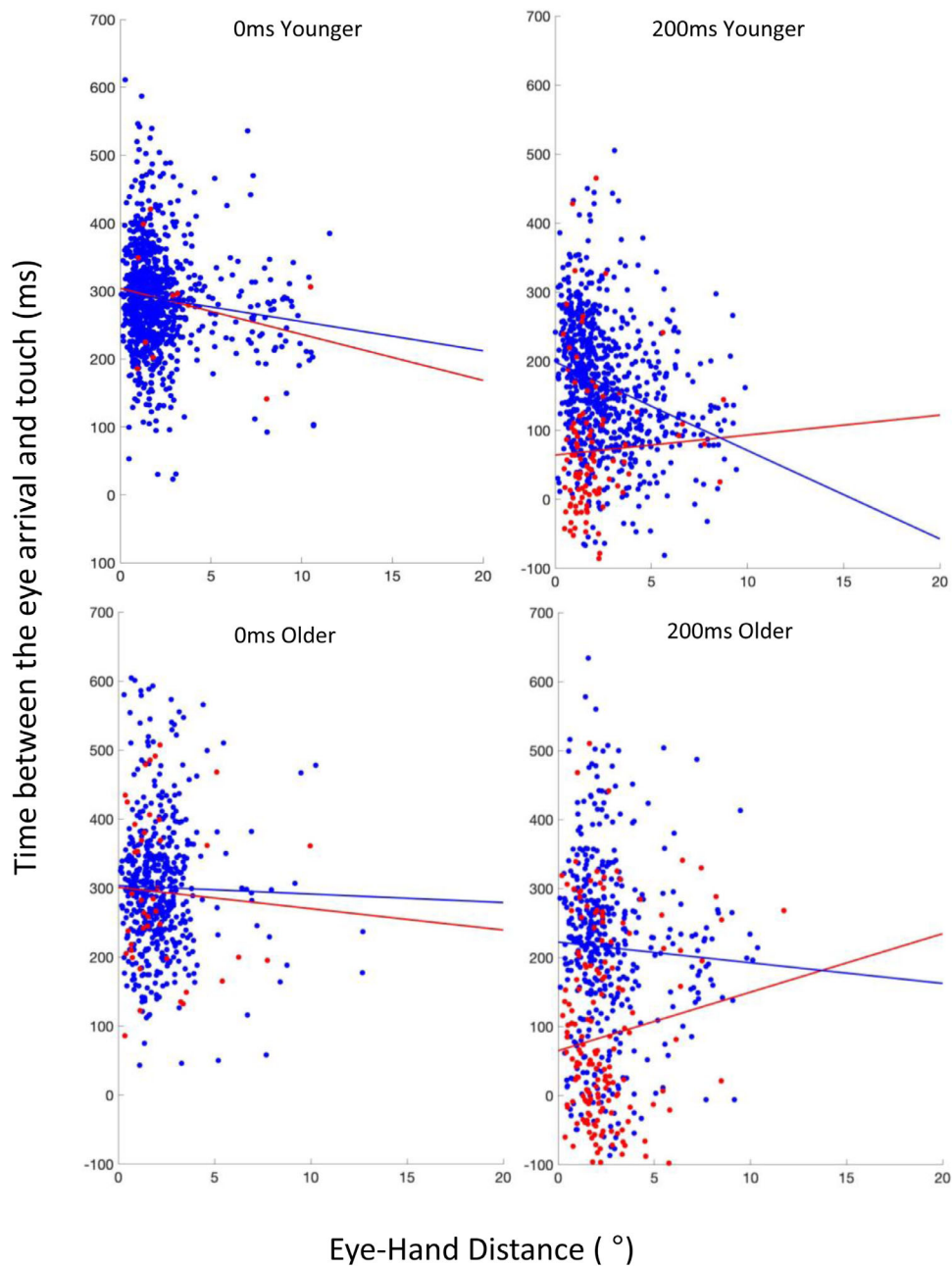


Figure 5. Scatterplots depicting the eye–hand distance (Euclidean degrees of visual angle) and the time between when the eye arrived at the perturbed target and touch (ms). Corrected trials with the least-squares line presented in blue and uncorrected trials with the least-squares line in red.

Pearson’s correlation

Trial	Younger group	Older group
0 ms	-0.09 ( $df = 913, p = 0.01, R^2 = 0.01$ )	-0.03 ( $df = 548, p = 0.46, R^2 = 0.00$ )
200 ms	-0.60 ( $df = 870, p = 0.00, R^2 = 0.36$ )	-0.71 ( $df = 614, p = 0.00, R^2 = 0.50$ )

Table 4. Pearson’s correlation between the Euclidian touch accuracy and the time between when the eye arrived at the perturbed target and touch.

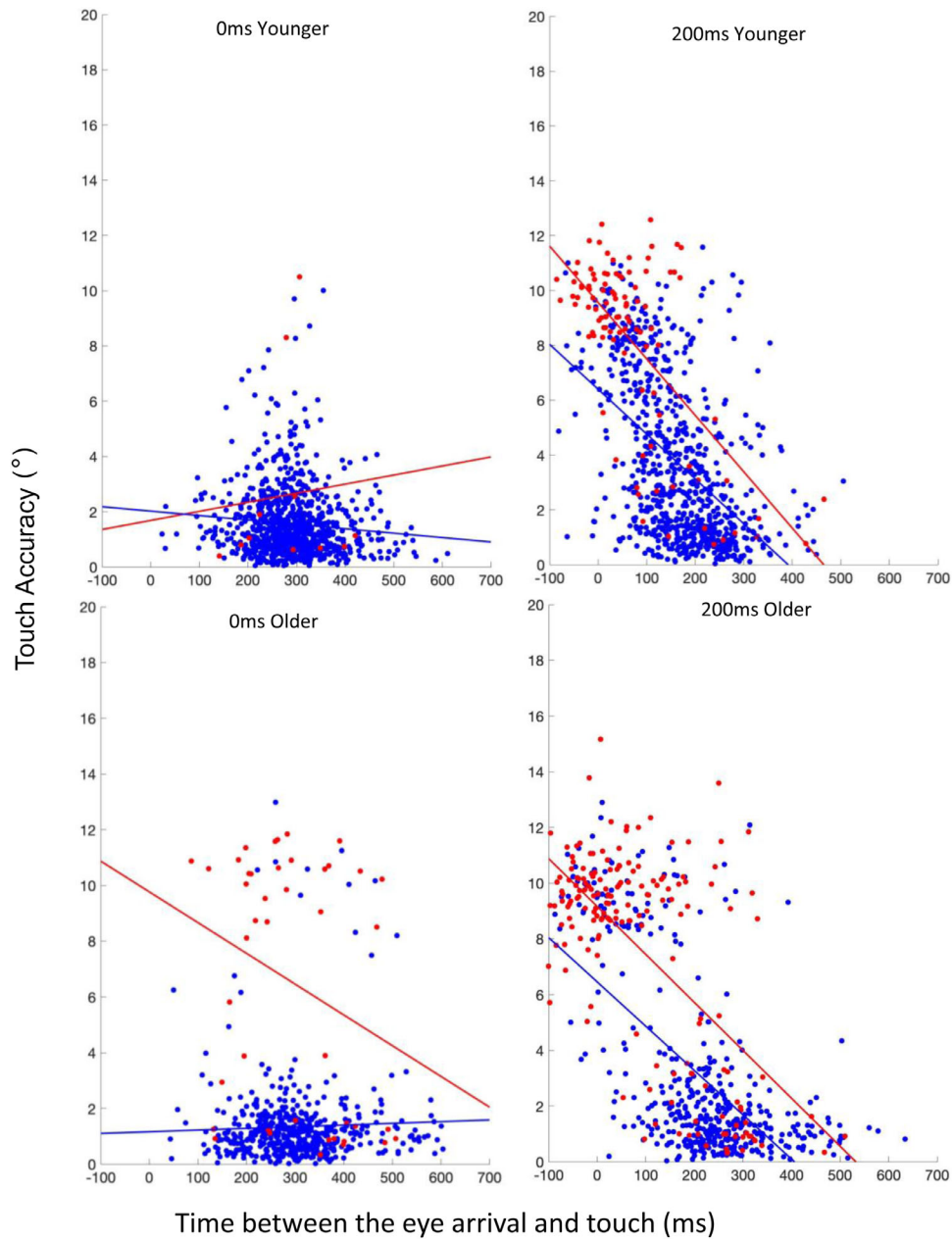


Figure 6. Scatterplots depicting touch accuracy (Euclidean degrees of visual angle) and the time between when the eye arrived at the perturbed target and touch (ms). Corrected trials with the least-squares line presented in blue and uncorrected trials with the least-squares line in red.

## Dynamics of eye–hand coordination during the initial stages of the reaching movement change with age

To gain an understanding of the dynamics of eye–hand coordination at reach initiation and how potential age-related changes in such may impact the execution of the reach as a whole, we first considered measures of eye–hand behavior at the beginning of the reaching movement. Our results show that saccade latencies to the initial target for older participants were significantly longer than younger participants. This is consistent with past research investigating saccade dynamics across the lifespan for saccades made to stationary targets (Peltsch, Hemraj, Garcia, & Munoz, 2011). Interestingly, though, there was no difference across groups for the eye–hand latency and no group difference in reach latencies. Given that the saccade latencies of the older participants were slower than those of their younger counterparts, this result indicates that older participants began their reaching movement sooner after making a saccade toward the target than did their younger counterparts. If we consider Figure 2 (top, right), we can see that on some occasions older participants’ hand movements began even before initiating a saccade, as indicated by negative values on the eye–hand latency measure. With less time between making a saccadic eye movement toward a target and initiating a reach toward that target, one could argue that older participants would therefore need to rely more heavily on visual feedback gained during the reaching movement to compensate for any planning deficits due to incomplete target localization at the initial stages of the reaching movement (Desmurget & Grafton, 2000). As such, we next consider reach correction latencies.

### Older participants produced corrections more slowly and less often

To understand how the age-related changes in eye–hand coordination may impact the functional consequences of the online control of goal-directed movement, we compared the reach correction latency across younger and older participants and perturbation time conditions. Our results showed that older participants initiated a correction to a perturbed target more slowly than did the younger participants. Indeed, this effect was consistent across perturbation time conditions, suggesting that, regardless of the time in the reach that the target perturbation occurred, older participants were consistently slower than younger participants to produce a trajectory correction. These results are consistent with those of Sarlegna (2006) and Kimura et al. (2015) who similarly showed that

older participants were consistently slower to initiate a correction toward a perturbed target location. The correction latencies seen within the study by Sarlegna (2006), however, were considerably longer (339 ms and 538 ms for younger and older participants, respectively) than those seen within our current work (mean correction latencies of 236 ms and 253 ms for younger and older participants, respectively). The differences observed are likely due to small differences in task requirements and analysis processes (for discussion of methodological approaches to analyzing correction latencies, see Oostwoud Wijdenes, Brenner, & Smeets, 2014). Despite these differences, both results clearly show an age-related slowing of the correction latency and by extension the online control of visually guided movement.

Across both early (0 ms) and later (200 ms) target perturbation conditions, older participants produced a corrective movement far less often than the younger participants, although this effect was considerably exacerbated within the later target perturbation condition (Table 1). This indicates that the age-related effect on the online control of movement is not limited to the latency in which the correction is enacted but rather how often a corrective movement is produced. We quantified the timing of the reach correction as it occurred during the reaching movement to investigate why older participants produced a reach correction less often in comparison to younger participants. Figure 3 shows that corrections to target perturbations that occurred later in the reach (e.g., 200 ms condition) occurred proportionally later and after peak velocity in the deceleration phase of the reaching movement. Additionally, older participants showed extended deceleration times. This may perhaps be a compensation mechanism given the delay in the initial saccade latencies for older participants. If visual information regarding the target position information is received later in the reaching movement, then participants may require additional time to incorporate this information into an ongoing movement, and any delay in this may negatively impact the reaching outcome. To investigate this further, we next considered the eye movement following the target perturbation.

### Saccade latencies after target perturbation were slower for the older participants, with considerable overlap between the corrective response and saccade

Not only were saccade latencies to the initial target slower for older participants, but subsequent saccadic eye movements to perturbed targets were also slower compared to the younger participants. For both groups, saccades to targets that occurred later in the reach

(200-ms condition) were slower than those that occurred earlier in the reach (0-ms condition). This is likely due to the timing of the saccade and the target perturbation that occurred at reach onset (0 ms), allowing for saccades to these targets to be planned concurrently (e.g., [Kiernan, Manson, Heath, Tremblay, & Welsh, 2016](#); [McPeck, Skavenski, & Nakayama, 2000](#)). The differences in the saccade latencies between age groups may provide some insight into the age-related effects on the online control of goal-directed movements. [Figure 4](#) plots the post-perturbation saccade latency (red) alongside the reach correction latency (black). Our results show that, for the early (0 ms) target perturbation condition, saccades to a perturbed target, for both groups, largely occurred before a correction was initiated ([Figure 4](#)). However, in the later (200 ms) target perturbation condition there was generally overlap between the post-perturbation saccade latency and the reach correction latency, and this effect was exacerbated within the older group. Interestingly, trials that did not elicit a reach correction in the later target perturbation condition (200 ms) tended to not have a post-perturbation saccade made toward the perturbed target location (84% of trials for younger and 79% for older participants). Because the older participants had slower saccade latencies for saccades after perturbation, these results suggest that the new foveal information gained from looking at the perturbed target or the eye position signal gained from planning a saccade would not be available until significantly later in the movement for older participants or in some cases not at all.

Although models of online control and goal-directed reaching suggest that new visual or proprioceptive information can be incorporated into the ongoing reach at any time during the movement’s process (e.g., [Desmurget & Grafton, 2000](#)), any delay in receiving this information could delay the benefit of such information to influence the unfolding reach. The delayed saccade latencies for older participants could have had flow-on effects as the reach progressed and may help explain the age-related effects on correction latencies and correction initiation seen within this study. To investigate the functional consequences of this flow-on effect of delayed saccade latencies on the outcome of the reaching movement, we next considered the time between the post-perturbation saccade landing and when the participant touched the screen.

### **Time between landing the post-perturbation saccade and touch had a significant impact on the outcome of the reaching movement in terms of eye–hand distance and touch accuracy**

The time between landing the post-perturbation saccade on the updated target location and the time

of touch provides insight into how much time before completion of the reaching movement that new foveal visual information was available for online control. Our results showed that across both younger and older participants there was less time between landing the post-perturbation saccade and when the hand touched the screen for the later target perturbation condition (200 ms) compared to the earlier (0 ms) perturbation condition. For target perturbations that occurred early in the reach (0-ms condition), there was more time to compensate for delays in the receipt of new visual information due to delayed oculomotor processes. However, for those target perturbations that occurred later in the reach (200 ms), there was, of course, less time to incorporate new visual information gained from the saccade toward the perturbed target position, and this may be exacerbated by the increased saccade latencies of older participants.

Previous work has demonstrated that the landing position of the eye and hand are typically spatially correlated for goal-directed movements in a lab setting (e.g., [Neggers & Bekkering, 2001](#); [Wilmot, Wann, & Brown, 2006](#)) and in more naturalistic studies ([Land, Mannie, & Rusted, 1999](#)). Although the temporal correlation of the eye and hand position may vary, the spatial correlation of the endpoints is typically strong. These patterns are thought to indicate that the final visual information gathered by the saccade to the target is used to refine the trajectory as the hand reaches the target. We were interested in understanding how the amount of time after the post-perturbation saccade affected eye–hand endpoint correlation and how that related to a correction. We correlated the Euclidian distance between the eye and the hand at the time of touch with the time between landing the post-perturbation saccade and touch ([Table 3](#)). For the younger participants, there was a significant negative correlation between the eye–hand distance and the time between when the eye arrived at the perturbed target and touch for both the 0-ms and 200-ms conditions. Although this relationship can also be observed in the scatterplots, the correlation was not significant for the older participants. Interestingly, for trials in which a correction to a target perturbation was not produced (depicted in red in [Figure 5](#)) the distance between the eye and the hand is small, and the time between when the eye arrived at the perturbed target and touch is short. This suggests that, when there is minimal time following landing the post-perturbation saccade and touch, the touch location is directed toward the eye position location at that time. For the small proportion of uncorrected trials, this pattern could be observed irrespective of whether or not the eye position was close to the updated location of the target.

Our results showed a negative correlation between when the eye arrived at the perturbed target location

and touch with the accuracy of the touch response for the later (200 ms) perturbation time condition for both younger and older participants. This suggests that, in general, the greater the time between when the post-perturbation saccade lands and the touch response, the greater the touch accuracy. This was especially the case when the reach was under a time constraint, such as when the target was perturbed late in the 200-ms perturbation condition or there was a delay in the initiation of a saccadic eye movement after target perturbation. Furthermore, when there was no reach correction in response to a target perturbation (trials depicted in red in Figure 6), there was little time between when the eye arrived at the perturbed target and touch, so the touch was also inaccurate. Taken together, these results lend further support to the idea that the age-related effect on performance may be due to the delayed acquisition of visual and oculomotor information to inform the movement, stemming from the increase in saccade latencies before and after target perturbation for older participants.

### Underlying mechanisms and future directions

Our results lend support to the age-related changes in sensorimotor performance stemming from changes in visual performance. There is a wealth of evidence to suggest that, as people age, various aspects of motor control and visual performance decline. These age-related changes in performance and function have been attributed to a variety of factors, spanning across multiple sensory and motor processes. For example, some age-related performance deficits have been attributed to visual changes (Owsley, 2011), declines in speed of processing (Salthouse, 1994), and deficits in the planning, execution, and control of guided goal-directed movement (Welsh et al., 2007). Because a number of factors are thought to contribute to age-related changes in sensorimotor performance, it is not immediately clear what the underlying neural mechanisms driving the effects seen within this study might be. Indeed, given the well-known heterogeneity of age-related functioning and performance (see Brabyn, Schneck, Haegerstrom-Portnoy, & Lott, 2001), it is likely that these potential mechanisms may exist independently or in some combination, dynamically across individuals, to produce the age-related effects seen on performance.

The results of this study are not inconsistent with any of the potential mechanisms mentioned above, but they do lend support to the age-related changes in sensorimotor performance stemming from changes in visual performance—specifically, the delay in the acquisition of visual information used to inform a goal-directed reach, through

the increased saccade latencies seen within older participants. Although models of sensorimotor control broadly highlight the importance of visual information as an important source of information in the localization, planning, and execution of a goal-directed reach, most models of sensorimotor control (e.g., Desmurget & Grafton, 2000) have no means to formally account for the changes in sensorimotor control with age in a way that would elicit testable predictions of behavior. A number of potential mechanisms are thought to contribute to the age-related changes in performance, and further work is needed to understand and account for how these mechanisms may influence the underlying processes of sensorimotor control (e.g., Yttri, Liu, & Snyder, 2013). The results of this study provide an avenue of evidence that can be used in conjunction with other accounts of sensorimotor behavior to inform future models of sensorimotor control that are valid across age.

### Conclusions

The age-related changes in eye–hand coordination during the online control of reaching movements were investigated using a double-step target perturbation task. Target perturbations could occur either early (0 ms) or later (200 ms) in the reaching movement. We used an analysis of the reach correction latency coupled with an analysis of saccades across all stages of the movement. The results clearly show an age-related effect on the online control of movement captured by the latency and frequency of a correction to a perturbed target. Older participants also had longer saccade latencies toward the initial and perturbed target. Our results suggest that this age-related effect may be due to the delayed acquisition of visual and oculomotor information to inform the movement, stemming from the increase in saccade latencies before and after target perturbation for older participants.

*Keywords:* ageing, online control, double-step task, saccade, eye movement, reaching

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## Footnote

<sup>1</sup>A reviewer requested post hoc power analyses. Although there is no standard method for conducting power analyses for LMM designs, some have argued that Monte Carlo simulations of observed data may be used to estimate post hoc power (for further discussion of this topic, see Brysbaert & Stevens, 2018). However, it is worth noting that other groups have suggested that post hoc power estimates are of limited use (for detailed discussions, see Dziak, Dierker, & Abar, 2018; Hoenig & Heisey, 2001). At the request of a reviewer, we did conduct post hoc power analyses for the fixed effects of all dependent variables using Monte Carlo simulations run with the simR package in R (Green & MacLeod, 2016). The results of these simulations generally followed the trends of the analysis presented in the analyses sections that follow. Although we have not included these analyses here for the reasons outlined, we would welcome any interested reader to contact us for further details of those analyses.

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