Title:

Older adults' double-step reaching is associated with motor imagery: a mouse-tracking task

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Abstract

Age-related declines in motor control are well-documented. However, mixed findings are reported on the age-related changes in the ability to rapidly adjust ongoing movements in response to target perturbations. When age-related differences are observed, they are often attributed to a general age-related slowing rather than a specific decline in online correction. The lack of age-related differences is often speculated to result from compensatory strategies or preserved neurocomputational processes for online correction in older adults. This study aimed to (1) investigate whether there are age-related changes specific to online motor control and (2) explore the association between online motor control and motor imagery ability in older adults, as both processes rely on forward modelling to predict movement outcomes. Fifty-six young and 29 older participants completed a computer-based double-step reaching task. We found that older adults exhibited longer correction latencies, more rigid corrective movements, and reduced endpoint accuracy compared to younger adults. Notably, the prolonged correction times could not be fully explained by general age-related slowing in information processing. While older adults could use a speed-accuracy trade-off to enhance single-step reaching accuracy, this strategy was insufficient for double-step reaching, indicating age-related challenges in online motor correction. Moreover, older adults' online correction and double-step reaching accuracy were linked to their motor imagery ability, suggesting a reliance on forward modelling.

Keywords: online motor control, double-step reaching, motor imagery, forward modelling, mouse-cursor tracking

Public Significance Statement:

As we age, our motor control declines. Older adults can improve accuracy by slowing down when reaching for stationary targets, but this strategy isn't enough when targets move during the reach. They take longer to correct their movements and are less accurate. This isn't just due to general age-related slowing; they seem to rely more on mentally picturing their movements to make corrections.

Introduction

Rapid online control (ROC) refers to one's ability to rapidly adjust a prepared or ongoing movement in response to unexpected changes. For example, when trying to catch a ball, it may suddenly veer off to the side, and when trying to reach out to grab the hand of a toddler running around, they may change direction unexpectedly. In these cases, rapidly adjusting one's reach in accordance with environmental changes is key to successful object manipulation and social interactions. Unlike other aspects of motor control, which often show significant declines with age, manifesting as slower movements (Madden, 2001), reduced accuracy (Weir et al., 1998), and more variable, less coordinated actions (Seidler et al., 2010) – ROC is often found preserved in older adults (Kadota & Gomi, 2010; Kimura et al., 2015; O'Rielly & Ma-Wyatt, 2018, 2019, 2020; Rossit & Harvey, 2008; Zhang et al., 2018).

Rapid online control is often studied using the double-step reaching paradigm, where the target suddenly shifts at the start or during the reach, requiring participants to adjust their movement in real-time to reach the displaced target. Hand kinematics are analysed to assess one's reaching performance. For example, correction latency, the time interval between the target perturbation and the initiation of corrective movement, marks the efficiency of movement reprogramming (Dubrowski et al., 2002). Endpoint error, measuring the difference between the endpoint of an actual reach and the target location (i.e., the ideal reach endpoint), marks the accuracy of the reaching movement (Rossit & Harvey, 2008). Using this paradigm, O'Rielly & Ma-Wyatt (2019) found that correction latencies were similar for older adults (60–78 years) and younger adults (20–30 years), averaging around 250 ms. In studies where age-related differences were observed, the delays were relatively small, where older adults (60–80 years) took approximately 15–60 ms longer to correct their movements than younger adults (18–30 years;

Kadota & Gomi, 2010; Kimura et al., 2015; O'Rielly & Ma-Wyatt, 2020; Rossit & Harvey, 2008; Zhang et al., 2018). Given that older people also show age-related prolongations in movement time and reaction time, studies argued that the differences in correction latency do not necessarily indicate an age-related decline in rapid online control. Instead, they attributed such differences to a general age-related slowdown in moving speed (Kimura et al., 2015; Rossit & Harvey, 2008; Zhang et al., 2018) and information processing (Kadota & Gomi, 2010a).

The lack of age-related decline in performance is often considered a result of compensation (Bernard & Seidler, 2014). Using compensatory strategies to complete a fast movement usually leads to compromised performance in other aspects of the same task, such as reduced accuracy or vice-versa (Salthouse, 1979). However, where endpoint accuracy was examined, older people reached the displaced target as accurately as young people in double-step reaching (Kadota & Gomi, 2010; Kimura et al., 2015; O'Rielly & Ma-Wyatt, 2018, 2019; Rossit & Harvey, 2008; Zhang et al., 2018), suggesting that older people do not need to sacrifice endpoint accuracy to maintain correction speed.

However, some evidence suggests otherwise. Sarlegna (2006) studied older adults aged 50-63 years and found that they took significantly more time to correct their reaching trajectory than young adults aged 24-38 years, with the correction latency being approximately 200 ms longer. However, in this study, the participants were asked to swipe through the target rather than stop at it, making it impossible to compute the endpoint accuracy or overall movement duration. It is, therefore, impossible to examine whether the extended correction time led to better accuracy or whether it was also due to a general movement slowdown. More recently, in O'Rielly & Ma-Wyatt (2019), while the analyses of correction latency and endpoint accuracy did not reveal age-related differences, in 10-50% of the double-step reaching trials, older adults failed to adjust their reach in response to the target perturbation, which was not reflected in the analysis of latency or accuracy data. Thus, it remains unclear whether the ROC ability is truly preserved with ageing.

An explanation for the lack of age-related differences in double-step reaching is that the neurocomputational mechanisms for online control are preserved along ageing (Kadota & Gomi, 2010a; Kimura et al., 2015). Rapid online control relies on the neural system's ability to anticipate the future position of a moving limb. This capability is facilitated by an internal forward model that predicts the endpoint of the movement, which is continuously compared to the target location, allowing successful correction for discrepancies (Desmurget & Grafton, 2000). While directly assessing forward modelling is difficult, examining age-related changes in other functions that share similar mechanisms may provide insights into its preservation with ageing. One such function is motor imagery, which involves simulating an action internally without physical execution and also relies on the forward model to predict movement outcomes (Rieger et al., 2024).

Motor imagery is often assessed using a hand laterality task, in which participants make judgments about the laterality (left or right) of hand images presented at various angles and orientations (e.g., a hand palm rotating 45° clockwise). To judge the laterality of a given hand image, one needs to mentally rotate an internal representation of one's own hand to match the presented stimulus, which elicits motor imagery (Kosslyn et al., 1998). Using this task, Hyde et al. (2013) found that young adults' rapid online control performance is associated with their motor imagery ability, with more efficient adjustments in double-step reaching linked to faster and more accurate imagery performance. Similar developmental trajectories between online correction and motor imagery were observed in children and adolescents (ages 6-17), where enhanced motor imagery predicted greater efficiency in online correction (Fuelscher et al., 2015; Sooley et al., 2018). There is evidence showing that motor imagery ability declines with age, characterised by decreased accuracy and increased reaction times (Passarello et al., 2022; Wang et al., 2020). However, the link between motor imagery and online correction in older adults has not been examined yet. Whether online control can escape the age-related functional decline in forward modelling remains unknown.

Thus, this study sought to address two questions: (1) Are there age-related differences specific to online correction during double-step reaching – as opposed to single-step reaching – that cannot be accounted for by general slowdowns? (2) Is older adults' double-step reaching performance associated with their motor imagery ability? Instead of motion tracking systems, we used a computer-based reaching task combined with mouse cursor tracking in this study. Such techniques have been found to be a valid tool for studying human sensorimotor control (Tsay et al., 2021, 2023) and are sensitive to age-related differences in movement kinematics (Zhang et al., 2024).

We hypothesised that older adults would have a longer correction latency than young adults. To clarify whether such prolongation is due to a general age-related slowdown, we propose that reaction time is a better measure to account for general age-related slowdown for correction latency than movement time. This is because the mental processes involved in the correction latency are similar to those involved in reaction time, such as visual signal detection, decision-making, movement planning and initiation, which differs from what is involved in performing a reach. Regarding the possible underlying mechanisms, we hypothesised that young and older adults' online correction performances would be associated with their motor imagery abilities. We also considered whether the corrective and post-corrective actions would make specific functional contributions to the accuracy of the reach and the age-related differences. We hypothesised that the corrective action would predict reaching accuracy and that further adjustments during the post-corrective phase would also enhance accuracy. Age-related differences in these associations were also explored.

Another parameter that plays an important role in studying rapid online correction is the perturbation onset time. Swift and successful adjustment was often observed when the target perturbation occurs at the moment of reaching movement initiation (Castiello et al., 1991; Rossit & Harvey, 2008) or shortly after (e.g., 60 ms after movement initiation; Kadota & Gomi, 2010b; Zhang et al., 2018). However, a later target perturbation tends to lead to less optimal reaching performance, marked as elongated movement duration and reduced hit accuracy (e.g., 100 to 300 ms after movement initiation; Liu & Todorov, 2007). The current study used mouse cursor travel distance to trigger early and late perturbations instead of fixed time elapses used in previous studies. This is to avoid perturbations being triggered by unwanted pauses in movements. An early onset occurred at the beginning of the movement, and a late onset occurred when the mouse cursor travelled a third of the original trajectory (from the start point to the original target location). We hypothesised that late-onset perturbations would be more difficult to correct, resulting in longer movement duration and compromised endpoint accuracy. Presumably, such effects would be more pronounced in older adults than young adults.

Methods

Transparency and Openness

We report how we determined our sample size and describe all data exclusions, manipulations, and all measures in the study. All data, analysis code, and research materials are available (Wang et al., 2022). Data were analysed using R 4.4.0 (R Core Team, 2021) and the packages bruceR v2024.6 (Bao, 2024), emmeans v1.10.3 (Lenth, 2024), ppcor v1.1 (Kim, 2015), stats v4.4.1 (R Core Team, 2021) and boot v 1.3.31 (Canty & Ripley, 2024). This study's design and its analysis were not pre-registered.

Participants

Prior power analyses with a medium effect size ($f = 0.25$) and power of 0.95 were conducted for the two designs separately. The 3 × 2 repeated measures mixed design required an estimated total sample size of 44, with 22 in either group. The 2 × 2 × 2 repeated measures mixed design required an estimated total sample size of 36, with 18 in either group. Fifty-six young participants (43 females) and 29 older participants (19 females) were recruited from Duke Kunshan University and the local communities. Young participants' ages ranged from 18 to 22 years, with an average of 19.09 (sd = 1.03), and older participants' ages ranged from 52 to 68 years, with an average of 58.61 (sd = 4.97). It should be noted that the older sample is composed of a mixture of middle-aged and young-old participants. All the participants are Chinese by ethnicity. All the older participants completed the Chinese version of the Mini-Mental State Examination (MMSE; Li et al., 2016) and were scored to have normal cognitive abilities according to their educational level (Katzman et al., 1988). For older participants with one to six years of education (n = 10; age ranged from 52 to 68 years with a mean of 58.50 years), their MMSE total scores ranged from 19 to 29 with a mean of 24.90 (optimal threshold 19/20; Li et al., 2016). For those with seven years or more of education (n = 19; age ranged from 52 to 68 years with a mean of 58.58 years), their MMSE total scores ranged from 26 to 30 with a mean of 28.74 (optimal threshold 23/24; Li et al., 2016). All the participants reported having normal or correct-to-normal vision and were free from any known neurological or psychological disorders.

Participants' handedness was measured using the Edinburgh Handedness Inventory – Short Form (Veale, 2014). Eight young participants are ambidextrous. The rest of the 48 young participants and all the older participants are right-handed. All the participants (both older and young) reported being right-handed with computer mouse use. The study was reviewed and approved by the Duke Kunshan University Institutional Review Board (Protocol #2020SW0048). Informed consent was obtained from the participants in writing before study participation. The data collection was in 2021 and 2022 on the campus of Duke Kunshan University in China.

Tasks & Measures

Double-step reaching task

The double-step reaching paradigm was adopted to assess one's rapid motor control. A computer-based double-step reaching task (Figure 1) was designed and programmed using PsychoPy (Peirce et al., 2019) and executed on a Dell Latitude 7490 laptop with Windows 10. Participants were seated at a comfortable distance of approx. 60 cm from a 23-inch LCD screen. The monitor was operated at a resolution of 1920 × 1080 pixels (px) with a refresh rate of 60 Hz. The display consisted of a green home button at the bottom centre of the monitor (coordinates = [0, -400]) and three possible target locations (yellow) presented in a semi-circular formation across the top of the screen. Both the home button and the target button were 30 pixels in diameter. The target locations were evenly spaced apart at 20° to the left (coordinates = [-272, 352]), 0° (coordinates = [0, 400]) and 20° to the right (coordinates = [272, 352]) with respect to the centre of the home button. The distance from the centre of the home button to the centre of each target location was identical at 800 pixels. The magnitude of perturbation is approx. 6.8° of visual angle.

At the beginning of each trial, the home button was presented. Participants were instructed to fixate on the screen while holding down the mouse key on the home button with the dominant hand's index finger. Their non-dominant hand rested comfortably on the table. The central target appeared after a random interval from 500 to 1500 ms. In the case of a participant releasing the home button before the target appeared, the trial re-started. This holding time interval was designed to reduce anticipatory error. Participants were asked to reach and click on the target as accurately and quickly as possible. The target remained visible until it was clicked. Once clicked, the target disappeared, and the trial ended.

The target remained at the central location without perturbation in 75% of the trials. In the remaining 25% of the trials, the target first appeared at the central location and then jumped laterally to peripheral locations. In this task, two perturbation onsets were used (i.e., early and late). The perturbation onset was defined spatially rather than temporally – when participants' cursor reached a certain location the target jumped. Early-onset is triggered by moving the mouse cursor out of the home button, and late-onset is triggered by the mouse cursor reaching one-third of the distance vertically from the home button to the central target location. Participants were instructed that the target would always appear at the central location first and sometimes may jump to one of the two other locations during their movement (i.e., perturbation trials). Participants were asked to follow and click on the target during the perturbation trials.

A trial could be completed by clicking on the target within 2000 ms of the initial target onset. The trial would be repeated if a participant's movement time exceeded 2000 ms. Participants were instructed to move the mouse cursor within the screen area and avoid overshooting. A warning tone with text information would be provided if the mouse cursor touched the edge of the screen during the reach movement. The participants were first provided with step-by-step instructions, followed by eight practice trials consisting of two perturbation trials and six non-perturbation trials. The two perturbation trials consisted of one left and one right jump, either early or late onset. Thus, the combinations of the perturbation trials could be early-left & late-right or late-left & early-right. Each participant completed a total of 128 trials, consisting of 96 non-perturbation trials and 32 perturbation trials, with 16 early onsets (eight to each side) and 16 late onsets (eight to each side). The testing trials were grouped into four blocks. For each block of 32 trials, the trial type (non-perturbation, early-onset perturbation, late-onset perturbation) was presented in random order.

All the responses were made using a wired laser computer mouse (Dell MS116, movement resolution: 1000 dpi). The enhanced computer mouse cursor acceleration was disabled during the task, resulting in a hand-to-cursor ratio of approx. 0.3 cm per 100 px. The mouse cursor movement trajectories were recorded at a sampling rate of 60 Hz, identical to the monitor refreshing rate. The experiment took place in a quiet lab with normal lighting. A stable grey background was used throughout the task.

Daily computer mouse use

Participants rated their daily mouse use from 1 to 5, with 1 = “I rarely use a mouse”, 2 = “Less than 1 hour per day”, 3 = “1-2 hours per day”, 4 = “2-4 hours per day”, 5 = “More than 4 hours per day”. This measure was used as a covariate to account for participants’ familiarity with mouse use in the analyses. See Supplemental Material 1 for more details.

Hand laterality task

Motor imagery was measured using a computer-based hand laterality task. During the task, participants were presented with a series of hand images, one at a time. Each image contains a single hand, either left or right, presented at one of the eight possible rotation angles, i.e., 0°/360°, 45°, 90°, 135°, 180°, 225°, 270° and 315° clockwise, in either a palm or a back view. The task was to identify whether the image was showing a left or a right hand. Each participant completed 80 trials with 0°, 180° rotation appearing four times and other angles twice. The data was averaged across medial and lateral rotations, resulting in each rotation angle (0°, 45°, 90°, 135°, and 180°) appearing four times. The hand stimuli were presented in a random order for each participant, with each stimulus remaining on the screen until a response was given or 10 seconds had elapsed. The intertrial interval was 500 ms. The responses were made using a keyboard. During the task, the participants were instructed to rest their index fingers on the two keys labelled "LEFT" and "RIGHT" and not to move their hands during the task. The task was presented using PsychoPy 3.0. Age-related performances on such motor imagery related tasks have been well-documented elsewhere (Wang et al., 2020). Therefore, these data were analysed separately from the double-step task, and the findings are reported in Supplemental Materials 2.

Data analysis

Kinematic analysis

Details of the kinematic analysis are reported in Supplemental Material 3. Two young participants were excluded from the analysis due to missing data and recording errors. Five older participants were excluded due to a large number of repeated trials (over 50%) caused by releasing the home button too early, movement time exceeding 2000 ms, or the cursor going beyond the valid testing area. Thus, the data from 54 young participants and 24 older participants were included in the analyses. Across these participants, a total of 123 trials (73 from young participants, 1.06%; and 50 from older participants, 1.63%) were excluded due to unsuccessful movement trajectories, e.g., involving multiple back-and-forth movements and swiping-through movements. The data were also screened for response time (RT, from the central target's onset to the reach movement initiation). A total of 227 trials (187 from young, 2.71%; and 40 from older, 1.30%) were excluded due to RTs less than 100 ms or longer than the mean + 2.5 sd (486 ms for young and 570 ms for older participants). After the screening, among participants included in analyses, the minimum number of trials for non-perturbation, early and late perturbations was 85 (88.5%), 14 (87.5%) and 13 (81.3%), respectively. After screening, the data from 54 young participants and 24 older participants were included in the analyses.

A series of kinematic measures were calculated: (a) movement duration (ms), the time between movement onset and movement offset, reflecting overall movement efficiency and speed; (b) end-point absolute error (px), the Euclidian distance between the target centre and cursor location at the moment of movement offset, measuring the final accuracy of the movement; (c) correction latency (ms), the time between target perturbation and the moment of trajectory correction towards the displaced target, indicating how quickly participants detect and initiate a correction after a perturbation, reflecting rapid online control abilities; (d) ratio of correction latency / individual's mean RT, normalizing the correction speed relative to the individual's RT; (e) correction deviation (px), the perpendicular distance from the cursor trajectory at the moment of correction to the straight line connecting the cursor location at the moment of perturbation onset and the final target centre, measuring how directly participants corrected their trajectory; (f) post-correction duration (ms), the time between the correction and the movement offset, representing the time taken to stabilize and refine the movement after correction. Additional measures of the overall path length, peak velocity, time to peak velocity and jump latency, the time between movement onset and target perturbation onset, are reported in Supplemental Material 4.

Statistical analysis

Variables available in both perturbed and unperturbed trials were entered into separate 3 × 2 mixed ANCOVAs, with Jump Condition (no-jump vs early-jump vs late-jump) being the within-subject variable and Age Group (young vs older) being the between-subject variable. The participants' self-reported daily mouse use (centred) was entered as a covariate. For variables relevant only to perturbed trials, each variable was entered into a 2 × 2 mixed ANCOVA, with Jump Onset (early vs late) being the within-subject variable, Age Group (young vs older) being the between-subject variable, and the centred daily mouse use being the covariate. In the ANCOVAs, where sphericity was violated, Greenhouse-Geisser correction was used. Simple effects analyses were applied when significant interactions were found. Post-hoc analyses with Bonferroni-type correction were conducted when required, and the corrected significance level for each analysis was reported. Where significant differences were found in the ANCOVAs, Cohen's *d* was computed for the pairwise comparisons. For all the analyses, when the results were found to be statistically significant, bootstrapping was performed using 10,000 samples, and bias-corrected and accelerated (BCa) 95% confidence intervals (CIs) are reported for the estimates. This procedure was applied repeatedly throughout the analyses.

Partial correlations were used to examine if the correction for perturbation (correction latency, correction deviation) was associated with one's motor imagery (mean accuracy and reaction time) and to control for daily mouse use. The analyses were conducted separately for early and late perturbations of young and older adults.

We further examined possible constraints of the endpoint accuracy in double-step reaching using stepwise regression for young and older adults. The endpoint absolute error was entered as the outcome variable. Participants' daily mouse use and jump latency were entered in the first step. In the second step, kinematic measures describing correction for perturbation were entered, including correction latency and correction deviation. The post-correction duration was entered in the third step. In the last step, motor imagery accuracy and RT were entered. We also examined whether motor imagery was predictive of single-step reaching accuracy using step-wise regressions. Participants' daily mouse use and jump latency were entered in the first step, and motor imagery measures were entered in the second step.

Results

The mean and standard deviation of each kinematic measure are reported in Table 1 for young and older participants in each condition.

Temporal and spatial features of the single-step and double-step reaching

Reaction time (RT):

The only significant effect was from the Age Group, $F(1, 75) = 27.38$, $p < .001$, $\eta^2_p = .27$, where older participants' RT was longer than young participants' (Cohen's $d = 1.72$; MD = 47.07, BCa 95% CI [35.34, 60.04]).

Movement Duration:

The Age Group × Jump Condition interaction was significant, $F(1.91, 143.42) = 9.85$, $p < .001$, $\eta^2_p = .12$ (Figure 2). Across all the jump conditions, older adults had a longer movement duration than young adults (all *p*s < .001; no jump: Cohen's $d = 4.71$, MD = 444.21, BCa 95% CI [367.68, 509.06]; early jump: Cohen's $d = 3.64$, MD = 344.60, BCa 95% CI [272.49, 412.39]; late jump: Cohen's $d = 3.84$, MD = 367.20, BCa 95% CI [289.10, 435.31]). Regarding jump condition, for both older and young adults, a late jump required longer movement duration than an early jump and an early jump longer than no jump (older adults – late vs. early: $p < .001$, Cohen's *d* = 1.01, MD = 97.52, BCa 95% CI [0.06, 193.03]; early vs. no jump: p = .002, Cohen's *d* = 0.79, MD = 74.31, BCa 95% CI [-20.84, 174.44]; young adults – late vs. early: $p < .001$, Cohen's *d* = 0.81, MD = 74.69, BCa 95% CI [46.21, 105.26]; early vs. no jump: $p < .001$, Cohen's *d* = 1.86, MD = 174.01, BCa 95% CI [141.26, 204.12]).

Endpoint absolute error:

The Age Group × Jump Condition interaction was significant, $F(1.82, 136.54) = 3.22$, $p = .048$, $\eta^2_p = .04$ (Figure 3-A). A significant age difference was found for early ($p = .020$, Cohen's *d* = 0.71, MD = 1.90, BCa 95% CI [0.12, 4.06]) and late jump ($p = .008$, Cohen's *d* = 0.82, MD = 1.98, BCa 95% CI [0.29, 4.09]), where older adults had a larger error than young adults. However, no significant age difference was found for no jump ($p = .31$). A significant effect of Jump Condition was found for older adults only, where a larger error was made for late jump than no jump ($p = .036$, Cohen's *d* = 0.47, MD = 1.18, BCa 95% CI [-0.84, 3.56]), but not other conditions (both *p*s > .13), or for young adults (all *p*s > .71).

Correction latency:

The main effect of the Age Group was significant, $F(1, 75) = 75.40$, $p < .001$, $\eta^2_p = .50$, that older participants took longer to correct the movements than young participants (Cohen's *d* = 1.95, MD = 67.01, BCa 95% CI [51.04, 85.68]; Figure 2). The main effect of Jump Onset was also significant, $F(1, 75) = 17.82$, $p < .001$, $\eta^2_p = .19$, where the correction latency was shorter for late jump onset than for early jump onset (Cohen's *d* = -0.53, MD = -16.09, BCa 95% CI [-1.59, -31.82]).

Correction latency/RT ratio:

The Age Group difference was still significant, $F(1, 75) = 8.15$, $p = .006$, $\eta^2_p = .10$, that older adults had a prolonged correction ratio than young adults (Cohen's $d = 0.75$, MD = 0.08, BCa 95% CI [0.02, 0.13]).

Correction deviation:

The Jump Onset × Age Group interaction was significant, $F(1, 75) = 53.81$, $p < .001$, $\eta^2_p = .42$ (Figure 3-B). The Age Group difference was significant for both early and late jump, where young adults had a larger deviation than older adults (both *p*s < .001; early jump: Cohen's $d = 3.08$, MD = 83.80, BCa 95% CI [62.04, 105.57]; late jump: Cohen's $d = 1.19$, MD = 31.38, BCa 95% CI [15.91, 49.98]). The effect of Jump Onset was significant for both young and older adults, where late jump had a larger deviation than early jump (both *p*s < .001; young adults: Cohen's $d = 0.56$, MD = 14.75, BCa 95% CI [8.09, 23.96]; older adults: Cohen's $d = 2.45$, MD = 67.32, BCa 95% CI [39.93, 92.52]).

Post-correction duration:

The Jump Onset × Age Group interaction was significant, $F(1, 75) = 7.03$, $p = .010$, $\eta^2_p = .09$ (Figure 2). A significant Age Group difference was found for both early and late jump, where older participants had a longer post-correction duration than young participants (both *p*s < .001; early jump: Cohen's $d = 2.32$, MD = 266.03, BCa 95% CI [194.37, 331.99]; late jump: Cohen's $d = 1.64$, MD = 191.76, BCa 95% CI [135.06, 259.00]). The effect of Jump Onset was significant for older participants only, where a longer post-correction duration was found for early jump than for late jump ($p = .018$, Cohen's $d = 0.51$, MD = 55.73, BCa 95% CI [37.41, 139.63]).

The effect of the covariate (centred daily mouse use) was not significant throughout the analyses, all *F*s < 3.65, *p*s > .06.

Motor imagery and its associations with the correction for perturbation

For young people, one's motor imagery ability was not associated with their correction performance for either early jump (-.12 < *r*s < .22, *p*s > .11) or late jump (all *r*s < .08, *p*s > .55). Older adults' motor imagery mean RT was negatively correlated with their correction deviation for late jump ($r = -.45$, $p = .036$, BCa 95% CI [-0.80, 0.06]). Other correlations for early (-.36 < *r*s < .19, *p*s > .10) and late jump (-.10 < *r*s < .41, *p*s > .06) were not significant.

Constraints of reaching movement accuracy for young and older adults

For young adults, correction deviation and post-correction duration were predictive of endpoint accuracy, with larger deviation and shorter post-correction duration leading to greater endpoint errors. Young adults' correction latency and motor imagery performance did not predict their endpoint accuracy (Table 2). For older adults, correction latency was predictive of their endpoint accuracy, with longer correction latency leading to more accurate end-movement. On top of the kinematic variables, older adults' motor imagery accuracy was predictive of their endpoint accuracy towards perturbed targets, with more accurate motor imagery leading to better endpoint accuracy (Table 2). Moreover, motor imagery performance was not predictive of either young or older adults' single-step reaching accuracy (Table 2).For older adults, the association between daily mouse use and the single-step reaching accuracy was statistically significant, but the bootstrapped 95% CI includes a zero, suggesting the effect is not robust.

Discussion

We first examined whether double-step reaching poses greater challenges for older adults than young adults, in contrast to single-step reaching. In both single- and double-step reaching, older adults had longer movement durations than young adults, which is consistent with the literature (Farnè et al., 2003). In single-step reaching, the slower and more extended movement enabled older adults to achieve similar endpoint accuracy to young people, showing a speed-accuracy trade-off. However, in double-step reaching, older adults not only had longer movement duration but also reduced endpoint accuracy compared to young adults. However, it should be noted such difference was no longer significant according to bootstrapped CI. While consistent with the literature (Seidler et al., 2010), the data from the current study shows a small and less robust effect. These results suggest that double-step reaching is indeed more challenging for older adults, where sacrificing movement speed could not fully compensate for the age-related decline in movement accuracy.

Analyses of the correction needed in double-step reaching also revealed age-related differences. The correction latencies observed for older (320 ms) and young participants (250 ms) in this study are similar to those reported by Rossit and Harvey (2008). Older adults needed approx. 70 ms (28%) longer to correct their reaching trajectory than young adults. Previous research has argued that such differences are due to a general age-related decrease in movement speed, as similar differences in movement time have been observed between older and younger adults (Kimura et al., 2015; Rossit & Harvey, 2008; Zhang et al., 2018). However, it should be noted that movement time elongation varies depending on the moving distance and other possible task constraints, e.g., target size and target setup. According to the constraint model (Newell, 1986) and Fitts' law (Fitts, 1954), smaller target sizes impose greater constraints on reaching movements, leading to longer movement times. Consequently, relying on movement time as a proxy for general age-related slowing is problematic, as it can be disproportionately influenced by task constraints and may obscure age-related differences in correction latency, which are comparatively smaller and do not scale in the same manner as movement time. We argued that reaction time is a better measure to account for a general age-related slowdown in correction. Indeed, even after adjusting correction time to reaction time for that individual, the older adults still showed a prolonged correction ratio (approximately 10% slower) compared to young adults, suggesting that the extended correction latency in older adults cannot be fully attributed to the general age-related slowdown in information processing and movement initiation. Correcting an ongoing movement in response to a target perturbation seems more demanding for older adults than initiating a movement from stationary.

While older adults took longer to correct their movements, their movement trajectories were more rigid than those of young adults during the correction – older adults had a smaller deviation from the path to the displaced target than young adults. One possible explanation is that older adults might perform the task less confidently and adopt a more cautious approach. Indeed, young adults moved much faster and covered a greater distance along the original trajectory before correcting. However, this does not mean that older adults deliberately slowed down in anticipation of perturbation, as their peak velocity was greater in double-step reaching than in single-step reaching. In sum, older adults had a slower and more cautious correction than young adults, even after accounting for general age-related slowdown.

We have further considered the effect of early and late target perturbation. In this study, target perturbation was triggered by the mouse cursor moving distance. The jump latency for early perturbation ranges from 50 to 55 ms for young and older participants, respectively, similar to studies that used a 60 ms delay for perturbations (Kadota & Gomi, 2010; Zhang et al., 2018). The jump latency for late perturbation varied between 100 and 250 ms for young and older participants in our study, which is comparable to studies that used a fixed time of 200 ms for late perturbation (Kimura et al., 2015; Liu & Todorov, 2007; O'Reilly, 2018; 2019; 2020). We found that perturbation occurring late into a reaching movement is particularly difficult for older adults to adjust, manifesting as longer movement time and reduced endpoint accuracy.

Older adults' difficulties in online movement correction align with previous research highlighting age-related challenges in cognitive-motor control. For example, older adults demonstrated difficulties in proactive inhibition and required compensatory mechanisms (e.g., increased frontal activation) to offset declines in behavioral performance (Hsieh & Lin, 2016). Additionally, they showed challenges in response reprogramming, characterised by reduced efficiency in movement planning and execution (Bellgrove et al., 1998; Trewartha et al., 2013). Putting together, these findings underscore age-related difficulties in dynamic adjustments to motor and cognitive demands.

The second question this study sought to answer is whether older adults' double-step reaching performance is associated with their motor imagery ability. We first examined the latency and deviation of the corrective response to target perturbation and found that young people's corrective response performance was not associated with their motor imagery ability. For older adults, a smaller correction deviation for late perturbations was linked to longer motor imagery response times. Older adults generally showed less deviation in their correction paths than younger adults. Among older adults, those with slower motor imagery performance had even more limited path deviation during correction. This suggests that a cautious and rigid movement strategy might serve as compensation for their less efficient mental representation and prediction of actions. However, it should be noted that the bootstrapped CI showed non-significant result, which is discussed further as a limitation. The lack of association between online correction and motor imagery among young adults contradicts previous findings (Hyde et al., 2013). One possible explanation is that the current study used a computer-based task, which is more familiar and presumably easier for young adults. Young people may be able to correct for both early and late perturbations automatically without relying heavily on imagery or prediction. For older adults, however, this automatic correction mechanism seemed to operate only for early perturbations, whereas correction for late perturbations required more motor imagery.

We further explored how corrective action, post-corrective reaching, and motor imagery ability contribute to double-step reaching accuracy. For young adults, the endpoint accuracy was associated with the kinematics of the correction and post-correction phases. Specifically, a smaller correction deviation and a longer post-correction period predicted a more accurate reach, suggesting that error corrections during the post-correction phase enhance endpoint accuracy. However, motor imagery performance did not predict young people's double-step reach. For older adults, a longer correction latency was predictive of better endpoint accuracy, suggesting that a slower, more carefully planned correction can lead to a more accurate reach. This finding supports the speed-accuracy trade-off. For older people, controlled and deliberate correction is crucial for accurate movements. Additionally, older adults' endpoint accuracy in double-step reaching was associated with their motor imagery performance, where more accurate imagery led to more accurate endpoint reaching. This finding supports the role of forward modelling in online correction, highlighting the importance of predicting motor consequences during movements with online perturbations. Interestingly, this was only observed in older adults, suggesting that it may be a compensatory strategy – as online control becomes less optimal, older adults use other mechanisms to compensate for the motor control decline. Moreover, motor imagery was not predictive of single-step reaching in either young or older adults, showing that forward modelling is particularly relevant for adjusting ongoing movement in response to target perturbations, especially when the motor control ability is less optimal. Future research should further explore the role of visual feedback in age-related changes in rapid online control. Coats and Wann (2011) found that older adults rely more on visual feedback than younger adults when performing prehension tasks requiring precise manual control. Their accuracy declines significantly when hand visibility is removed, highlighting an increased dependence on visual guidance. Investigating both the individual contributions and the interplay between internal forward modeling and reliance on sensory feedback, such as vision, could provide valuable insights into the mechanisms underlying age-related changes in double-step reaching. By examining how these processes interact and adapt with aging, we can better understand the compensatory strategies employed by older adults and the neural or cognitive shifts that contribute to declines in motor precision and adaptability.

There are several limitations to consider. First, the reaching task required participants to click on the target to complete each trial, which prevented us from examining the correction failure in older and young people. Moreover, while we recorded the number of repeated trials due to task criterion violations, we did not record the specific types of errors that triggered these repetitions. Capturing such details in future studies would provide valuable insights into motor control, particularly for older adults. Additionally, the target size in the current study was relatively small, and the reaching path was confined to the monitor display area to ensure the mouse cursor was tracked. Both factors make the reach movement more challenging, regardless of correction. These requirements might have imposed different levels of constraints on the movements of older and younger participants. Future work shall also consider participants' visual attention and visual acuity as the Useful Field of View (UFOV) declines with age (Lunsman et al., 2008) as well as participants' computer gaming experiences. Although our findings regarding kinematic features are consistent with the literature, future studies should directly compare two-dimensional computer-based reaching with three-dimensional real-world reaching.

It should also be noted that the current study has a relatively small number of perturbation trials (32 in total, 16 per onset condition) comparing to studies of this type, e.g., ranging from 14 (Hyde et al., 2013) to 30 (O'Rielly & Ma-Wyatt, 2019) for each condition. This was due to the low percentage of perturbation trials in the task design, and we limited the number of trials to maintain participant engagement and minimize fatigue. However, it may lead to reduced reliability of the estimates and the results. Thus, to provide a better picture, we compared the performance between the first half and the second half trials and found the participants' performance was relatively stable (see Supplemental Materials 5). We also performed bootstrapping of 10,000 samples, where the results were found to be statistically significant. While the bootstrapping results found several effects less robust, this did not change our key findings or the conclusion. Future studies should explore the optimal number of trials for perturbation or the double-step reaching paradigm in general, taking into account age-related differences in attention span and task tolerance. Furthermore, the sample size was unevenly distributed between the young and older adult groups due to data collection occurring during the COVID-19 pandemic. Despite extensive efforts, pandemic-related restrictions limited opportunities for older adults from the local community to access campus and participate in the study. While prior power analysis confirmed that the sample size was sufficient to detect age-related differences in double-step reaching, replication with a larger and more evenly distributed sample would strengthen the findings. The older participants in the current study are relatively young (52-68 years). Thus, we need to be cautious when generalising such findings to old-older adults. While we identified significant age-related differences in double-step reaching, demonstrating the computer-based task's sensitivity to age-related changes, including a broader age range spanning the adult lifespan in future research could help map the trajectory of these changes more accurately across ageing.

In sum, age-related declines were observed in double-step reaching, as older adults showed longer correction latencies, more rigid correction movements, and reduced endpoint accuracy compared to young adults. While older adults could slow down to achieve better accuracy in single-step reaching, this speed-accuracy trade-off was insufficient for double-step reaching. In fact, the quality of older adults' double-step reaching was constrained not only by their movement kinematics but also by their internal representation and prediction of motor outcomes, as indicated by their motor imagery abilities.

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Tables & Figures

Table 1 Mean and SD of the kinematic variables in Jump and No Jump conditions for both older and young adults.

	Young			Older		
	No Jump	Early Jump	Late Jump	No Jump	Early Jump	Late Jump
Reaction time (ms)	285	285	283	333	331	331
	(34)	(35)	(33)	(47)	(54)	(45)
Movement duration (ms)	632	807	881	1077	1151	1248
	(90)	(73)	(84)	(169)	(170)	(171)
End movement error (px)	12.06	11.84	11.72	12.50	13.73	13.69
	(1.66)	(2.43)	(2.84)	(3.23)	(4.63)	(4.38)
Correction latency (ms)		256	244		330	304
		(19)	(20)		(66)	(52)
Correction latency/RT ratio		0.91	0.89		1.00	0.92
		(0.11)	(0.09)		(0.20)	(0.15)
Correction deviation (px)		232	247		149	216
		(26)	(13)		(51)	(41)
Post-correction duration (ms)		501	520		767	711
		(70)	(66)		(165)	(147)

Table 2 F-change, R^2-change, beta, t-value, associated p-value, and model post-hoc power from the hierarchical regression when predicting double-step reaching and single-step reaching endpoint absolute error for young and older participants. Where significant effects were found, Bias-corrected and Accelerated (BCa) bootstrapping confidence intervals of the *F*-values based on 10,000 samples are reported.

		***F* change**	***BCa 95% CI***	**R^2 change**	***p - Model comparison***	**Variables**	***β***	***BCa 95% CI***	***t***	***p***	***Post-hoc power***
						Double-step reaching					
Young	**Model 1**	1.61		0.030	.204	Daily mouse use	0.167		1.04	.302	
						Jump latency	-0.010		-1.52	.131	
	Model 2	5.19	[0.82, 11.48]	0.089	.007**	+ Correction latency	-0.018		-1.49	.139	0.45
						+ Correction deviation	0.030	[0.007, 0.054]	2.61	.010*	
	Model 3	23.07	[6.44, 50.97]	0.163	<.001***	+ Post-correction duration	-0.017	[-0.025, -0.011]	-4.80	<.001***	0.83
	Model 4	0.87		0.012	.424	+ Motor imagery (accuracy)	-2.000		-0.39	.695	0.09
						+ Motor imagery (RT/s)	0.623		0.87	.386	
Older	**Model 1**	1.30		0.057	.284	Daily mouse use	0.925		1.40	.170	
						Jump latency	-0.005		-0.76	.450	
	Model 2	2.94		0.118	.064	+ Correction latency	-0.024	[-0.048,	-2.17	.036*	0.25

		F change	*BCa 95% CI*	R^2 change	*p - Model comparison*	Variables	*β*	*BCa 95% CI*	*t*	*p*	*Post-hoc power*
								-0.001]			
						+ Correction deviation	0.010		0.80	.429	
	Model 3	<0.01		<0.001	.963	+ Post-correction duration	<0.001		0.046	.963	0.04
	Model 4	7.55	[1.14, 19.36]	0.235	.002**	+ Motor imagery (accuracy)	-18.43	[-26.95, -9.84]	-3.88	<.001***	0.46
						+ Motor imagery (RT/s)	0.091		-0.10	.925	
						<u>Single-step reaching</u>					
Young	**Model 1**	0.10		0.002	.756	Daily mouse use	-0.045		-0.31	.756	
	Model 2	0.19		0.007	.829	+ Motor imagery (accuracy)	-0.349		-0.06	.948	0.07
						+ Motor imagery (RT/s)	-0.407		-0.55	.583	
Older	**Model 1**	4.80	[-0.004, 46.35]	0.186	.040*	Daily mouse use	1.378	[-0.32, 2.54]	2.19	.040*	
	Model 2	2.50		0.170	.109	+ Motor imagery (accuracy)	-9.552		-2.01	.059	0.35
						+ Motor imagery (RT/s)	-0.822		-0.93	.363	

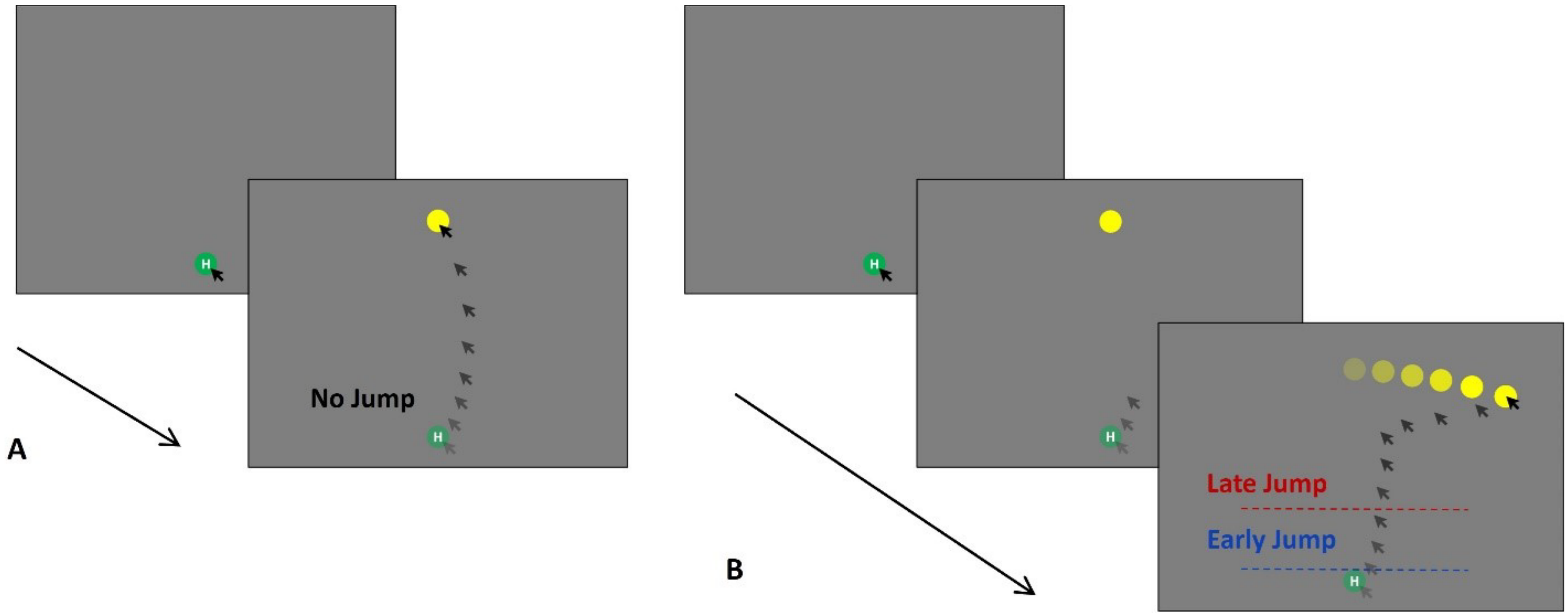


Figure 1 Computer-based reaching task: A. Single-step reaching; B. Double-step reaching with reference lines for the mouse cursor to reach to trigger early (blue) and late (red) perturbations (perturbation to the right side as an example). The reference lines and texts were not presented in the task. The yellow target trace illustrates the direction of the perturbation, which was not presented in the task either.

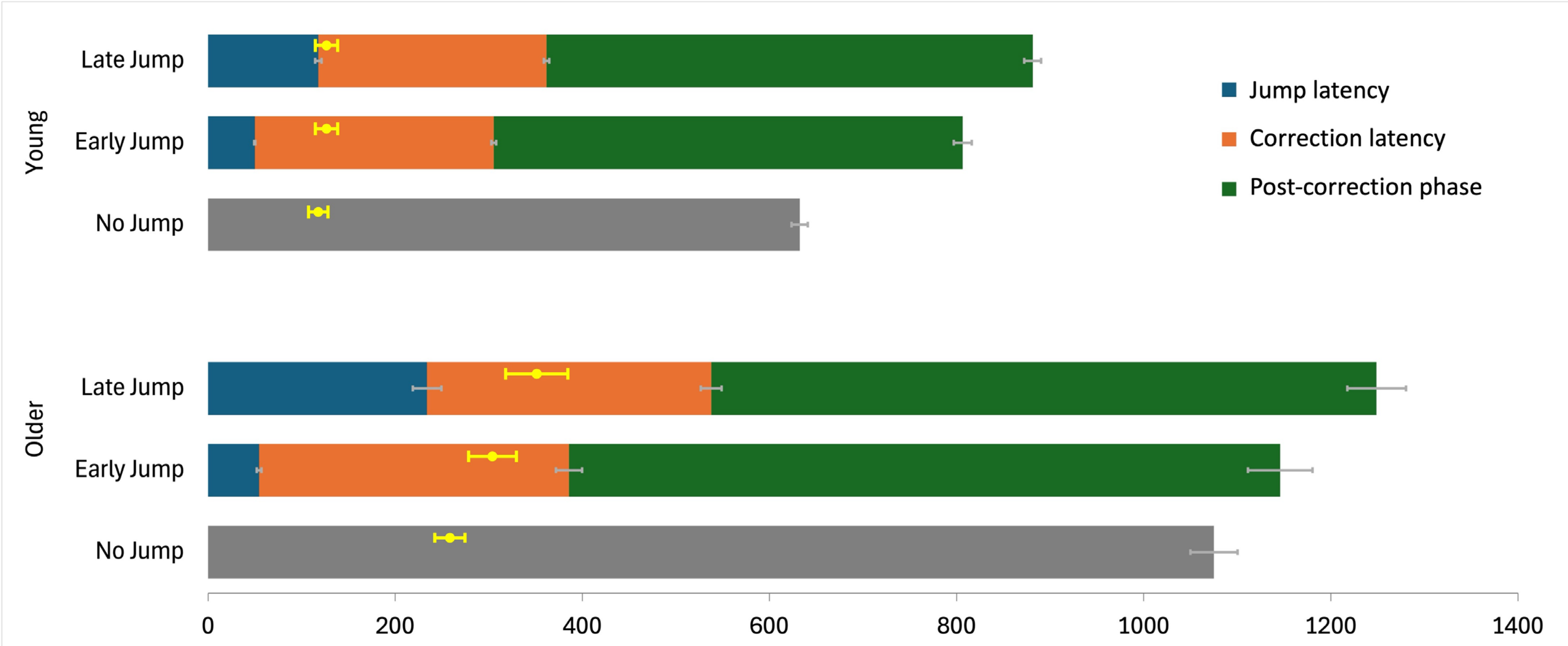


Figure 2 Young and older participants' movement duration in each reaching condition with the time of peak velocity (yellow), and a breakdown of time spent before target perturbation (jump latency; blue), from perturbation to correction (correction latency; orange) and post-correction phase (green). Error bars show standard errors.

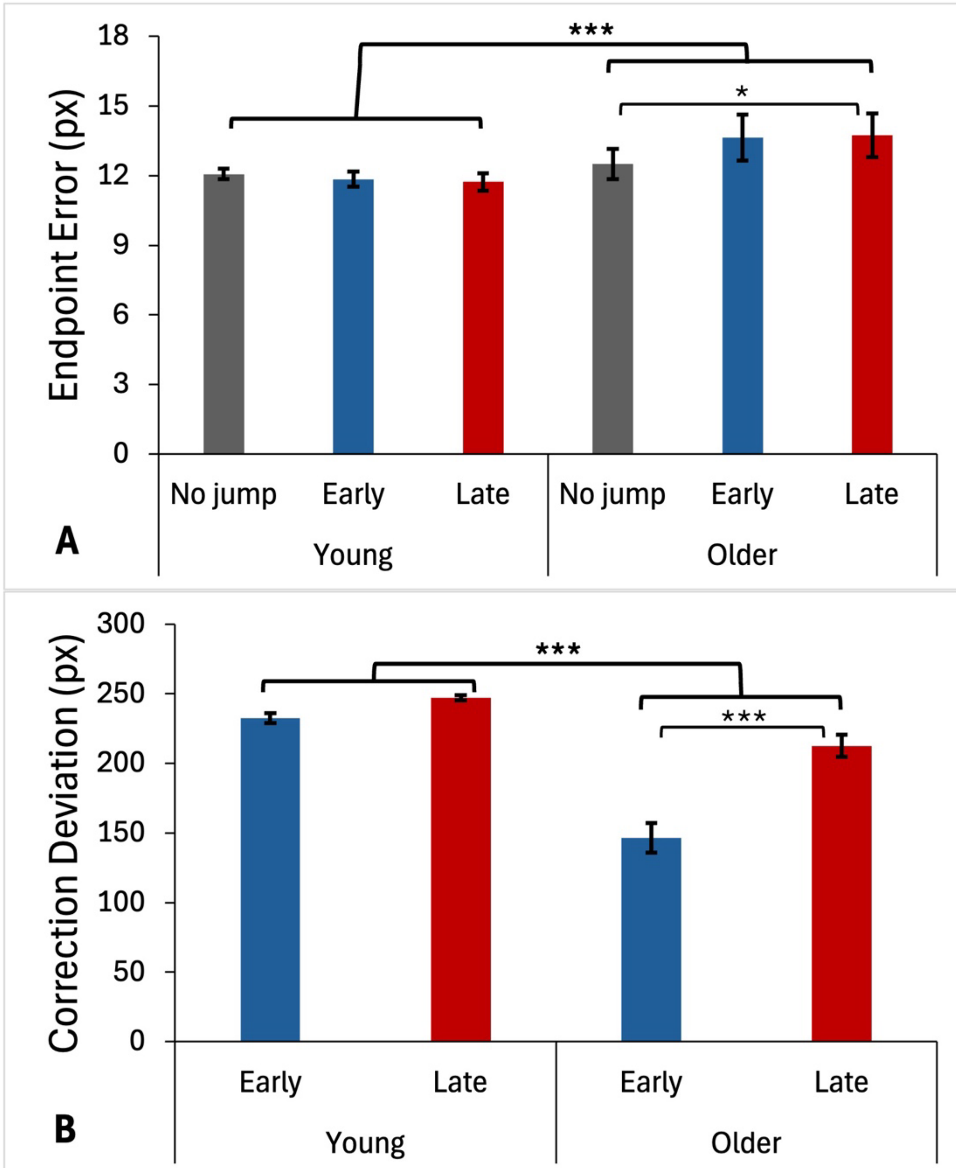


Figure 3 Mean values of A –endpoint error (px), and B – correction deviation (px) for young and older participants in each condition. Error bars show standard errors. *** for $p < .001$, ** for $p < .01$, * for $p < .05$.

1. **Daily computer mouse use**

Young participants (mean rating = 2.15, sd = 1.58) used computer mouse significantly more than older participants (mean rating = 1.33, sd = 1.01) in their daily life ($t(76) = 2.32$, $p = .023$).

2. **Motor imagery analysis and results**

Prior to analyses, data of the hand laterality task was screened to remove anticipatory (RT < 250 ms) and significantly delayed responses (RT > mean + 2.5 sd) for young and older participants separately. Eighty-one trials (4.2%) were removed from older participants, and 101 trials (2.3%) were removed from young participants. After screening, a minimum number of 12 trials (75%) per rotation angle per participant was included in the analysis.

The accuracy and RT data were entered into two separate 5 × 2 mixed ANOVAs, with Rotation (0° vs 45° vs 90° vs 135° vs 180°) being the within-subject variable and Age Group (young vs older) being the between-subject variable.

Results: A significant interaction of Rotation × Age Group was found for the accuracy of hand laterality identification, $F(2.74, 208.10) = 6.11$, $p < .001$, $\eta^2_p = .03$ (Young adults: 0° = 45° = 90° > 135° > 180°, significant *p*s < .005; Old adults: 0° = 45° = 90° = 135° > 180°, significant *p*s < .001). Significant age differences were found for 45°, 90°, 135° and 180° (all *p*s < .022).

A significant Rotation × Age Group interaction was also found for the RT, $F(2.60, 197.68) = 8.24$, $p < .001$, $\eta^2_p = .02$ (Young adults: 0° = 45° = 90° < 135° < 180°, significant *p*s < .010; Old adults: 0° = 45° = 90° < 135° = 180°, significant *p*s < .005). The age difference was not significant for each rotation (all *p*s > .661).

		0°	45°	90°	135°	180°
Accuracy	Young	96% (6%)	96% (6%)	95% (6%)	90% (9%)	82% (13%)
	Older	92% (12%)	89% (13%)	86% (15%)	86% (13%)	67% (20%)
RT (ms)	Young	1171 (341)	1212 (340)	1332 (408)	1642 (552)	2128 (597)
	Older	1385 (650)	1412 (615)	1441 (775)	1756 (781)	1873 (874)

3. **Kinematic analysis**

The computer mouse movement data was filtered using an optimised Woltring filter with a low-pass cutoff frequency of 10 Hz and analysed using tailored MATLAB routines. The displacement data were differentiated to gain the instantaneous tangential velocity at each time point of the movement. The movement onset and offset were defined as the time point at which the mouse cursor velocity surpassed and fell below 3% of the peak velocity of the movement, respectively. These time points of each trial were first detected automatically and then inspected visually.

The identification of the trajectory correction moment followed Veerman et al. (2008). We compared the movement velocity on the x-axis between a perturbed trial and the x-axis velocity averaged across all the non-perturbed trials of the same participant and computed the additional lateral velocity for each perturbed movement. The zero-crossing point extrapolated from the line connecting the 25% and the 75% of the maximum additional velocity was determined as the time point of movement correction. This method was found to be one of the most robust methods in identifying the correction moment (Holmes & Dakwar, 2015; Veerman et al., 2008).

4. Analysis of additional kinematic measures

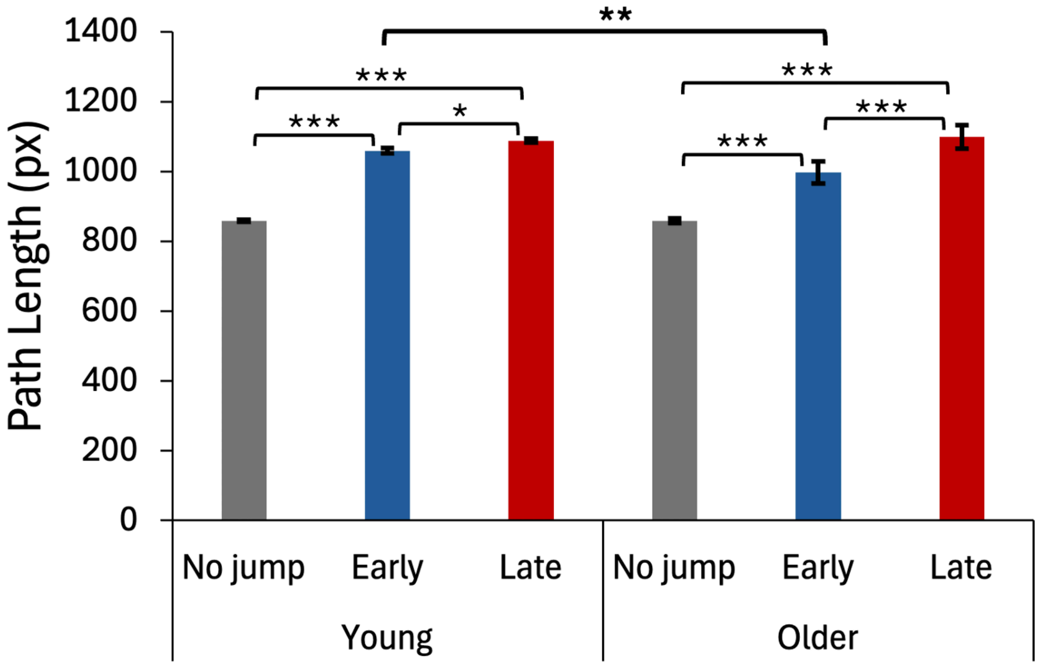
	Young			Older		
	No Jump	Early Jump	Late Jump	No Jump	Early Jump	Late Jump
Path length (px)	858 (22)	1059 (58)	1088 (41)	859 (30)	999 (150)	1099 (155)
Peak velocity (px/s)	5535 (1031)	5622 (1038)	5512 (1004)	3029 (1054)	3382 (1202)	3315 (1157)
Time to peak velocity (ms)	117 (26)	121 (39)	121 (37)	268 (104)	300 (112)	358 (177)
Jump latency (ms)		50 (5)	118 (25)		55 (12)	233 (72)

4.1. Jump latency

Jump latency (ms) refers to the time between movement onset and target perturbation onset, reflecting how fast the participants moved at the beginning of the movement. The analysis revealed that the Age Group × Jump Onset interaction was significant, $F(1, 75) = 96.61$, $p < .001$, $\eta^2_p = .56$. The effect of Jump Onset was significant for both older ($F(1, 75) = 375.32$, $p < .001$, $\eta^2_p = .83$) and young participants ($F(1, 75) = 127.80$, $p < .001$, $\eta^2_p = .63$), where early jump happened earlier than late jump. Such difference was larger for older adults (Cohen's $d = 4.10$) than for young adults (Cohen's $d = 1.58$). The Age Group difference was significant for both early ($F(1, 75) = 9.83$, $p = .002$, $\eta^2_p = .12$) and late jump ($F(1, 75) = 102.06$, $p < .001$, $\eta^2_p = .58$) that the jump latency was longer for older participants than young participants, with the difference being greater for late jump (Cohen's $d = 2.66$) than early jump (Cohen's $d = 0.14$).

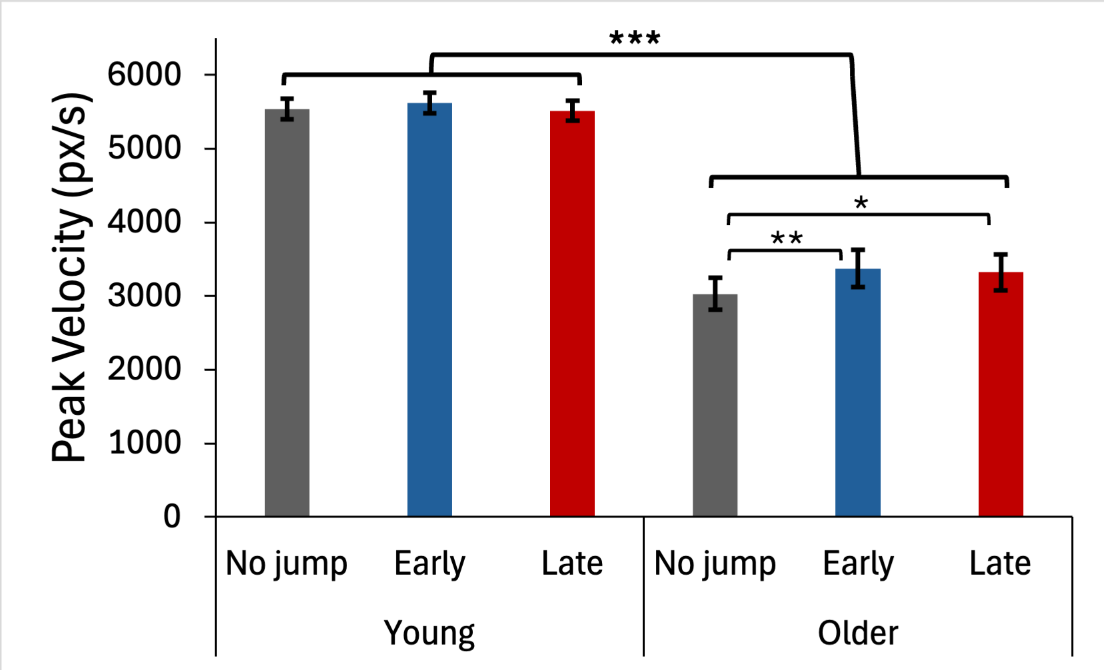
4.2. Path length

Path length (px) measures the total distance travelled by the mouse cursor, considering the trajectory and correction taken to achieve the goal of reach. The analysis revealed that *t*he Age Group × Jump Condition interaction was significant, $F(1.99, 148.93) = 5.30$, $p = .006$, $\eta^2_p = .07$. For both older and young adults, the path length was longer for the late jump than for the early jump than for no jump (older adults – late vs. early: $p < .001$, Cohen's $d = 1.10$, MD = 99.94, BCa 95% CI [8.83, 178.51]; early vs. no jump: $p < .001$, Cohen's $d = 1.62$, MD = 140.88, BCa 95% CI [95.73, 231.55]; young adults – late vs. early: $p = .038$, Cohen's $d = 0.37$, MD = 29.28, BCa 95% CI [10.30, 48.09]; early vs. no jump: $p < .001$, Cohen's $d = 2.34$, MD = 200.44, BCa 95% CI [182.82, 215.32]). A significant age difference was only found for early jump, where young people had a longer path length than older adults ($p = .01$, Cohen's $d = 0.75$, MD = 59.84, BCa 95% CI [-37.64, 104.88]).



4.3 Peak velocity

Peak velocity (px/s) refers to the maximum velocity between movement onset and offset. The analysis revealed that the Age Group × Jump Condition interaction was significant, $F(1.86, 139.81) = 3.32$, $p = .042$, $\eta^2_p = .04$ (Figure 3-A). Young participants had a greater peak velocity than older participants in all conditions (all *p*s $< .001$; no jump: Cohen's $d = 5.49$, MD = 2504.99, BCa 95% CI [1951.01, 2963.94]; early jump: Cohen's $d = 4.91$, MD = 2238.57, BCa 95% CI [1620.91, 2730.04]; late jump: Cohen's $d = 4.93$, MD = 2196.62, BCa 95% CI [1646.99, 2723.18]). A significant effect of Jump Condition was found for older participants, where a greater peak velocity was found for both early ($p < .001$, Cohen's $d = 0.77$, MD = 353.46, BCa 95% CI [271.05, 1018.79]) and late jump ($p = .028$, Cohen's $d = 0.55$, MD = 290.74, BCa 95% CI [-373.40, 871.33]) than no jump trials, but no significant difference between early and late jump (p = 1.00). Such an effect was not found for young participants (all ps > .39).



4.4 Time to peak velocity

The time to peak velocity (ms) refers to the time length from movement onset to peak velocity. The analysis revealed that the Age Group × Jump Condition interaction was significant, $F(1.50, 112.14) = 9.15$, $p < .001$, $\eta^2_p = .11$ (Figure 2). Young participants reached peak velocity earlier than older participants in all jump conditions (all ps < .001; no jump: Cohen's d = -2.04, MD = -151.06, BCa 95% CI [-111.70, -196.02]; early jump: Cohen's d = -2.42, MD = -179.37, BCa 95% CI [-132.75, -224.92]; late jump: Cohen's d = -3.12, MD = -237.27, BCa 95% CI [-171.77, -312.12]). The effect of the Jump Condition was only significant for older participants, where the peak velocity was reached earlier for no jump trials than early jump and earlier for early jump than late jump (all ps < .008; no jump vs. early: Cohen's d = -0.44, MD = -32.28, BCa 95% CI [-92.40, 29.41]; early vs. late: Cohen's d = -0.73, MD = -58.86, BCa 95% CI [-145.64, 22.88]). However, no difference was found for young participants (all ps = 1.00).

5. Comparison between the first half and the second half of the perturbation trials

To examine whether the performance was stable, we split the perturbation trials into the first half and the second half, and compared each kinematic measure between them for older and young adults' early-onset and late-onset. Paired t-tests revealed one significant difference for young adults' late-onset path length, $t(53) = 2.12$, p

= .038, 95% CI [0.94, 32.84], where first half had longer path than the second half. None of the rest *t*-tests were significant (*p*s > .06), showing the performance was relatively stable.