

Factors underlying age-related changes in discrete aiming

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Abstract Age has a clear impact on one's ability to make accurate goal-directed aiming movements. Older adults seem to plan slower and shorter-ranged initial pulses towards the target, and rely more on sensory feedback to ensure endpoint accuracy. Despite the fact that these age-related changes in manual aiming have been observed consistently, the underlying mechanism remains speculative. In an attempt to isolate four commonly suggested underlying factors, young and older adults were instructed to make discrete aiming movements under varying speed and accuracy constraints. Results showed that older adults were physically able to *produce fast primary submovements* and that they demonstrated similar *movement-programming capacities* as young adults. On the other hand, considerable evidence was found supporting a decreased *visual feedback-processing efficiency* and the implementation of a *play-it-safe strategy* in older age. In conclusion, a combination of the latter two factors seems to underlie the age-related changes in manual aiming behaviour.

Keywords Manual aiming · Motor control · Ageing · Kinematics

Introduction

According to the *multiple-process model of limb control* (Elliott et al. 2010), manual aiming movements such as pressing a light button or picking up a glass of wine consist of two consecutive phases: a primary submovement and a homing-in phase. The primary submovement corresponds to the initial pulse towards the vicinity of the target. Although this preprogrammed movement phase is traditionally associated with open-loop control (Woodworth 1899), recent work has shown that subtle movement trajectory corrections can occur during the primary submovement (Khan et al. 2006; Saunders and Knill 2003). Still, the main body of closed-loop control occurs during the homing-in phase. Here, proprioceptive and visual feedback is used to reduce any spatial discrepancy between hand and target positions (i.e., *limb-target control*). Previous research has shown that the primary submovement generally undershoots the target to allow corrections to occur in the same direction as the initial pulse (Engelbrecht et al. 2003; Helsen et al. 1998). This type of correction entails lower energy-costs than correcting for target overshoots, as reversals involve overcoming the inertia of a zero-velocity situation and the limb travelling a greater total distance (Elliott et al. 2004, 2010; Welsh et al. 2007).

By slowing down their primary submovement, older adults tend to undershoot the target to a greater extent than young controls. As a consequence, they need more time-consuming adjustments during the homing-in phase to end their aiming movement accurately onto the target. This ultimately results in greater overall movement times (Ketcham et al. 2002; Poston et al. 2009; Seidler-Dobrin and Stelmach 1998). Although these age-related movement adaptations during manual aiming have been described rather consistently, their underlying mechanism remains

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speculative. Nevertheless, several factors have already been suggested to cause the abovementioned age-related differences in manual aiming. Though often allocated different names, four factors can generally be distinguished: (1) an inability to produce fast movements, (2) an impaired programming of aiming movements, (3) a decline in visual feedback-processing efficiency, and (4) an adapted aiming strategy (Pratt et al. 1994; Walker et al. 1997).

Factor 1: Ability to produce fast primary submovements

The gradual age-related decline in muscle strength (i.e., sarcopenia) may limit older adults' ability to produce fast initial pulses towards the target (Walker et al. 1997). Slower primary submovements may compel older adults to undershoot the target to a greater extent, consequently resulting in longer homing-in phases. The traditionally observed movement adaptations in older age may thus be caused by older adults' physical inability to generate the same amount of force as young controls (Pratt et al. 1994).

Factor 2: Programming the aiming movement

Alternatively, several researchers have suggested that a reduced ability to accurately programme the movement may underlie the movement adaptations in older age (Pohl and Winstein 1998; Rey-Robert et al. 2012). Specifically, older adults are thought to have augmented levels of motor noise, thereby increasing the random, unintentional error inherent to human force production (Walker et al. 1997). This view is supported by studies reporting increased motor output variability in older age during force production tasks in general (Christou and Carlton 2001; Galganski et al. 1993), as well as during manual aiming in particular (Ketcham et al. 2002; Pratt et al. 1994). Taking into account the linear relationship between movement velocity and movement endpoint variability (Schmidt et al. 1979), a simple way to cope with increased levels of variability would be to slow down the initial pulse towards the target. As described for Factor 1, reducing the primary submovement speed could easily result in the set of movement adaptations typically observed in older adults' aiming behaviour. These movement adaptations may therefore reflect older adults' reaction to a decreased ability to accurately programme the movement.

Factor 3: Visual feedback-processing efficiency

Instead of impaired movement programming capacities, various researchers have proposed that older adults may encounter difficulties during the processing of online visual feedback (Boisseau et al. 2002; Chaput and Proteau 1996;

Coats and Wann 2011). This limitation would explain why the homing-in phase of the movement is longer in older adults. Despite the fact that visual feedback-processing efficiency is extremely difficult to quantify, basic evidence supporting this hypothesis has recently arisen. For instance, in contrast to previous work, Welsh et al. (2007) conducted a study in which young and older adults initially undershot the target to the same extent. Though both age groups exhibited a similar number of corrective submovements during the homing-in phase to accurately hit the target, older adults needed more time to complete these corrections. As there was no evidence for increased processing demands in the older adults, the authors suggested that adjusting the movement trajectory based on visual feedback takes longer in older age (Welsh et al. 2007). In addition to this kinematic evidence, Temprado et al. (2013) recently confirmed this outcome using *efficiency functions* and *Brinley plots*. In sum, a reduced efficiency in visual feedback processing may well underlie the movement alterations observed in older adults' manual aiming behaviour.

Factor 4: Aiming strategy

As older adults tend to be more cautious when performing motor tasks (Boisseau et al. 2002), the hypothesis of older adults adopting a different aiming strategy has also gained recent interest. To avoid the high energy costs associated with overshooting the target, older adults are thought to undershoot the target to a greater extent than young adults (Elliott et al. 2004, 2010; Welsh et al. 2007). Afterwards, they may rely completely on limb-target control to ensure endpoint accuracy. This prudent approach is known as the *play-it-safe* strategy believed to be adopted by older adults (Elliott et al. 2004, 2010; Welsh et al. 2007).

Finally, it should be noted that older adults might also change their aiming strategy to cope with physical limitations such as an impaired programming of the aiming movement or a less-efficient perceptual feedback processing. The age-related differences in manual aiming may thus also be caused by a combination of factors (Rey-Robert et al. 2012).

The aim of this study was to investigate which of these four commonly identified factors underlie(s) the age-related movement adaptations during manual aiming. Young and older adults therefore performed manual aiming movements under different conditions. These different aiming conditions allowed us to isolate all four factors and compare them between age groups. Based on previous work of our laboratory showing that older adults were able to achieve similar peak velocity values as young controls during fast aiming movements, we did not expect to find a difference between young and older adults in Factor 1 (Van Halewyck et al. 2014b). In line with the abovementioned

literature, however, it was expected that Factors 2, 3, and 4 would cause the movement alterations observed during manual aiming in older age.

Methods

Participants

Eleven young (mean age 22.9 years; range 19.5–25.6; six males) and twelve older (mean age 65.1 years; range 60.0–71.4; five males) volunteers participated in the study. Young adults were recruited on the university campus, whereas older adults were recruited via a local senior club. All participants were right-handed according to the Edinburgh Handedness Inventory (Oldfield 1971) and had normal or corrected-to-normal vision. Fine motor skills were considered intact, as all participants met the age- and gender-dependent criteria for the *Nine Hole Pegboard Test* (Mathiowetz et al. 1985; Oxford Grice et al. 2003). To control for mild dementia or other anomalies in cognitive functioning, older adults were exposed to a *Mini-Mental State Examination* (Folstein et al. 1975). The minimum score for inclusion was set at 28 out of 30, which all achieved. The study was approved by the Medical Ethics Committee of the KU Leuven and was conducted in

accordance with the 1964 Declaration of Helsinki. Prior to the experiment, written informed consent was obtained from all participants.

Apparatus

The apparatus was identical to the one used in previous work (see Fig. 1; Van Halewyck et al. 2014a, b). Participants sat in a comfortable chair with their preferred, right forearm in an orthosis. The axis of the orthosis was aligned with the anatomical axis of the wrist joint and positioned in a way that participants could only flex and extend their wrist in the horizontal plane. A high-precision shaft encoder with an accuracy of 0.006° and sampling frequency of 250 Hz was attached onto the orthosis. In all conditions, wrist angular position was presented as a 1.5 cm diameter circular cursor on a 60-cm computer monitor, which was located at a standardized distance of 125 cm in front of the participant at eye level. Apart from this cursor, two fixed targets also appeared on the monitor. These square targets had a width of 1 cm and stood 18 cm apart. In short, the task consisted of moving the cursor from the right target to the left, corresponding to a wrist flexion movement. In conditions in which the left target had to be entirely surrounded by the cursor, the aiming movement had an index of difficulty (ID) of 6.2 bits ($\text{ID: } \log_2[2 \times 18/(1.5 - 1)]$).



Fig. 1 Test set-up. Participants placed their right forearm into an orthosis while seated in front of a computer screen showing two fixed square targets and a round cursor. Wrist flexion and extension movements moved the cursor towards the left and right of the screen, respectively. In the CONTROL condition, participants were asked to move the cursor as fast and accurate as possible from the right (start-

ing) target towards the left target after a visual GO-stimulus. This trajectory corresponded to a 15° wrist flexion movement. Eye closure was registered with an Applied Science Laboratories (ASL) 6000 pan-tilt eye-tracker system that was positioned in front of the computer screen

The exact instructions per condition are further explained in the “[Task and protocol](#)” section.

Concurrent to the hand movement, eye closure was recorded using an Applied Science Laboratories (ASL) 6000 pan-tilt eye-tracker system (Bedford, MA) with a sampling frequency of 240 Hz. As both effectors were registered at different sampling frequencies, custom-written software was used to ensure the high-precision shaft encoder and ASL started sampling simultaneously (i.e., at the same millisecond). This allowed us to temporally link both effectors after data were collected.

Task and protocol

Participants performed blocks of ten aiming movements in three different conditions (CONTROL, ACCURACY and SPEED). In all conditions, participants were asked to start the block by positioning the cursor around the right target and to wait for the first GO-stimulus. As soon as the right target turned red (GO-stimulus), they were instructed to aim towards the left, corresponding to a wrist flexion movement. After movement completion, participants were asked to return to the right starting target to prepare for the next GO-stimulus. The interval between two consecutive GO-stimuli varied randomly between 6000, 6500, 7000, 7500, and 8000 ms to avoid movement anticipation. First, three CONTROL aiming blocks were practiced to obtain a steady aiming performance before the start of the experimental blocks. Then, a first experimental session consisting of five CONTROL aiming blocks was performed. After a 30-min break, a second experimental session started in which the order of the ACCURACY and SPEED blocks was counterbalanced.

CONTROL condition

Participants were instructed to surround the left target as fast and accurately as possible after the GO-stimulus (ID: 6.2 bits). Once the left target was entirely surrounded by the cursor, participants were asked to briefly close their eyes to indicate their movement had ended. Participants who did not adhere to these instructions (e.g., closing the eyes too early) were consistently reminded of the instructions by the experimenter. All participants performed five blocks of 10 aiming movements, resulting in 50 aiming movements per participant.

ACCURACY condition

Similar to the CONTROL condition, participants were instructed to surround the left target as fast and accurate as possible with the cursor after the GO-stimulus (ID: 6.2 bits). Participants were told that the time between the GO-stimulus

and the end of the aiming movement would be accumulated over all ACCURACY condition movements. Both the young and older participants who needed the least amount of total time would receive a €25 gift voucher. However, participants were also told that primary submovements overshooting the target, as well as endpoint inaccuracy, would be penalized with an additional 2000 ms. Thus although participants were motivated to move quickly, the emphasis was shifted towards endpoint accuracy with a particular concentration on the avoidance of target overshoots. Again, participants performed five blocks of 10 aiming movements, resulting in 50 aiming movements in this condition.

SPEED condition

In contrast to the CONTROL and ACCURACY conditions, the task’s accuracy demands were eliminated in the SPEED condition: Participants now reacted to the GO-stimulus by making identical, ballistic aiming movements *beyond* the left target. The experimenter repeatedly emphasized that participants should try to move as fast as possible here and that they should pay no attention to endpoint accuracy. To prevent fatigue, only three SPEED condition blocks were performed resulting in 30 aiming movements per participant.

Factor isolation

A first-order low-pass Butterworth filter with a cut-off frequency of 20 Hz was applied on all hand movement data. Afterwards, the filtered data were differentiated twice to obtain instantaneous hand velocity and acceleration profiles of all aiming movements (see Fig. 2). Then, the four reported factors were isolated as described below (cf. Walker et al. 1997).

Factor 1: Ability to produce fast primary submovements

Potential age-related declines in the ability to produce fast primary submovements were examined via peak velocity values (highest value in the velocity profile) in the SPEED condition (Walker et al. 1997). For this variable, we disregarded conditions that required accuracy constraints as age-related slowing could be caused here by specific aiming strategies rather than a physical limitation. If older adults would be unable to produce the same level of primary submovement speed as young controls, an age-related decline in muscle strength (i.e., sarcopenia) could be a mechanism underlying the movement adaptations traditionally observed in older age.

Factor 2: Programming the aiming movement

In line with the study of Welsh et al. (2007), potential age-related difficulties to programme consistent actions were

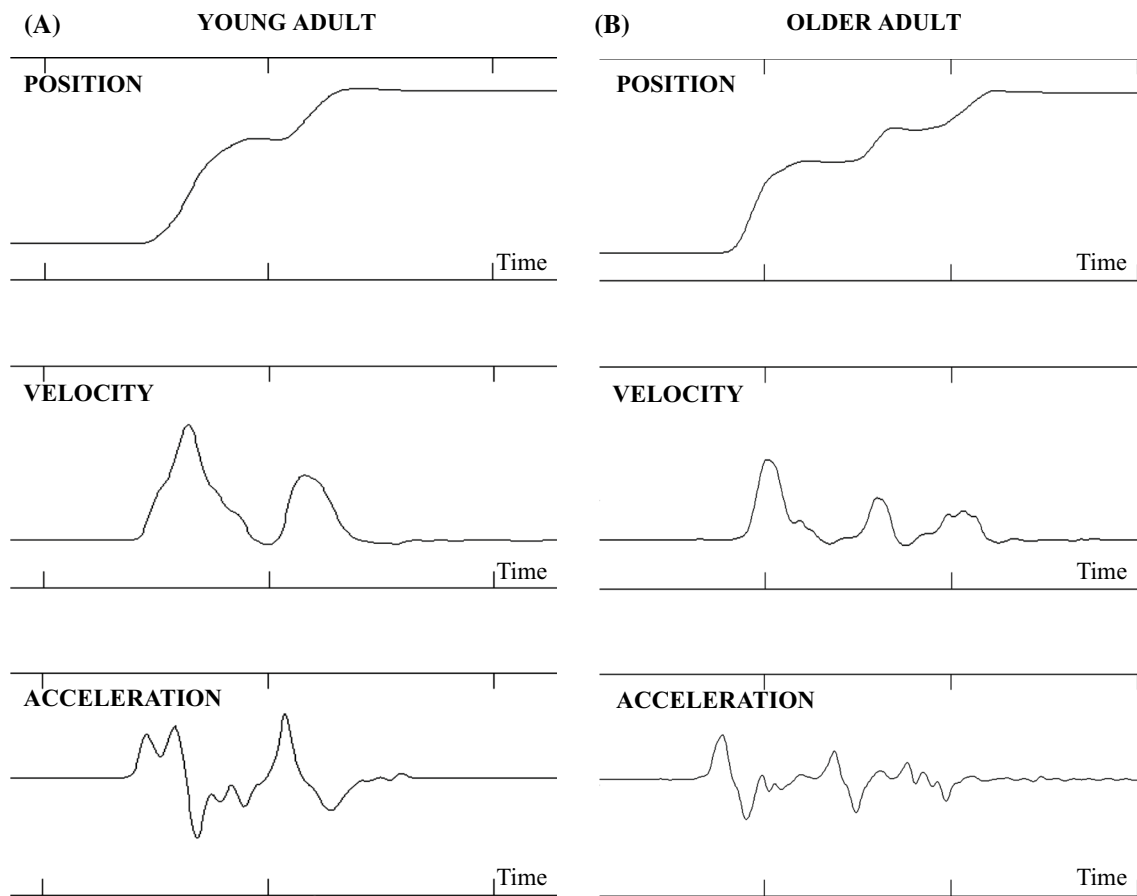


Fig. 2 Hand movement kinematics. Examples of typical position, velocity, and acceleration profiles of the aiming movements of **a** a young and **b** an older adult in the CONTROL condition. Young adults typically undershot the target with their primary submovement. As a result, they generally needed only a few small corrections to end their aiming movement accurately onto the target. Older adults, on the

other hand, tended to slow down their primary submovement, thereby undershooting the target to a greater extent. To obtain endpoint accuracy, they consequently needed more time-consuming corrections during the homing-in phase of the movement, which ultimately led to longer overall movement times

examined by comparing the temporal and spatial variability at four kinematic markers. This was done by first calculating the absolute time participants needed between the start the movement (first sample when the standard deviation of the hand velocity profile was inferior to 0.75 mm/s for 80 ms from peak velocity backwards), and reaching peak acceleration (highest value in the acceleration profile), peak velocity, peak deceleration (lowest value in the acceleration profile), and the end of the movement (first sample when the standard deviation of the hand velocity profile was inferior to 0.75 mm/s for 80 ms from peak velocity onwards) in all SPEED condition aiming movements. Then, the standard deviation of these kinematic events was calculated per block and used as an indicator of temporal variability. A similar procedure involving the absolute positions in the primary direction of the movement at the kinematic markers was used to determine the spatial variability per block. Again, we limited our analysis to the SPEED condition

to rule out potential strategy differences between young and older adults. Also, as participants were instructed to make *identical* ballistic movements, all participants strived towards the lowest possible temporal and spatial movement variability in this condition. Thus, if older adults were to show greater temporal and/or spatial variability of kinematic markers than younger adults, this would indicate age-related difficulties associated with accurately programming the aiming movement.

Factor 3: Visual feedback-processing efficiency

Visual feedback-processing ability is extremely difficult to disentangle from movement execution abilities in behavioural experiments. Nevertheless, Walker et al. (1997) attempted to isolate the visual component by asking participants to release a pressed button in order to indicate their aiming movement had ended. They considered the time

between the end of the aiming movement and the release of the button a basic indicator for the processing speed of visual feedback. Though still not perfect, this approach may provide the best behavioural method for comparing the processing speed of visual feedback between groups. Instead of focusing on a distal motor component such as the finger muscles, it may nevertheless be more appropriate to involve a more proximal motor component to minimize conduction time (Boisgontier et al. 2014; Kimura 2001). As described in the “Task and protocol” section, participants were therefore asked to briefly close their eyes in the CONTROL condition to indicate the cursor accurately surrounded the target and the aiming movement had ended. Based on the original study of Walker et al. (1997), the time between the end of the hand movement and the closure of the eyes was considered the *verification time* of the movement. Though this verification time still contains a minimal motor component associated with the eyelids, its duration is clearly dominated by visual feedback processing. If older adults demonstrate longer verification times, this was considered to reflect an age-related slowing in visual feedback processing.

Factor 4: Aiming strategy

To investigate age-related differences in aiming strategy, an ACCURACY condition was added to the experiment. As described in the “Task and protocol” section, inaccurate movement endpoints and primary submovements overshooting the target were penalized in this condition. Age-related differences in aiming strategy would be supported by two specific outcomes. On the one hand, if older adults adopt a play-it-safe strategy to ensure endpoint accuracy and prevent target overshoots in the CONTROL condition, the ACCURACY condition instructions should have a minimal effect on their aiming kinematics. On the other hand, if the ACCURACY condition results in young adults demonstrating aiming characteristics traditionally described in older adults, these movement adaptations might be viewed as a more universal strategy used to ensure endpoint accuracy and prevent target overshoots. Besides endpoint accuracy, we therefore compared the five variables that are

traditionally altered in older adults’ aiming movements (i.e., peak velocity, relative distance of the primary submovement, relative duration of the homing-in phase, number of corrective submovements, and overall movement time) between the CONTROL and ACCURACY conditions. The end of the primary submovement was assessed using the criterion of Khan et al. (1998), whereas the number of corrections was calculated as described by Ketcham et al. (2002). If young adults change their aiming kinematics significantly in the direction of older adults, and if older adults in turn keep these variables unchanged between conditions, our findings would be consistent with a play-it-safe strategy in older adults.

Data analysis

First, the mean score and standard deviation were calculated per block for all dependent variables. Then, Factors 1–3 were compared between the two age groups using independent *t* tests. For Factor 4, however, a dependent *t* test was used to compare the variables of interest between the CONTROL and ACCURACY conditions separately for each age group. In other words, we determined whether young and older adults changed their aiming behaviour going from the CONTROL to the ACCURACY condition. The significance level in all tests was set at $p < .05$. Results are displayed as group mean score \pm standard error of the mean (SEM).

Results

To highlight the validity of our test set-up, we start our *Results* section with some notable group differences in the CONTROL condition. As expected, all five movement adaptations traditionally described in older age were observed in older participants: lower peak velocities, shorter-ranged primary submovements, relatively greater homing-in phase durations, more corrective submovements, and greater overall movement times [all $t(21) > 2.84$; all $p < .01$; see Table 1].

Table 1 Traditional age-related differences in aiming kinematics in the CONTROL condition

Parameter	Unit	Young	Older	<i>P</i> value
Peak velocity	cm/s	83.9 \pm 8.6	65.9 \pm 7.8	<.01
Relative distance primary submovement	% Target distance	72.5 \pm 4.1	61.0 \pm 4.4	<.01
Relative duration homing-in phase	% Movement time	63.0 \pm 3.6	68.0 \pm 3.1	<.01
Number of corrective submovements	/	2.3 \pm 0.3	2.8 \pm 0.3	<.01
Overall movement time	ms	892 \pm 62	1074 \pm 65	<.01

Results are presented as mean \pm SEM. All five expected differences between age groups were observed in the CONTROL condition. Adapted from Van Halewyck et al. (2014a). Copyright 2014 by Elsevier

Factor 1: Ability to produce fast primary submovements

In contrast to the CONTROL condition, older adults (311.6 ± 26.2 cm/s) did not move significantly slower than young adults in the SPEED condition [321.9 ± 27.0 cm/s; $t(21) = 0.10$; $p = .93$; see Fig. 3].

Factor 2: Programming the aiming movement

Participants adhered well to the SPEED condition instructions, as the target was overshoot in 95.7 % of the SPEED condition movements. As displayed in Fig. 4a, temporal variability in the SPEED condition was comparable between groups at all kinematic markers [all $t(21) < 1.32$; all $p > .18$]. Similarly, no significant differences were observed for spatial variability [all $t(21) < 1.97$; all $p > .05$; see Fig. 4b].

Factor 3: Visual feedback-processing efficiency

In the CONTROL condition, significantly greater verification times were detected in older (498 ± 81 ms) compared to young adults [297 ± 45 ms; $t(21) = 5.30$; $p < .01$; see Fig. 5].

Factor 4: Aiming strategy

Endpoint accuracy

Before focusing on the five specific variables of interest, we should highlight that only young adults increased their percentage of aiming movements resulting in target hits in the ACCURACY condition (94.4 ± 2.7 %) as compared to the CONTROL condition [91.1 ± 3.5 %; $t(10) = 2.41$; $p < .05$]. In contrast, older adults did not change endpoint

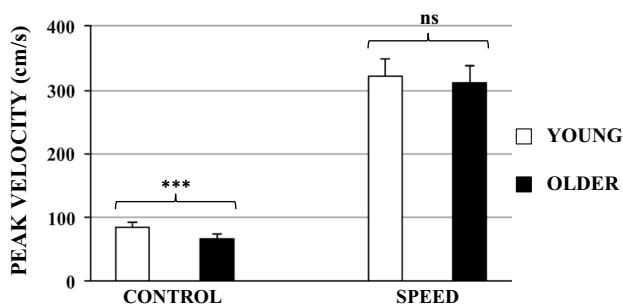


Fig. 3 Factor 1: Ability to produce fast primary submovements. Comparison of mean peak velocities in the SPEED condition. CONTROL condition data are also displayed for the sake of completeness. Group scores are presented as mean \pm SEM. Significant group differences are highlighted by *** (if $p < .01$), nonsignificant group differences by ns (if $p > .05$)

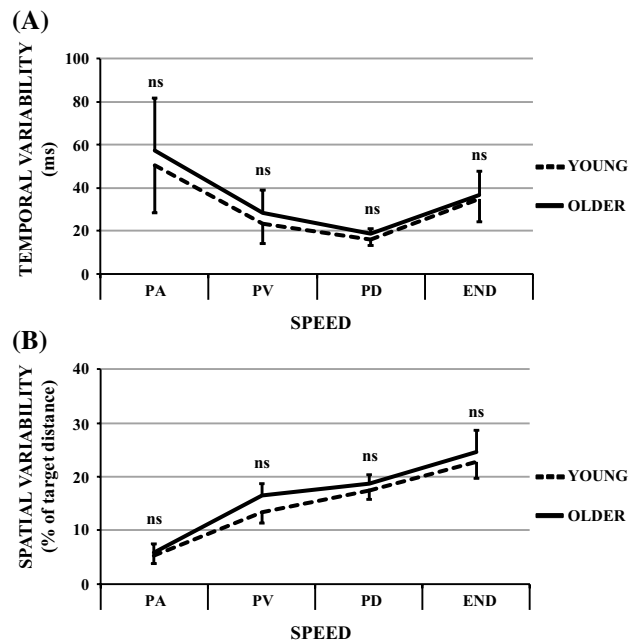


Fig. 4 Factor 2: Programming the aiming movement. Comparison of a temporal and b spatial variability at four kinematic markers in the SPEED condition. PA Peak acceleration, PV peak velocity, PD peak deceleration, END end of aiming movement. Nonsignificant group differences are highlighted by ns (if $p > .05$)

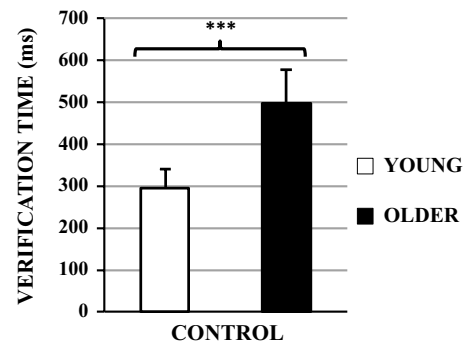


Fig. 5 Factor 3: Visual feedback-processing efficiency. Comparison of the mean verification time in the CONTROL condition. Group scores are presented as mean \pm SEM. Significant group differences are highlighted by *** (if $p < .01$)

accuracy between conditions [going from 85.4 ± 3.7 in the CONTROL condition to 86.4 ± 4.5 in the ACCURACY condition; $t(11) = 0.38$; $p = .71$; see Fig. 6a].

Peak velocity

Compared to the CONTROL condition (83.9 ± 8.6 cm/s), young adults tended to speed up their initial pulse towards the target in the ACCURACY condition [92.4 ± 8.9 cm/s; $t(10) = 1.80$; $p = .06$]. Older adults, on the other hand,

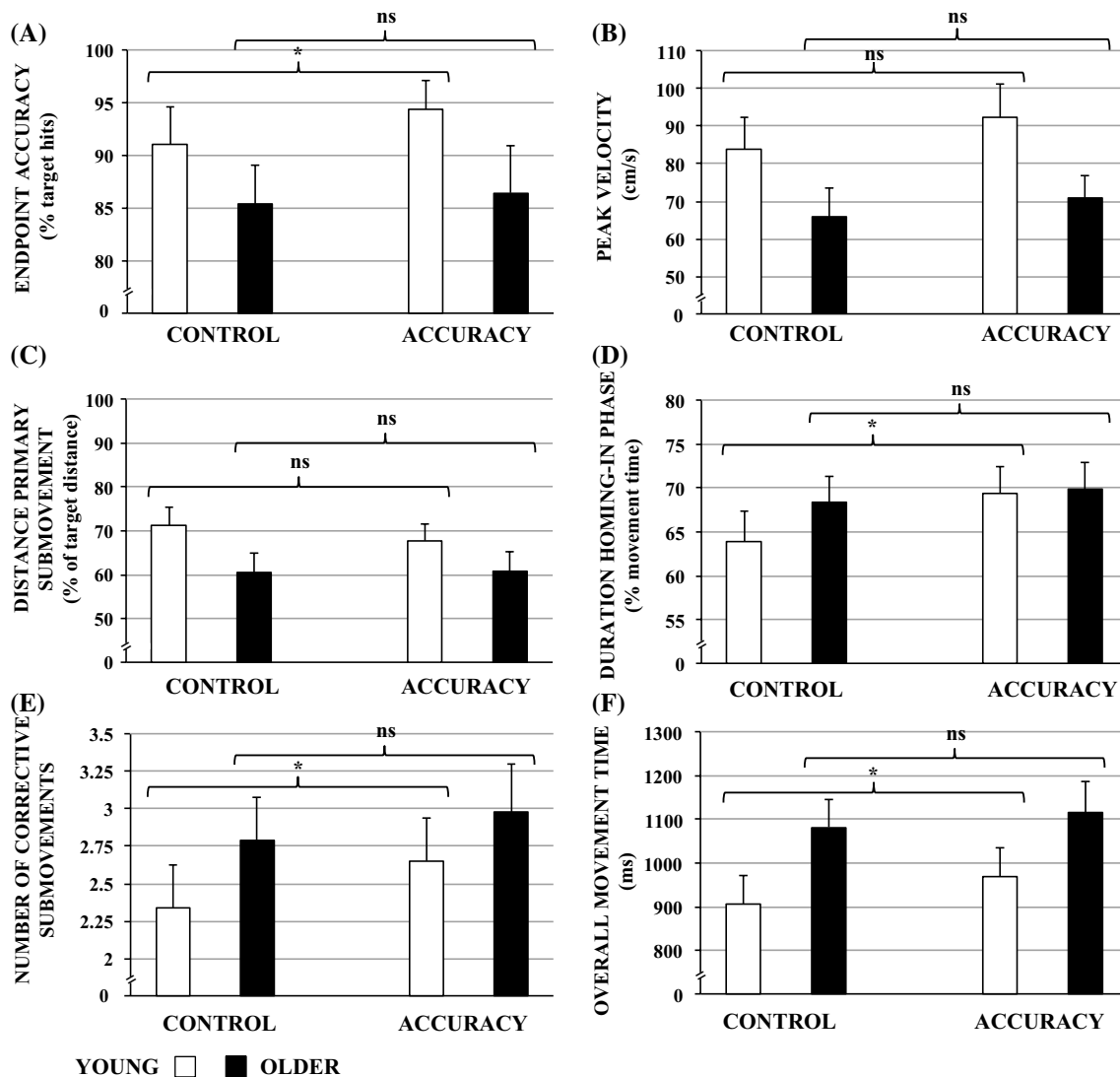


Fig. 6 Factor 4: Aiming strategy. Comparison of **a** endpoint accuracy, **b** peak velocity, **c** relative distance of the primary submovement, **d** relative duration of the homing-in phase, **e** number of corrective submovements, and **f** overall movement time between conditions to

investigate the play-it-safe strategy. Significant group differences are highlighted by *** (if $p < .01$) or * (if $p < .05$), nonsignificant group differences by *ns* (if $p > .05$)

demonstrated similar peak velocity values [65.9 ± 7.8 cm/s in the CONTROL condition and 70.9 ± 6.1 cm/s in the ACCURACY condition; $t(11) = 1.15$; $p = .37$; see Fig. 6b].

Relative distance of primary submovement

Young adults also tended to undershoot the target to a slightly greater extent in the ACCURACY condition (67.7 ± 3.8 % of target distance) compared to the CONTROL condition [71.3 ± 4.1 % of target distance; $t(10) = 1.76$; $p = .08$]. Older adults, on the other hand, did not shorten their primary submovement in the ACCURACY condition [61.0 ± 4.4 % of target distance in the CONTROL condition and 60.8 ± 4.5 % of target distance

in the ACCURACY condition; $t(11) = 0.11$; $p = .95$; see Fig. 6c].

Relative duration of the homing-in phase

Young adults spent proportionally more time on the homing-in phase during ACCURACY condition aiming movements (69.4 ± 3.0 % of the movement time) compared to CONTROL condition aiming movements [63.9 ± 3.5 % of the movement time; $t(10) = 3.86$; $p < .01$]. Again, older adults did not adapt their aiming movements in this respect [68.0 ± 3.1 of the movement time in the CONTROL condition and 69.5 ± 3.0 of the movement time in the ACCURACY condition; $t(11) = 1.25$; $p = .21$; see Fig. 6d].

Number of corrective submovements

Compared to the CONTROL condition (2.3 ± 0.3), young adults significantly increased their number of corrective submovements during the ACCURACY condition [2.7 ± 0.3 ; $t(10) = 2.54$; $p < .05$]. In contrast, the older adults did not change their number of corrections in the hand movement trajectory [2.8 ± 0.3 in the CONTROL condition and 3.0 ± 0.3 in the ACCURACY condition; $t(11) = 1.25$; $p = .22$; see Fig. 6e].

Overall movement time

Young adults significantly increased their movement times going from the CONTROL condition (906 ± 64 ms) to the ACCURACY condition [969 ± 66 ms; $t(10) = 1.98$; $p < .05$]. Again, the difference in older adults' movement times did not reach the level of significance [1081 ± 65 ms in the CONTROL condition and 1116 ± 71 ms in the ACCURACY condition; $t(11) = 0.81$; $p = .41$; see Fig. 6f].

Discussion

The aim of this study was to determine the mechanism(s) underlying the movement adaptations traditionally observed in older adults' aiming behaviour. Four commonly suggested factors were isolated in different aiming conditions and compared between age groups. After discussing the observations for each factor separately, a general conclusion is provided.

Factor 1: Ability to produce fast primary submovements

Older adults generally make slower and shorter-ranged primary submovements compared to young adults, suggesting they may encounter difficulties generating fast initial pulses towards the target (Pratt et al. 1994). Though we did not look specifically into participants' maximal force levels, results from the SPEED condition suggest that an age-related degradation in force generation capacity (i.e., sarcopenia) is not the limiting factor during goal-directed aiming movements. Without accuracy constraints, older adults demonstrated similar primary submovement speeds as young controls (see Fig. 3). The age-related differences in movement speed that were observed in the CONTROL condition must therefore be caused by factors other than an age-related physical limitation to produce fast primary submovements. Instead, Fig. 3 suggests older adults may intentionally slow down the primary submovement to a greater extent during CONTROL condition movements in order to deal with the imposed accuracy constraints. Age-related

strategy differences to cope with the speed–accuracy trade-off are discussed in greater detail when interpreting the results associated with Factor 4.

Factor 2: Programming the aiming movement

We also investigated whether movement programming capacities are degraded in older age by looking into the movement trajectory's consistency during SPEED condition movements. As is evident in Figs. 2a, b, similar levels of temporal and spatial variability were observed at all kinematic markers. These outcomes suggest that movement-planning capacities do not deteriorate with age.¹

At first glance, this result seems to be contradicted by several studies reporting greater levels of movement variability in older adults (Ketcham et al. 2002; Pratt et al. 1994). There are, however, several possible explanations for this dissimilarity in results. For instance, in contrast to the current study, the work of Ketcham et al. (2002) used varying target sizes and amplitudes that may have affected variability levels. Also, instead of focusing on

¹ Since this result was rather unexpected, two complementary analyses were performed to control the outcome. First, we investigated whether older adults demonstrated longer reaction times to programme their movements more accurately. SPEED condition data showed that older adults indeed used more time between the GO-stimulus and movement initiation (359 ± 25 ms) compared to young adults [259 ± 19 ms; $t(21) = 3.20$; $p < .01$]. However, this difference corresponded to the well-documented changes in simple reaction time with age (e.g., Poston et al. 2009; Yan et al. 1998; see Hinder et al. 2012 for a physiological explanation for longer reaction times in older age), which was also observed in the CONTROL condition [older adults: 427 ± 23 ms, young adults: 333 ± 18 ms; $t(21) = 3.13$; $p < .01$]. All in all, these outcomes were therefore seen as evidence that older adults did not deliberately prolong their reaction times in the SPEED condition to programme the aiming movements more accurately.

Second, a *coefficient of determination* (R^2) analysis was performed to control whether SPEED condition movements were indeed based primarily on programming processes (Heath 2005; Khan et al. 2006; Messier and Kalaska 1999). In short, such analysis examines the proportion of movement endpoint variability that can be explained by the limb position at different kinematic markers. The rationale behind this regression technique is the following: in case of aiming movements purely based on planning processes, one should be able to predict the movement endpoint based on (early) kinematic marker positions, as no corrections occur late in the movement. Accurate predictions are reflected by high R^2 values. On the other hand, if aiming movements are strongly modified based on online feedback during the homing-in phase, movement endpoints are more difficult to predict from (early) kinematic marker positions. These types of movements are typically associated with low R^2 values. Results of this additional R^2 analysis showed that the percentage of explained endpoint variance in the SPEED condition exceeded 94.0 % in both groups when movement endpoints were estimated based on the peak velocity position, whereas this value exceeded 99.0 % when the estimation was based on peak deceleration position. This analysis thus confirms that SPEED condition aiming movements were primarily based on movement-planning capacities, as originally intended.

the entire movement trajectory, other variability analyses (e.g., Ketcham et al. 2002; Pratt et al. 1994) were limited to two kinematic markers late in the movement (i.e., end of the primary submovement and end of the movement) in aiming conditions with high-accuracy constraints. For this reason, greater variability levels in older adults may well represent other factors than an age-related deterioration in movement-planning capacities. To our knowledge, the only other ageing study to perform a more comprehensive variability analysis was the previously mentioned investigation of Welsh et al. (2007). In line with our current results, they too found equal variability levels at the same kinematic markers among young and older adults. However, they focused on aiming movements with high-accuracy constraints, analogous to our CONTROL and ACCURACY conditions. For the sake of completeness, we should therefore note that—in general—comparable results were observed in our CONTROL and ACCURACY conditions as well. However, they are not discussed in detail since strategy differences were hypothesized to emerge here (see Factor 4). All in all, we can conclude that movement-planning capacities remain intact in older age.

Factor 3: Visual feedback-processing efficiency

As explained in the “Factor isolation” section, it is particularly difficult to determine visual feedback-processing efficiency. However, based on previous work (Walker et al. 1997), we considered the time span between the end of the hand movement and the closure of the eyes (i.e., *verification time*) a basic indicator for visual feedback-processing speed. Since older adults demonstrated significantly greater verification times (see Fig. 5), our results provide limited evidence for slower visual feedback processing in older age. This finding is supported by several studies reporting older adults generally need more time than young controls to process the same amount of visual information (Coats and Wann 2011; Temprado et al. 2013; Welsh et al. 2007). Also, when the amount of visual information to be processed is increased by, for instance, presenting additional information (Boisseau et al. 2002) or increasing the number of choices in a multiple-choice task (Falkenstein et al. 2006; Yordanova et al. 2004), older adults have been shown to prolong their reaction and movement times relative to young adults. Similar outcomes have been reported for proprioceptive feedback processing in older adults (Boisgontier et al. 2012; Boisgontier and Nougier 2013). All in all, these studies thus seem consistent with our conclusion that an age-related decrease in visual feedback-processing efficiency may underlie the movement alterations traditionally observed in older adults.

Factor 4: Aiming strategy

Finally, we examined whether age-related changes in aiming strategy could also provide an explanation for movement alterations in older age. In short, older adults are thought to adopt a *play-it-safe* strategy by undershooting the target to a greater extent, and relying more on limb-target control during the homing-in phase (Elliott et al. 2010; Welsh et al. 2007). This cautious approach is believed to prevent the high energy costs associated with target overshoots and may help ensure high levels of endpoint accuracy. To reveal potential strategy differences between both age groups, an ACCURACY condition was added to the experiment. Here, participants were financially rewarded for ending all aiming movements accurately onto the target without overshooting it initially. Our expectations regarding the ACCURACY condition were largely confirmed.

Firstly, on the variables of interest, older adults did not exhibit any difference in performance between the CONTROL and ACCURACY conditions. This result seems to suggest they already emphasized endpoint accuracy and the prevention of target overshoots under normal aiming circumstances (i.e., CONTROL condition). Alternatively, it could also reflect the fact that older adults are less able to adapt their aiming movements to specific instructions or contexts (see Pratt et al. 1994; Seidler-Dobrin and Stelmach 1998). However, this potential limitation does not seem applicable to our task, as older adults were clearly able to change their aiming characteristics in response to our SPEED condition instructions (see Fig. 3).

Secondly, when comparing the CONTROL to the ACCURACY condition data in young adults, three of the five variables of interest changed significantly towards the pattern typically seen in older adults (i.e., relative duration of the homing-in phase, number of corrective submovements, and overall movement time; all $p < .05$; see Fig. 6d–f). Moreover, an interesting trend towards conventional levels of significance was observed for a fourth variable (relative distance of the primary submovement; $p = .08$; see Fig. 6c). Making these movement adjustments resulted in an increased percentage of target hits (see Fig. 6a). Thus, these modifications to the movement trajectory seem to reflect an effective approach to ensure endpoint accuracy. The only variable not to meet the expected outcome was peak velocity (see Fig. 6b). The finding that only young adults were able to increase the maximum speed of their initial pulse and yet demonstrate higher levels of endpoint accuracy suggests that in the ACCURACY condition, they adopted a strategy of moving to the target area quickly so that they had more real and proportional time to use visual feedback during the homing-in phase of their movement. This explanation is consistent with other work involving young adults (e.g., Hansen et al. 2006).

All in all, because most variables met the expected outcome, the overall picture provides evidence for older adults adopting a play-it-safe strategy under natural circumstances.²

General conclusion

In sum, results of the SPEED condition showed that older adults were physically able to move as fast as young controls. The movement slowing typically observed in older adults thus appears to be caused by factors other than the *physical inability to produce fast primary submovements* (Factor 1). Also in the SPEED condition, the absence of age-related differences in temporal and spatial variability suggest that older adults' *movement programming capacities* remain intact as well (Factor 2). Instead, the traditional aiming movement adaptations in older age appeared to be caused by two other key mechanisms. On the one hand, older adults showed greater verification times. This outcome suggests *less-efficient visual feedback processing* in older age (Factor 3) and is strongly supported by the recent literature (Boisgontier et al. 2012; Boisseau et al. 2002; Falkenstein et al. 2006; Temprado et al. 2013; Welsh et al. 2007; Yordanova et al. 2004). On the other hand, evidence was found for older adults adopting a *play-it-safe strategy* during manual aiming (Factor 4; Elliott et al. 2010; Welsh et al. 2007). Compared to the CONTROL condition, older participants' aiming characteristics stayed relatively unchanged in the ACCURACY condition, whereas the movements of young adults shifted to resemble those of older adults. The former suggests that older adults already emphasized endpoint accuracy and the prevention of target overshoots in the CONTROL

condition; the latter seems to imply that this approach is indeed an effective strategy to end aiming movements accurately. In summary, the movement adaptations traditionally observed in older age thus appear to reflect less-efficient visual feedback processing in combination with a play-it-safe strategy.

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² Again, two complementary analyses were performed to control these outcomes. First, we investigated whether the traditional age-related changes in movement kinematics were still apparent in the ACCURACY condition. Results showed that the relative duration of the homing-in phase and the number of corrective submovements did no longer significantly differ between young and older adults [both $t(21) < 1.40$; both $p > .09$], thereby supporting the notion that young changed their aiming kinematics towards those of older adults in the ACCURACY condition. Second, to further investigate the aspect of slowing in older adults, we calculated the mean peak velocity values of all CONTROL condition aiming blocks relative to the participant's highest peak velocity value in the SPEED condition. The rationale was that if older adults slow down their aiming movements to a greater extent than young adults, they should systematically demonstrate lower *relative* peak velocity values. In contrast to absolute peak velocity values, such analysis takes into account personal capacities as well. Results showed that under natural circumstances, older adults ($14.1 \pm 2.2\%$) indeed aimed at a lower percentage of their maximal movement speed compared to young adults [$21.4 \pm 3.0\%$; $t(21) = 3.40$; $p < .01$], thereby further supporting the play-it-safe strategy in older age.

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