Title:

Factors Underlying Age-related Changes in Discrete Aiming

Author names and affiliations:

Florian Van Halewyck[1], Ann Lavrysen[1], Oron Levin[1], Matthieu P. Boisgontier[1], Digby Elliott[2], Werner F. Helsen[1]

[1] KU Leuven, Department of Kinesiology, Movement Control and Neuroplasticity Research Group, Tervuursevest 101, 3001 Leuven - Belgium

[2] Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Tom Reilly Building, Byrom Street, L3 3AF Liverpool - United Kingdom

Corresponding author:

      Prof. Dr. Werner Helsen

      E-mail: werner.helsen@faber.kuleuven.be

      Telephone: +32-16-32.90.68

      Fax: +32-16-32.91.97

1   **Abstract**

2   Age has a clear impact on one's ability to make accurate goal-directed aiming movements. Older adults

3   seem to plan slower and shorter-ranged initial pulses towards the target, and rely more on sensory feedback

4   to ensure endpoint accuracy. Despite the fact that these age-related changes in manual aiming have been

5   observed consistently, the underlying mechanism remains speculative to date. In an attempt to isolate four

6   commonly suggested underlying factors, young and older adults were instructed to make discrete aiming

7   movements under varying speed and accuracy constraints. Results showed that older adults were physically

8   able to *produce fast primary submovements*, and that they demonstrated similar *movement-planning*

9   *capacities* as young adults. On the other hand, considerable evidence was found supporting a decreased

10   *sensory feedback-processing efficiency* and the implementation of a *play-it-safe strategy* in old age. In

11   conclusion, a combination of the latter two factors seems to underlie the age-related changes in manual

12   aiming behavior.

13

14   **Keywords:** Manual aiming, Motor Control, Aging, Kinematics

| 1 | **Factors Underlying Age-related Changes in Discrete Aiming** |

2   According to the *multiple-process model of limb control* (Elliott et al. 2010), manual aiming

3   movements such as pressing a light button or picking up a glass of wine consist of two consecutive phases:

4   a primary submovement and a homing-in phase. The primary submovement corresponds to the initial pulse

5   towards the vicinity of the target. Although this pre-programmed movement phase is traditionally

6   associated with open-loop control (Woodworth 1899), recent work has shown that subtle movement

7   trajectory corrections can occur during the primary submovement (Khan et al. 2006; Saunders and Knill

8   2003). Still, the main body of closed-loop control occurs during the homing-in phase. Here, proprioceptive

9   and visual feedback is used to reduce any spatial discrepancy between hand and target positions (i.e., *limb-*

10   *target control*). Previous research has shown that the primary submovement generally undershoots the

11   target to allow corrections to occur in the same direction as the initial pulse (Engelbrecht et al. 2003;

12   Helsen et al. 1998). This type of correction entails lower energy-costs than correcting for target overshoots,

13   as reversals involve overcoming the inertia of a zero-velocity situation and the limb traveling a greater total

14   distance (Elliott et al. 2004; Elliott et al. 2010; Welsh et al. 2007).

15   By slowing down their primary submovement, older adults tend to undershoot the target to a

16   greater extent than young controls. As a consequence, they need more time-consuming adjustments during

17   the homing-in phase to end their aiming movement accurately onto the target. This ultimately results in

18   greater overall movement times (Ketcham et al. 2002; Poston et al. 2009). Although these age-related

19   movement adaptations during manual aiming have been described rather consistently, their underlying

20   mechanism remains speculative. Nevertheless, several factors have already been suggested to cause the

21   abovementioned age-related differences in manual aiming. Though often allocated different names, four

22   factors can generally be distinguished: (1) an inability to produce fast movements, (2) an impaired

23   programming of aiming movements, (3) a decline in sensory feedback-processing efficiency, and (4) an

24   adapted aiming strategy.

25   **Factor 1: Ability to produce fast primary submovements.** The gradual age-related decline in

26   muscle strength (i.e., sarcopenia) may limit older adults' ability to produce fast initial pulses towards the

27   target (Walker et al. 1997). Slower primary submovements may compel older adults to undershoot the

28   target to a greater extent, consequently resulting in longer homing-in phases. The traditionally observed

1   movement adaptations in old age may thus be caused by older adults' physical inability to generate the

2   same amount of force as young controls (Pratt et al. 1994).

3   **Factor 2: Programming the aiming movement.** Alternatively, several researchers have suggested

4   that a reduced ability to accurately program the movement may underlie the movement adaptations in old

5   age (Pohl and Winstein 1998; Rey-Robert et al. 2012). Specifically, older adults are thought to have

6   augmented levels of motor noise, thereby increasing the random, unintentional error inherent to human

7   force production (Walker et al. 1997). This view is supported by studies reporting increased motor output

8   variability in old age during force production tasks in general (Christou and Carlton 2001; Galganski et al.

9   1993), as well as during manual aiming in particular (Ketcham et al. 2002; Pratt et al. 1994). Taking into

10 account the linear relationship between movement velocity and movement endpoint variability (Schmidt et

11 al. 1979), a simple way to cope with increased levels of variability would be to slow down the initial pulse

12 towards the target. As described for Factor 1, reducing the primary submovement speed could easily result

13 in the set of movement adaptations typically observed in older adults' aiming behavior. These movement

14 adaptations may therefore reflect older adults' reaction to a decreased ability to accurately program the

15 movement.

16   **Factor 3: Sensory feedback-processing efficiency.** Instead of impaired movement programming

17 capacities, various researchers have proposed that older adults may encounter difficulties during the

18 processing of online sensory feedback (Boisgontier et al. 2012; Boisseau et al. 2002; Chaput and Proteau

19 1996; Coats and Wann 2011). This limitation would explain why the homing-in phase of the movement is

20 longer in older adults. Despite the fact that sensory feedback-processing efficiency is extremely difficult to

21 quantify, basic evidence supporting this hypothesis has recently arisen. In contrast to previous work, Welsh

22 et al. (2007) for instance conducted a study in which young and older adults initially undershot the target to

23 the same extent. Though both age groups exhibited a similar number of corrective submovements during

24 the homing-in phase to accurately hit the target, older adults needed more time to complete these

25 corrections. As there was no evidence for increased processing demands in the older adults, the authors

26 suggested that adjusting the movement trajectory based on sensory feedback takes longer in old age (Welsh

27 et al. 2007). In addition to this kinematic evidence, Temprado et al. (2013) recently confirmed this outcome

1   using *efficiency functions* and *Brinley plots*. In sum, a reduced efficiency in sensory feedback processing

2   may well underlie the movement alterations observed in older adults' manual aiming behavior.

3   **Factor 4: Aiming strategy.** As older adults tend to be more cautious when performing motor tasks

4   (Boisseau et al. 2002), the hypothesis of older adults adopting a different aiming strategy has also gained

5   recent interest. To avoid the high energy costs associated with overshooting the target, older adults are

6   thought to deliberately undershoot the target to a great extent (Elliott et al. 2010; Welsh et al. 2007).

7   Afterwards, they may rely completely on limb-target control to ensure endpoint accuracy. This prudent

8   approach is known as the *play-it-safe* strategy believed to be adopted by older adults.

9   Finally, it should be noted that older adults may also change their aiming strategy to cope with

10   physical limitations such as an impaired programming of the aiming movement or a less efficient

11   perceptual feedback processing. The age-related differences in manual aiming may thus also be caused by a

12   combination of factors (Rey-Robert et al. 2012).

13   The aim of this study was to investigate which of these four commonly identified factors

14   underlie(s) the age-related movement adaptations during manual aiming. Young and older adults therefore

15   performed manual aiming movements under different conditions. These different aiming conditions

16   allowed us to isolate all four factors, and compare them between age groups. In line with the literature, it

17   was expected that Factors 2, 3 and 4 would cause the movement alterations observed during manual aiming

18   in old age.

19   **Methods**

20   **Participants**

21   Twenty-two young (age range: 19 - 26 years old) and 24 older (60 - 72 years old) volunteers

22   participated in the study. Young adults were recruited on the university campus, whereas older adults were

23   recruited via a local senior club. All participants were right-handed according to the Edinburgh Handedness

24   Inventory (Oldfield 1971) and had normal or corrected-to-normal vision. Fine motor skills were considered

25   intact, as all participants met the age- and gender-dependent criteria for the *Nine Hole Pegboard Test*

26   (Mathiowetz et al. 1985; Oxford Grice et al. 2003). To control for mild dementia or other anomalies in

27   cognitive functioning, older adults were exposed to a *Mini-Mental State Examination* (Folstein et al. 1975).

28   The minimum score for inclusion was set at 28 out of 30, which all achieved. Both young and older adults

1 were subdivided based on their physical activity levels as measured by a Baecke questionnaire. As a

2 previous study revealed the traditional age-related movement adaptations are best observed when

3 comparing active older adults to active young controls (Van Halewyck et al. 2014a), the current analysis

4 only focuses on the physically active subsamples. The study was approved by the Medical Ethics

5 Committee of the KU Leuven and was conducted in accordance with the 1964 Declaration of Helsinki.

6 Prior to the experiment, written informed consent was obtained from all participants.

7 **Apparatus**

8 The apparatus was identical to the one used in previous work (Van Halewyck et al. 2014a; Van

9 Halewyck et al. 2014b). Participants sat in a comfortable chair with their preferred, right forearm in an

10 orthosis. The axis of the orthosis was aligned with the anatomical axis of the wrist joint and positioned in a

11 way that participants could only flex and extend their wrist in the horizontal plane. A high-precision shaft

12 encoder with an accuracy of $0.006°$ and sampling frequency of 250 Hz was attached onto the orthosis. In all

13 conditions, wrist angular position was presented as a 1.5 cm diameter circular cursor on a 60 cm computer

14 monitor, which was located at a standardized distance of 125 cm in front of the participant at eye level.

15 Apart from this cursor, two fixed targets also appeared on the monitor. These square targets had a width of

16 1 cm and stood 18 cm apart. In short, the task consisted of moving the cursor from the right target to the

17 left, corresponding to a wrist flexion movement. In conditions in which the left target had to be entirely

18 surrounded by the cursor, the aiming movement had an index of difficulty (ID) of 6.2 bits (ID:

19 $\log_2[2*18/(1.5-1)]$). The exact instructions per condition are further explained in the *Task and Protocol*

20 section.

21 Concurrent to the hand movement, eye closure was recorded using an Applied Science

22 Laboratories (ASL) 6000 pan-tilt eye-tracker system (Bedford, MA) with a sampling frequency of 240 Hz.

23 As both effectors were registered at different sampling frequencies, custom-written software was used to

24 ensure the high-precision shaft encoder and ASL started sampling simultaneously (i.e., at the same

25 millisecond). This allowed us to temporally link both effectors after data were collected.

26 **Task and Protocol**

27 Participants performed blocks of 10 aiming movements in three different conditions (CONTROL,

28 ACCURACY and SPEED). In all conditions, participants were asked to start the block by positioning the

1   cursor around the right target and to wait for the first GO-stimulus. As soon as the right target turned red

2   (GO-stimulus), they were instructed to aim towards the left, corresponding to a wrist flexion movement.

3   After movement completion, participants were asked to return to the right starting target to prepare for the

4   next GO-stimulus. The interval between two consecutive GO-stimuli varied randomly between 6000, 6500,

5   7000, 7500 and 8000 ms to avoid movement anticipation. The experiment started with an extensive

6   familiarization phase in which three CONTROL aiming blocks were practiced. Then, a first experimental

7   session consisting of five CONTROL aiming blocks was performed. After a 30-minute break, a second

8   experimental session started in which the order of the ACCURACY and SPEED blocks was

9   counterbalanced.

10   **CONTROL condition.** Participants were instructed to surround the left target as fast and

11   accurately as possible after the GO-stimulus (ID: 6.2 bits). Once the left target was entirely surrounded by

12   the cursor, participants were asked to briefly close their eyes to indicate their movement had ended. All

13   participants performed five blocks of 10 aiming movements, resulting in 50 aiming movements per

14   participant.

15   **ACCURACY condition.** Similar to the CONTROL condition, participants were instructed to

16   surround the left target as fast and accurate as possible with the cursor after the GO-stimulus (ID: 6.2 bits).

17   Participants were told that the time between the GO-stimulus and the end of the aiming movement would

18   be accumulated over all ACCURACY condition movements. Both the young and older participant who

19   needed the least amount of total time, would receive a €25 gift voucher. However, participants were also

20   told that primary submovements overshooting the target, as well as endpoint inaccuracy, would be

21   penalized with an additional 2000 ms. Thus although participants were motivated to move quickly, the

22   emphasis was shifted towards endpoint accuracy with a particular concentration on the avoidance of target

23   overshoots. Again, participants performed five blocks of 10 aiming movements, resulting in 50 aiming

24   movements in this condition.

25   **SPEED condition.** In contrast to the CONTROL and ACCURACY conditions, the task's accuracy

26   demands were eliminated in the SPEED condition: Participants now reacted to the GO-stimulus by making

27   identical, ballistic aiming movements *beyond* the left target. To prevent fatigue, only three SPEED

28   condition blocks were performed resulting in 30 aiming movements per participant.

1   **Factor isolation**

2   To address which factor may be the underlying mechanism for the age-related movement

3   adaptations in manual aiming, an attempt was made to isolate the four abovementioned factors.

4   **Factor 1: Ability to produce fast primary submovements.** Potential age-related declines in the

5   ability to produce fast primary submovements were examined via peak velocity values in the SPEED

6   condition (Walker et al. 1997). For this variable, we disregarded conditions that required accuracy

7   constraints as age-related slowing could be caused here by specific aiming strategies rather than a physical

8   limitation. If older adults would be unable to produce the same level of primary submovement speed as

9   young controls, an age-related decline in muscle strength (i.e., sarcopenia) could be a mechanism

10   underlying the movement adaptations traditionally observed in old age.

11   **Factor 2: Programming the aiming movement.** In line with the study of Welsh et al. (2007),

12   potential age-related difficulties to program consistent actions were examined by comparing the temporal

13   and spatial variability at four kinematic markers. This was done by first calculating the absolute time it took

14   participants to reach peak acceleration, peak velocity, peak deceleration, and the end of the movement in all

15   SPEED condition aiming movements. Then, the standard deviation of these kinematic marker timings was

16   calculated per block and used as an indicator of temporal variability. A similar procedure involving the

17   absolute positions in the primary direction of the movement at the kinematic markers was used to

18   determine the spatial variability per block. Again, we limited our analysis to the SPEED condition to rule

19   out potential strategy differences between young and older adults. Also, as participants were instructed to

20   make *identical* ballistic movements, all participants strived towards the lowest possible temporal and

21   spatial movement variability in this condition. Thus, if older adults were to show greater temporal and/or

22   spatial variability of kinematic markers than younger adults, this would indicate age-related difficulties

23   associated with accurately programming the aiming movement.

24   **Factor 3: Sensory feedback-processing efficiency.** Sensory feedback processing ability is

25   extremely difficult to disentangle from movement execution abilities in behavioral experiments.

26   Nevertheless, Walker et al. (1997) attempted to isolate the sensory component by asking participants to

27   release a pressed button in order to indicate their aiming movement had ended. They considered the time

28   between the end of the aiming movement and the release of the button a basic indicator for the processing

1   speed of visual feedback. Though not perfect, this approach may provide the best behavioral method for

2   comparing the processing speed of sensory feedback between groups. Instead of focusing on a distal motor

3   component such as the finger muscles, it may nevertheless be more appropriate to involve a more proximal

4   motor component to minimize conduction time (Boisgontier et al. 2014; Kimura 2001). As described in the

5   *Task and Protocol* section, participants were therefore asked to briefly close their eyes in the CONTROL

6   condition to indicate the cursor accurately surrounded the target and the aiming movement had ended.

7   Based on the original study of Walker et al. (1997), the time between the end of the hand movement and

8   the closure of the eyes was considered the *verification time* of the movement. Though this verification time

9   still contains a minimal motor component associated with the eyelids, its duration is clearly dominated by

10 visual feedback processing. If older adults demonstrate longer verification times, this was considered to

11 reflect an age-related slowing in sensory feedback processing.

12   **Factor 4: Aiming strategy.** To investigate age-related differences in aiming strategy, an

13 ACCURACY condition was added to the experiment. As described in the *Task & Protocol* section,

14 inaccurate movement endpoints and primary submovements overshooting the target were penalized in this

15 condition. Age-related differences in aiming strategy would be supported by two specific outcomes. On the

16 one hand, if older adults adopt a play-it-safe strategy to ensure endpoint accuracy and prevent target

17 overshoots in the CONTROL condition, the ACCURACY condition instructions should have a minimal

18 effect on their aiming kinematics. On the other hand, if the ACCURACY condition results in young adults

19 demonstrating aiming characteristics traditionally described in older adults, these movement adaptations

20 might be viewed as a more universal strategy used to ensure endpoint accuracy and prevent target

21 overshoots. Besides endpoint accuracy, we therefore compared the five variables that are traditionally

22 altered in older adults' aiming movements (i.e., peak velocity, relative distance of the primary

23 submovement, relative duration of the homing-in phase, number of corrective submovements, and overall

24 movement time) between the CONTROL and ACCURACY conditions. If young adults change their

25 aiming kinematics significantly in the direction of older adults, and if older adults in turn keep these

26 variables unchanged between conditions, our findings would be consistent with a play-it-safe strategy in

27 older adults.

28 **Data Analysis**

1   Prior to the calculation of the dependent variables, a first order low-pass Butterworth filter with a

2   cut-off frequency of 20 Hz was applied on the hand movement data. The filtered data were differentiated

3   twice to obtain instantaneous hand velocity and acceleration profiles. The criteria to define all dependent

4   variables are described in detail in a previous study (Van Halewyck et al. 2014a). First, the mean score and

5   standard deviation were calculated per block for all variables. Then, Factors 1 to 3 were compared between

6   the two age groups using independent t-tests. Finally, our specific expectations regarding aiming strategy

7   allowed us to calculate *a priori* comparisons for Factor 4. Specifically, we determined whether young and

8   older adults changed their aiming kinematics going from the CONTROL to the ACCURACY condition.

9   The significance level in all tests was set at $p < .05$. Results are displayed as group mean score ± standard

10   error of the mean (SEM).

11   **Results**

12   To highlight the validity of our test set-up, we start our *Results* section with some notable group

13   differences in the CONTROL condition. As expected, all five movement adaptations traditionally described

14   in old age were observed in older participants: lower peak velocities, shorter-ranged primary

15   submovements, relatively greater homing-in phase durations, more corrective submovements, and greater

16   overall movement times (all $p < .01$; see Table 1).

17   **Factor 1: Ability to produce fast primary submovements**

18   In contrast to the CONTROL condition, older adults (311.6 ± 26.2 cm/s) did not move significantly

19   slower than young adults (321.9 ± 27.0 cm/s) in the SPEED condition ($p = .93$; see Figure 1).

20   **Factor 2: Programming the aiming movement**

21   As displayed in Figure 2A, temporal variability in the SPEED condition was comparable between

22   groups at all kinematic markers (all $p > .18$). Similarly, no significant differences were observed for spatial

23   variability (all $p > .05$; see Figure 2B).

24   **Factor 3: Sensory feedback-processing efficiency**

25   In the CONTROL condition, significantly greater verification times were detected in older (498 ±

26   81 ms) compared to young adults (297 ± 45 ms ; $p < .01$; see Figure 3).

27   **Factor 4: Aiming strategy**

1   **Endpoint accuracy:** Before focusing on the five specific variables of interest, we should highlight

2   that only young adults increased their percentage of aiming movements resulting in target hits in the

3   ACCURACY condition (94.4 ± 2.7 %) as compared to the CONTROL condition (91.1 ± 3.5 %; $p < .05$). In

4   contrast, older adults did not change endpoint accuracy between conditions (going from 85.4 ± 3.7 in the

5   CONTROL condition to 86.4 ± 4.5 in the ACCURACY condition; $p = .71$; see Figure 4A).

6   **Peak velocity:** Compared to the CONTROL condition (83.9 ± 8.6 cm/s), young adults tended to

7   speed up their initial pulse towards the target in the ACCURACY condition (92.4 ± 8.9 cm/s; $p = .06$).

8   Older adults, on the other hand, demonstrated similar peak velocity values (65.9 ± 7.8 cm/s in the

9   CONTROL condition and 70.9 ± 6.1 cm/s in the ACCURACY condition; $p = .37$; see Figure 4B).

10   **Relative distance of primary submovement:** Young adults also tended to undershoot the target to

11   a slightly greater extent in the ACCURACY condition (67.7 ± 3.8 % of target distance) compared to the

12   CONTROL condition (71.3 ± 4.1 % of target distance; $p = .08$). Older adults, on the other hand, did not

13   shorten their primary submovement in the ACCURACY condition (61.0 ± 4.4 % of target distance in the

14   CONTROL condition and 60.8 ± 4.5 % of target distance in the ACCURACY condition; $p = .95$; see

15   Figure 4C).

16   **Relative duration of the homing-in phase:** Young adults spent proportionally more time on the

17   homing-in phase during ACCURACY condition aiming movements (69.4 ± 3.0 % of the movement time)

18   compared to CONTROL condition aiming movements (63.9 ± 3.5 % of the movement time; $p < .01$).

19   Again, older adults did not adapt their aiming movements in this respect (68.0 ± 3.1 of the movement time

20   in the CONTROL condition and 69.5 ± 3.0 of the movement time in the ACCURACY condition; $p = .63$;

21   see Figure 4D).

22   **Number of corrective submovements:** Compared to the CONTROL condition (2.3 ± 0.3), young

23   adults significantly increased their number of corrective submovements during the ACCURACY condition

24   (2.7 ± 0.3; $p < .05$). In contrast, the older adults did not change their number of corrections in the hand

25   movement trajectory (2.8 ± 0.3 in the CONTROL condition and 3.0 ± 0.3 in the ACCURACY condition; p

26   = .22; see Figure 4E).

27   **Overall movement time:** Young adults significantly increased their movement times going from

28   the CONTROL condition (906 ± 64 ms) to the ACCURACY condition (969 ± 66 ms; $p < .05$). Again, the

1   difference in older adults' movement times did not reach the level of significance (1081 ± 65 ms in the

2   CONTROL condition and 1116 ± 71 ms in the ACCURACY condition; p = .41; see Figure 4F).

3   **Discussion**

4   The aim of this study was to determine the mechanism(s) underlying the movement adaptations

5   traditionally observed in older adults' aiming behavior. Four commonly suggested factors were isolated in

6   different aiming conditions, and compared between age groups. After discussing the observations for each

7   factor separately, a general conclusion is provided.

8   **Factor 1: Ability to produce fast primary submovements**

9   Older adults generally make slower and shorter-ranged primary submovements compared to young

10   adults, suggesting they may encounter difficulties generating fast initial pulses towards the target (Pratt et

11   al. 1994). Results from the SPEED condition nevertheless indicate that an age-related degradation in force

12   generation capacity (i.e., sarcopenia) is not the limiting factor during goal-directed aiming movements.

13   Without accuracy constraints, older adults demonstrated similar primary submovement speeds as young

14   controls (see Figure 1). The age-related differences in movement speed that were observed in the

15   CONTROL condition must therefore be caused by factors other than an age-related physical limitation to

16   produce fast primary submovements. Instead, Figure 1 suggests older adults may intentionally slow down

17   the primary submovement to a greater extent during CONTROL condition movements in order to deal with

18   the imposed accuracy constraints. Age-related strategy differences to cope with the speed-accuracy trade-

19   off are discussed in greater detail when interpreting the results associated with Factor 4.

20   **Factor 2: Programming the aiming movement**

21   We also investigated whether movement programming capacities are degraded in old age by

22   looking into the movement trajectory's consistency during SPEED condition movements. As is evident in

23   Figures 2A and 2B, similar levels of temporal and spatial variability were observed at all kinematic

24   markers. This outcome suggests that movement-planning capacities do not deteriorate with age[1].

25   At first glance, this result seems to be contradicted by several studies reporting greater levels of

26   movement variability in older adults (Ketcham et al. 2002; Pratt et al. 1994), and is therefore not in line

27   with our original predictions. There are, however, several possible explanations for this dissimilarity in

28   results. For instance, in contrast to previous studies, we specifically instructed participants to make

1   *identical*, ballistic aiming movements. As such, all participants strived towards minimal movement

2   trajectory variability, which may not have been the case in previous research. Also, instead of focusing on

3   the entire movement trajectory, other variability analyses (e.g., Ketcham et al. 2002; Pratt et al. 1994) were

4   limited to two kinematic markers late in the movement (i.e., end of the primary submovement and end of

5   the movement) in aiming conditions with high accuracy constraints. For this reason, greater variability

6   levels in older adults may well represent other factors than an age-related deterioration in movement-

7   planning capacities. To our knowledge, the only other aging study to perform a more comprehensive

8   variability analysis was the previously mentioned investigation of Welsh and colleagues (2007). In line

9   with our current results, they too found equal variability levels at the same kinematic markers among young

10   and older adults. Based on both analyses, we may therefore conclude that movement-planning capacities

11   remain intact in old age.

12   **Factor 3: Sensory feedback-processing efficiency**

13   In the CONTROL condition, participants were asked to indicate their movement had ended by

14   briefly closing their eyes when the cursor surrounded the end target. As explained in the *Factor Isolation*

15   section, the time span between the end of the hand movement and the closure of the eyes (i.e., *verification*

16   *time*) can be seen as an indicator for visual feedback processing speed. Since older adults demonstrated

17   significantly greater verification times (see Figure 3), our results provide clear evidence for slower visual

18   feedback processing in old age. This finding is supported by several studies reporting older adults generally

19   need more time than young controls to process the same amount of information (Coats and Wann 2011;

20   Temprado et al. 2013; Welsh et al. 2007). Also, when the amount of sensory information to be processed is

21   increased by, for instance, presenting additional information (Boisgontier et al. 2012; Boisseau et al. 2002)

22   or increasing the number of choices in a multiple-choice task (Falkenstein et al. 2006; Yordanova et al.

23   2004), older adults have been shown to prolong their reaction and movement times relative to young adults.

24   Thus these studies are consistent with our conclusion that an age-related decrease in sensory feedback-

25   processing efficiency may underlie the movement alterations traditionally observed in older adults.

26   **Factor 4: Aiming strategy**

27   Finally, we examined whether age-related changes in aiming strategy could also provide an

28   explanation for movement alterations in old age. In short, older adults are thought to adopt a *play-it-safe*

1   strategy by deliberately undershooting the target to a greater extent, and relying more on limb-target control

2   during the homing-in phase (Elliott et al. 2010; Welsh et al. 2007). This cautious approach is believed to

3   prevent the high energy costs associated with target overshoots, and may help ensure high levels of

4   endpoint accuracy. To reveal potential strategy differences between both age groups, an ACCURACY

5   condition was added to the experiment. Here, participants were financially rewarded for ending all aiming

6   movements accurately onto the target without overshooting it initially. Our expectations regarding the

7   ACCURACY condition were largely confirmed.

8   Firstly, on the variables of interest, older adults did not exhibit any difference in performance

9   between the CONTROL and ACCURACY conditions. This result seems to suggest they already

10   emphasized endpoint accuracy and the prevention of target overshoots under normal aiming circumstances

11   (i.e., CONTROL condition). Alternatively, it could also reflect the fact that older adults are less able to

12   adapt their aiming movements to specific instructions or contexts (see Pratt et al. 1994; Seidler-Dobrin and

13   Stelmach 1998). However, this potential limitation does not seem applicable to our task, as older adults

14   were clearly able to change their aiming characteristics in response to our SPEED condition instructions

15   (see Figure 1).

16   Secondly, when comparing the CONTROL to the ACCURACY condition data in young adults,

17   three of the five variables changed significantly towards the pattern typically seen in older adults (i.e.,

18   relative duration of the homing-in phase, number of corrective submovements, and overall movement time;

19   all $p < .05$; see Figure 4D, 4E and 4F). Moreover, a fourth variable only just failed to reach the level of

20   significance (relative distance of the primary submovement; $p = .08$; see Figure 4C). Making these

21   movement adjustments resulted in an increased percentage of target hits (see Figure 4A). Thus these

22   modification to the movement trajectory seem to reflect an effective approach to ensure endpoint accuracy.

23   The only variable not to meet the expected outcome was peak velocity (see Figure 4B). The finding that

24   only young adults were able to increase the maximum speed of their initial pulse and yet demonstrate

25   higher levels of endpoint accuracy suggests that in the ACCURACY condition they adopted a strategy of

26   moving to the target area quickly so that they had more real and proportional time to use sensory feedback

27   during the homing phase of their movement. This explanation is consistent with other work involving

28   young adults (e.g., Hansen et al. 2006).

1   All in all, since most variables met the expected outcome, the overall picture provides evidence for

2   older adults adopting a play-it-safe strategy under natural circumstances[2].

3   **General Conclusion**

4   In sum, results of the SPEED condition showed that older adults were physically able to move as

5   fast as young controls. The movement slowing typically observed in older adults thus appears to be caused

6   by factors other than the *physical inability to produce fast primary submovements* (Factor 1). Also in the

7   SPEED condition, the absence of age-related differences in temporal and spatial variability suggest that

8   older adults' *movement programming capacities* remain intact as well (Factor 2). Instead, the traditional

9   aiming movement adaptations in old age appeared to be caused by two other key mechanisms. On the one

10   hand, older adults showed greater verification times. This outcome suggests *less efficient sensory feedback*

11   *processing* in old age (Factor 3), and is strongly supported by the recent literature (Boisgontier et al. 2012;

12   Boisseau et al. 2002; Falkenstein et al. 2006; Temprado et al. 2013; Welsh et al. 2007; Yordanova et al.

13   2004). On the other hand, evidence was found for older adults adopting a *play-it-safe strategy* during

14   manual aiming (Factor 4; Elliott et al. 2010; Welsh et al. 2007). Compared to the CONTROL condition,

15   older participants' aiming characteristics stayed relatively unchanged in the ACCURACY condition,

16   whereas the movements of young adults shifted to resemble those of older adults. The former suggests that

17   older adults already emphasized endpoint accuracy and the prevention of target overshoots in the

18   CONTROL condition; the latter seems to imply that this approach is indeed an effective strategy to end

19   aiming movements accurately. In summary, the movement adaptations traditionally observed in old age

20   thus appear to reflect less efficient sensory feedback processing in combination with a play-it-safe strategy.

21

25

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1   **Footnotes**

2   [1] To demonstrate that SPEED condition movements were indeed based primarily on planning processes, an

3   additional *coefficient of determination* (R^2) analysis was performed (Heath 2005; Khan et al. 2006; Messier

4   and Kalaska 1999). In short, such analysis examines the proportion of movement endpoint variability that

5   can be explained by the limb position at different kinematic markers. The rationale behind this regression

6   technique is the following: In case of aiming movements purely based on planning processes, one should

7   be able to predict the movement endpoint based on (early) kinematic marker positions, as no corrections

8   occur late in the movement. Accurate predictions are reflected by high R^2 values. On the other hand, if

9   aiming movements are strongly modified based on online feedback during the homing-in phase, movement

10   endpoints are more difficult to predict from (early) kinematic marker positions. These types of movements

11   are typically associated with low R^2 values. Results of this additional R^2 analysis showed that the

12   percentage of explained endpoint variance in the SPEED condition exceeded 94.0 % in both groups when

13   movement endpoints were estimated based on the peak velocity position, whereas this value exceeded 99.0

14   % when the estimation was based on peak deceleration position. This analysis thus confirms that SPEED

15   condition aiming movements were primarily based on movement-planning capacities, as originally

16   intended.

17

18   [2] Again, an additional analysis was performed to control these outcomes. To further investigate the aspect

19   of deliberate slowing in older adults, we calculated the mean peak velocity values of all CONTROL

20   condition aiming blocks relative to the participant's highest peak velocity value in the SPEED condition.

21   The rationale was that if older adults deliberately slow down their aiming movements to a greater extent

22   than young adults, they should systematically demonstrate lower *relative* peak velocity values. In contrast

23   to absolute peak velocity values, such analysis takes into account personal capacities as well. Results

24   showed that under natural circumstances, older adults (14.1 ± 2.2%) indeed aimed at a lower percentage of

25   their maximal movement speed compared to young adults (21.4 ± 3.0%; $p < .01$), thereby further

26   supporting the play-it-safe strategy in old age.

27

1   **Table Captions**

2   **Table 1: Traditional age-related differences in aiming kinematics in the CONTROL condition.** *Note:*

3   Results are presented as *mean ± SEM*. All five expected differences between age groups were observed in

4   the CONTROL condition. Adapted from "Both age and physical activity level impact on eye-hand

5   coordination" by Van Halewyck et al. 2014a, Hum Movement Sci. Copyright 2014 by Elsevier.
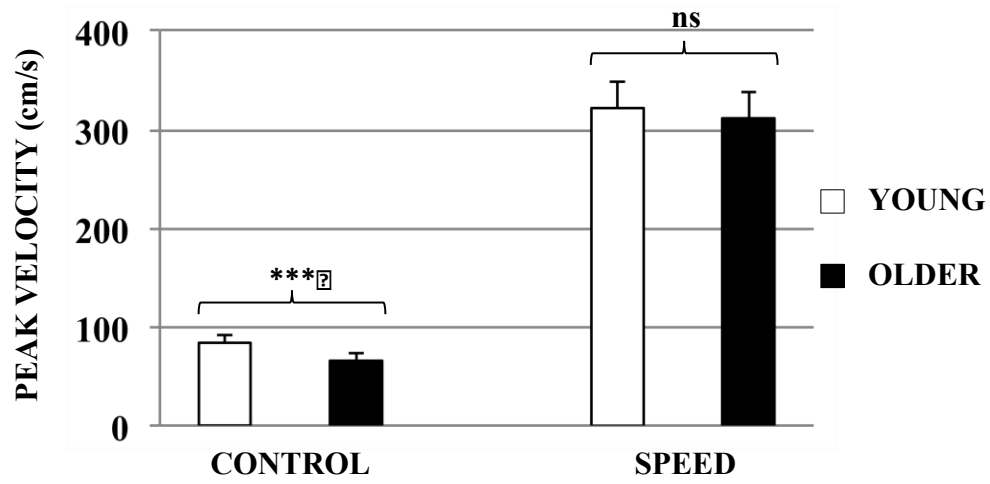
6

1 **Figure Captions**

2 **Figure 1: Factor 1: Ability to produce fast primary submovements.** Comparison of mean peak

3 velocities in the SPEED condition. CONTROL condition data are also displayed for the sake of

4 completeness. Group scores are presented as mean ± SEM. Significant group differences are highlighted by

5 *** (if $p < .01$), nonsignificant group differences by *ns* (if $p > .05$).

6

7 **Figure 2: Factor 2: Programming the aiming movement.** Comparison of (A) temporal and (B) spatial

8 variability at four kinematic markers in the SPEED condition. *Abbreviations*: PA = Peak acceleration; PV =

9 Peak velocity; PD = Peak deceleration; END = End of aiming movement. Nonsignificant group differences

10 are highlighted by *ns* (if $p > .05$).

11

12 **Figure 3: Factor 3: Sensory feedback-processing efficiency.** Comparison of the mean verification time

13 in the CONTROL condition. Group scores are presented as mean ± SEM. Significant group differences are

14 highlighted by *** (if $p < .01$),

15

16 **Figure 4: Factor 4: Aiming strategy.** Comparison of (A) endpoint accuracy, (B) peak velocity, (C)

17 relative distance of the primary submovement, (D) relative duration of the homing-in phase, (E) number of

18 corrective submovements, and (F) overall movement time between conditions to investigate the play-it-safe

19 strategy. Significant group differences are highlighted by *** (if $p < .01$) or * (if $p < .05$), nonsignificant

20 group differences by *ns* (if $p > .05$).

1   **Table 1**

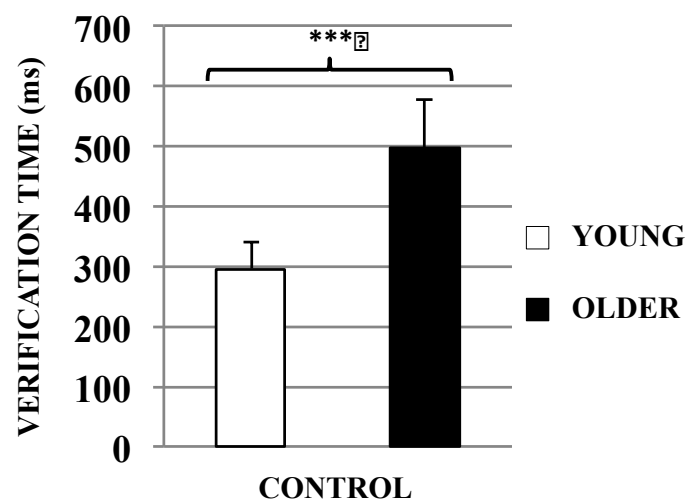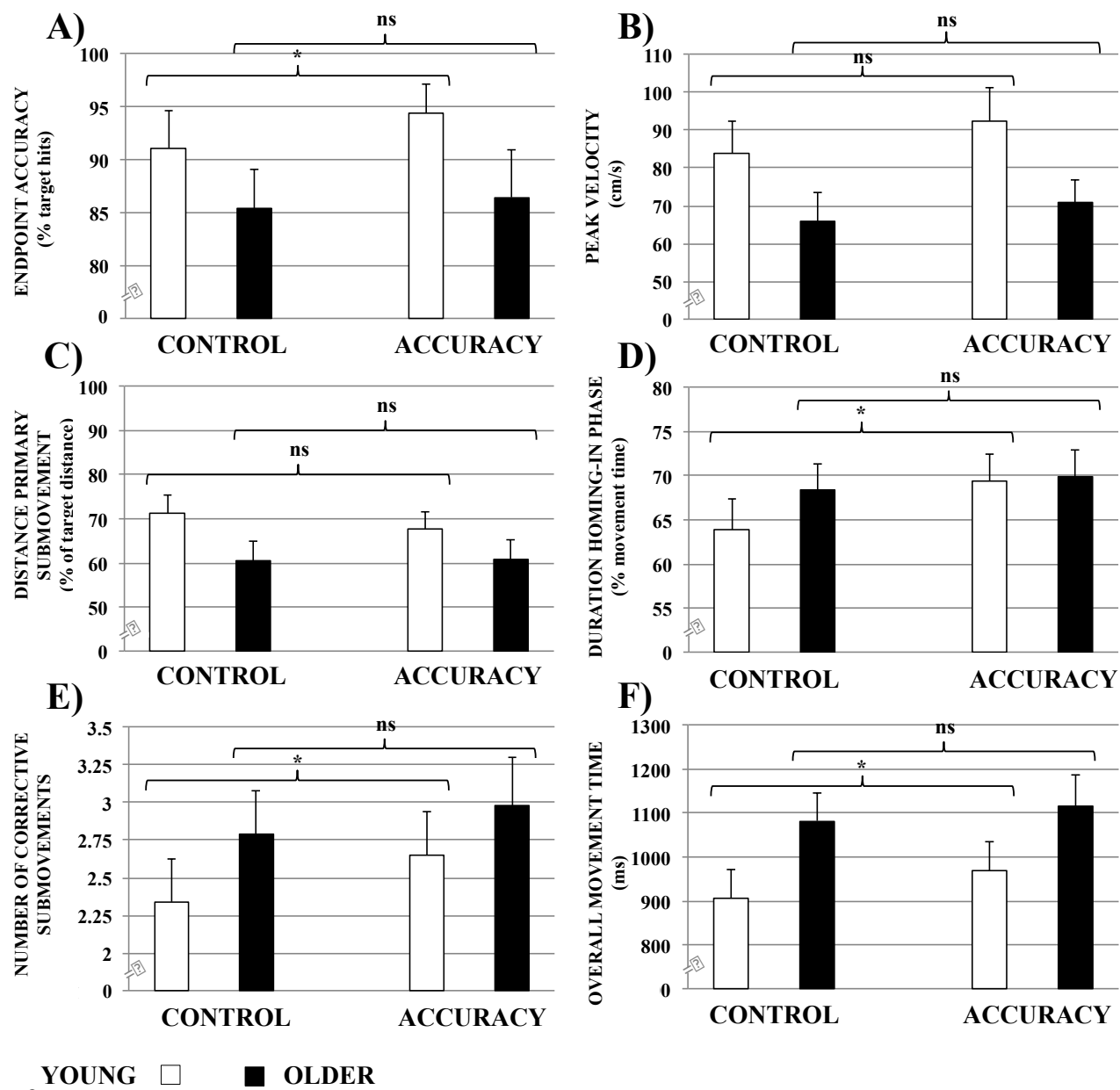| Parameter	Unit	Young	Older	*p*-value
Peak velocity	cm/s	83.9 ± 8.6	65.9 ± 7.8	$< .01$
Relative distance primary submovement	% target distance	72.5 ± 4.1	61.0 ± 4.4	$< .01$
Relative duration homing-in phase	% movement time	63.0 ± 3.6	68.0 ± 3.1	$< .01$
Number of corrective submovements	/	2.3 ± 0.3	2.8 ± 0.3	$< .01$
Overall movement time	ms	892 ± 62	1074 ± 65	$< .01$

2

3

1   **Figure 1**

2

3

1   **Figure 2**

A)

B)
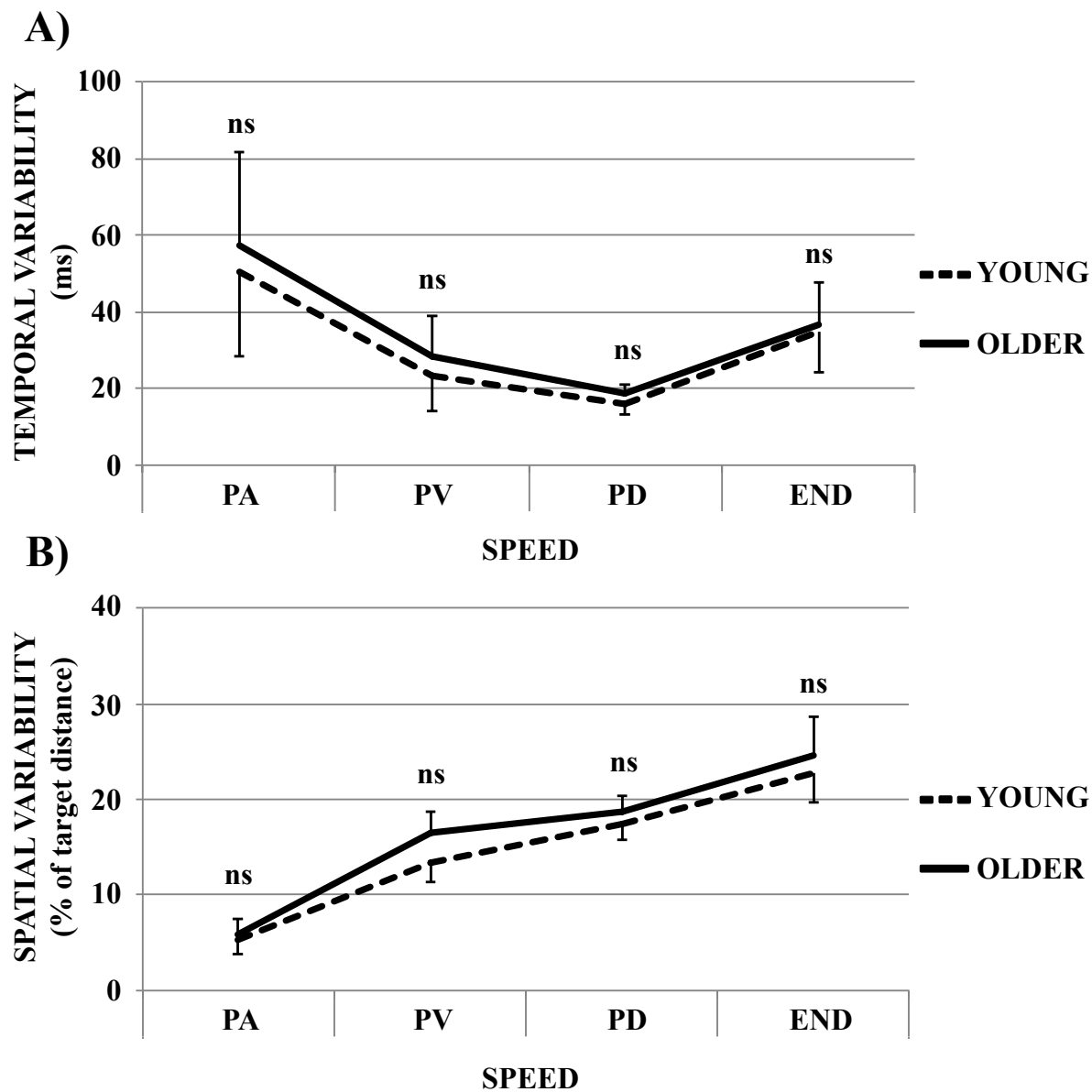
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1
2   **Figure 3**

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1   **Figure 4**

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