1

2

3

4

5

6

7

8

9

10   The Impact of Age and Physical Activity Level on Manual Aiming Performance

11

1   Abstract

2

3   Older adults traditionally adapt their discrete aiming movements, thereby travelling a

4   larger proportion of the movement under closed-loop control. As the beneficial impact of

5   a physically active lifestyle in old age has been described for several aspects of motor

6   control, we compared the aiming performance of young controls to active and sedentary

7   older adults. To additionally determine the contribution of visual feedback, aiming

8   movements were executed with and without saccades. Results showed only sedentary

9   older adults adopted the typical movement changes, highlighting the impact of a

10 physically active lifestyle on manual aiming in old age. In an attempt to reveal the

11 mechanism underlying the movement changes, evidence for an age-related decline in

12 force control was found, which in turn resulted in an adapted aiming strategy. Finally,

13 prohibiting saccades did not affect older adults' performance to a greater extent,

14 suggesting they do not rely more on visual feedback than young controls.

15

16   *Keywords:* aging, physical activity, manual aiming, eye movements

17

1   **The Impact of Age and Physical Activity Level on Manual Aiming Performance**

2   Ever since Woodworth's classic work on manual aiming (1899) motor control

3   researchers have shown that goal-directed upper limb movements traditionally consist of

4   two phases: a primary submovement and a homing-in phase. The former can be defined

5   as the initial impulse towards the vicinity of the target (mainly open-loop control),

6   whereas the latter phase is associated with feedback-based corrections as the limb

7   approaches the target (primarily closed-loop control; e.g., Elliott, Helsen, & Chua, 2001).

8   The relative contribution of open- versus closed-loop processes to the control of goal-

9   directed movements changes across the lifespan: Young adults generally end their

10   primary submovement just before the target to only make a small adjustment in the same

11   direction as the initial pulse, whereas older adults undershoot the target to a greater

12   extent. By making shorter-ranged and slower primary submovements, older adults need a

13   greater number of time-consuming adjustments during the homing-in phase, resulting in

14   longer overall movement times (Ketcham, Seidler, Van Gemmert, & Stelmach, 2002;

15   Poston, Van Gemmert, Barduson, & Stelmach, 2009; Pratt, Chasteen, & Abrams,

16   1994;Walker, Philbin, & Fisk, 1997).

17   Though these age-related changes in aiming behavior have been described

18   consistently, a study by Lyons and colleagues (1996) reported no differences between

19   young and older adults' movement times, accuracy levels, and primary submovement

20   trajectories. To explain these unexpected results, Lyons and colleagues (1996) argued

21   that older adults may make a better use of kinesthetic feedback for the control of goal-

22   directed movement. As an alternative explanation, the possible influence of a physically

23   active lifestyle in old age was raised. Indeed, recent evidence suggests that maintaining a

24   physically active lifestyle during aging allows older adults to slow declines in their

25   sensorimotor functions. For instance, better maintenance of interlimb coordination skills

1   (Capranica, Tessitore, Olivieri, Minganti, & Pesce, 2004; Cortis et al., 2009) and more

2   accurate proprioceptive perception (Adamo, Alexander, & Brown, 2009; Proske &

3   Gandevia, 2012) were observed in active older adults compared to sedentary controls.

4   Therefore, the first aim of the current study was to explore whether a physically active

5   lifestyle also attenuates the typical age-related changes in manual aiming. To address this

6   question, aiming performances in active and sedentary older adults were compared with

7   those observed in young controls.

8   To understand how physical activity may help to reduce these traditional age-

9   related changes, one should nonetheless know what mechanism underlies the movement

10   adaptations in old age. We shortly present two possibilities: A first hypothesis is that

11   older adults generally engage in more closed-loop control to cope with a deteriorated

12   ability to reliably tune muscular forces (Christou & Carlton, 2001; Galganski, Fuglevand,

13   & Enoka, 1993). This theory assumes that when an older adult produces a force, the noise

14   associated with the resulting movement is greater than when a younger adult produces

15   that same force (Walker et al., 1997). An *increased noise-to-force ratio* might compel

16   older adults to make less forceful and thus shorter primary submovements in order to

17   reduce their endpoint variability. As a result, the homing-in phase of the movement

18   becomes longer but also more predictable. However, the theory has recently been

19   challenged by Welsh and colleagues (2007) showing older adults' primary

20   submovements are not more variable in time and space than those of young adults. They

21   proposed the alternative that older adults adopt a *play-it-safe strategy* to avoid the higher

22   energy costs associated with target overshoots: When correcting for an overshoot, one

23   does not only have to overcome the inertia of a zero-velocity situation, but also reverse

24   the roles of the agonist and antagonist muscle groups (Elliott et al., 2001; Engelbrecht,

25   Berthier, & O'Sullivan, 2003). Undershooting the target to a greater extent and making

1   more use of sensory feedback to safely guide the hand to the target may be considered a

2   secure strategy to prevent overshoots and save energy. Here, we attempted to investigate

3   which of these two proposals is consistent with the traditional movement adaptations in

4   old age. Similar to the study of Welsh and colleagues, we examined movement variability

5   to compare the noise-to-force ratios between groups. On the other hand, the hypothesis

6   that the typical movement adaptations represent a play-it-safe strategy to prevent target

7   overshoots was tested by adding an aiming condition in which there was no time for the

8   movement adaptations (cyclical aiming). If this cyclical aiming condition results in an

9   increased amount of target overshoots, particularly for sedentary older adults, it would

10 provide support for the play-it-safe hypothesis.

11   Irrespective of which abovementioned hypothesis is correct, the greater

12 proportion of the movement occurring under closed-loop control suggests that sensory

13 feedback processing becomes increasingly important in old age. As online feedback

14 consists of proprioceptive and visual information, it is appropriate to look at the impact of

15 aging on both sources of feedback. On the one hand, a clear age-related decline in

16 proprioception has been described consistently in upper limb-matching tasks (e.g.,

17 Adamo et al., 2009; Adamo, Martin, & Brown, 2007; Wright, Adamo, & Brown, 2011).

18 On the other hand, the motor system of the eye seems to be only mildly affected or

19 perhaps even spared by the aging process (Kadota & Gomi, 2010; Pratt, Dodd, & Welsh,

20 2006). Many have therefore suggested that older adults increase their reliance on visual

21 feedback during the execution of manual aiming movements (Rand & Stelmach, 2011a,

22 2011b; Seidler-Dobrin & Stelmach, 1998), possibly as a means to compensate for

23 declines in proprioceptive acuity. In this theoretical context, the experimental data are

24 rather controversial (Chaput and Proteau 1996; Coats and Wann, 2011; Lyons, Elliott,

25 Swanson, & Chua, 1996; Pratt et al., 1994), and there is no general agreement about this

1   sensory reweighting in older adults. To determine whether visual feedback is indeed of

2   increased importance, particularly in sedentary older adults, the aiming task in the current

3   experiment was executed with and without saccades. Eye movements were recorded

4   throughout the experiment to control for the extent by which the aiming movements were

5   executed with visual guidance when saccades were allowed. This additional measurement

6   finally allowed us to look into the differential use of eye movements among groups.

7   In summary, the present study was designed to identify differences between

8   young controls and active and sedentary older adults during visually-guided aiming tasks.

9   These three participant groups were asked to aim as fast and accurate as possible towards

10 fixed targets. To determine the exact contribution of visual information, the aiming

11 movements were performed with or without saccades. The task was executed in a discrete

12 or cyclical way, putting less or more time constraint upon the movements. This

13 experiment enabled us to test the following three hypotheses: First, older adults were

14 expected to adopt the traditional movement adaptations when they were allowed

15 sufficient time in the discrete aiming task. However, if an active lifestyle could indeed

16 counteract the age-related changes in manual aiming behavior, these movement

17 characteristics should only emerge in the sedentary older adults. Specifically, we

18 expected the discrete aiming movements of sedentary older adults to be characterized by

19 slower and shorter-ranged primary submovements, and relatively more time spent in the

20 homing-in phase compared to the young and active older adults. Together this would

21 result in longer overall movement times. Second, by looking into the temporal and spatial

22 variability of the movements, we aimed to verify whether an increased noise-to-force

23 ratio may be responsible for these movement adaptations in sedentary older adults.

24 Conversely, the play-it-safe hypothesis would be supported by sedentary older adults

25 showing an increased amount of target overshoots during cyclical aiming. Third, it was

1   hypothesized that sedentary older adults depend more on visual feedback during manual

2   aiming. This would be reflected in a larger drop in accuracy levels when eye movements

3   were prohibited.

Method

Participants

6   Fifteen young and 28 older adults participated in the study on a voluntary basis. Young

7   participants were recruited via flyers distributed over the university campus, whereas

8   active and sedentary older adults were recruited at local running and senior clubs,

9   respectively. All participants were right-handed according to the Edinburgh Handedness

10   Inventory (Oldfield, 1971). They self-claimed to be in good health and to have normal or

11   corrected-to-normal vision. The latter was controlled by asking them to read the task

12   instructions on the screen prior to the experiment. Here, visual acuity demands were

13   considerably higher compared to those required in the experimental task. Since all

14   participants were able to read the instructions aloud, we assumed visual acuity was

15   sufficient for the experimental task. Participants performed a Nine Hole Pegboard Test

16   (NHPT; Mathiowetz, Volland, Kashman, & Weber, 1985) to check for intact fine motor

17   skills and were excluded if their score did not meet the age- and gender-dependent

18   inclusion criteria described by Oxford Grice and colleagues (2003). Two older

19   participants were excluded from the study for this reason. To exclude participants with

20   dementia or other severe anomalies in cognitive functioning, a Mini-Mental State

21   Examination (MMSE; Folstein, Folstein, & McHugh, 1975) was administered to the

22   older participants. The minimum score for inclusion was set at 27 out of 30, which all

23   achieved. Physical activity levels as measured by the Baecke questionnaire (Baecke,

24   Burema, & Frijters, 1982; Voorrips, Ravelli, Dongelmans, Deurenberg, & Van Staveren,

25   1991) were used to divide the older participants in two groups: participants with Baecke

1   scores over the median score of 7.3 were attributed to the physically active subgroup,

2   whereas participants scoring under the median were attributed to the sedentary subgroup.

3   This resulted in three groups: young controls (n=15), physically active older participants

4   (n=13) and sedentary older participants (n=13). The general characteristics of these

5   groups are summarized in Table 1. The study was approved by the Medical Ethics

6   Committee of the KU Leuven and was conducted in accordance with the 1964

7   Declaration of Helsinki. Prior to the experiment, written informed consent was obtained

8   from all participants.

9   **Task and Apparatus**

10   The task and apparatus were similar to those used in several previous studies (e.g.,

11   Lavrysen, Elliott, Buekers, Feys, & Helsen, 2007; Lavrysen et al., 2008; Lavrysen et al.,

12   2012). Participants sat in a comfortable chair and wore an orthosis on the preferred, right

13   forearm. The axis of this orthosis was aligned with the anatomical axis of the wrist joint

14   and positioned in a way that the hand could only move in the horizontal plane. A high-

15   precision shaft encoder with an accuracy of 0.0055° and sampling frequency of 250 Hz

16   was attached onto the orthosis. Wrist angular position was presented as a 1.5 cm diameter

17   circular cursor on a 60 cm computer monitor, located at a standardized distance of 100

18   cm in front of the participant at eye level. Apart from this cursor, two fixed targets also

19   appeared on the monitor. The size of these targets, each marked by two vertical lines,

20   depended upon aiming conditions that are further explained in the *Protocol* section. The

21   task consisted of moving the cursor from target to target by making flexion/extension

22   wrist movements after an auditory cue. Participants were asked to make the movements

23   as fast and accurate as possible, and to wait for the next auditory cue with the cursor

24   between the target boundaries. Point of gaze (PG) was recorded using an Applied Science

25   Laboratories (ASL) 6000 pan-tilt eye-tracker system (Bedford, MA) with a sampling

1   frequency of 240 Hz and an accuracy of 0.5°. A comfortable neck rest was installed onto

2   the participant's chair to prevent head movements and the loss of PG signal. Prior to the

3   experiment, a nine-point calibration was performed for every participant.

4   **Protocol**

5   As illustrated in Figure 1, participants started the experiment with two

6   familiarization blocks in which the different conditions were practiced. These blocks

7   consisted of four 25-second trials in which aiming movements were performed at a self-

8   selected pace. In the first trial, participants made horizontal aiming movements over a

9   distance of 27.5 cm on the screen (corresponding to a wrist angle of 52°) towards targets

10   of 5.2 cm (wrist angle of 10°), resulting in an index of difficulty (ID) of 3.4 bits (Fitts,

11   1954). In the second trial, the ID was increased to 4.4 bits by decreasing the target sizes

12   to 2.6 cm (wrist angle of 5°). As these trials were conducted with eye movements, this

13   visual condition was called *free vision*. Afterwards, the two trials were repeated in a

14   *fixation* condition. Here, participants were asked to fixate the eyes on an additional

15   vertical line in the middle of the screen, thus prohibiting eye movements. Even though

16   peripheral vision was still available, this manipulation made accurate aiming more

17   difficult by depriving the effective use of central vision (Binsted & Elliott, 1999).

18   After the familiarization, participants proceeded with the main experiment.

19   Blocks again consisted of four consecutive trials in which the conditions and sequence

20   remained identical to the familiarization blocks. The only difference was that instead of

21   moving at a self-selected pace, participants were instructed to start their aiming

22   movement at the onset of a 50-ms auditory cue and to move as fast and accurate as

23   possible towards the target. Every trial consisted of 25 auditory cues, and thus 25 aiming

24   movements. First, participants did two blocks of the discrete aiming task in which the

25   auditory cue was presented every 1500 ms. After a 20-minute break, the experiment

1   continued with two blocks in which the interval between auditory cues was shortened to

2   500 ms, resulting in cyclical aiming movements. In total 400 aiming movements were

3   recorded for each participant.

4   **Dependent Variables**

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

6   with a cut-off frequency of 20 Hz was applied on both the hand and eye movement data.

7   The filtered hand position data were differentiated to obtain instantaneous velocity, and

8   then differentiated again to obtain instantaneous acceleration. The first and final two

9   movements of a trial were not considered in the analysis.

10   **Hand movement time.** The hand movement time was defined as the time

11   between hand movement initiation (first sample when the standard deviation (SD) of the

12   velocity profile was inferior to 0.75 mm/s for 80 ms from peak velocity backwards) and

13   termination (first sample when the SD of the velocity profile was inferior to 3 mm/s for

14   120 ms from peak velocity onwards). Both criteria were validated based on a visual

15   inspection in Matlab.

16   **Endpoint accuracy.** If the entire cursor fell within the target boundaries at hand

17   movement termination, this was considered a target hit. If the cursor fell short or long of

18   the target, this was considered a target under- or overshoot, respectively. The percentage

19   of target hits was calculated for every trial and regarded as endpoint accuracy. The

20   percentages of target under- and overshoots were assessed accordingly.

21   **Peak velocity.** The highest velocity found in the primary submovement was

22   considered peak velocity.

23   **Relative distance and duration of the primary submovement.** The end of the

24   primary submovement was defined as the sample of the second zero-line crossing in the

25   acceleration profile. For every aiming movement, we calculated the distance travelled up

1   to this point relative to the distance between the middle of both targets. In addition, the

2   time spent during this primary submovement was also determined relative to the hand

3   movement time.

4   **Temporal and spatial variability.** Identical to the calculations for the end of the

5   primary submovement, the relative duration and distance travelled up to the moment of

6   peak acceleration (highest acceleration during the primary submovement) and peak

7   velocity were computed. By then calculating the mean SD of the relative durations and

8   distances of all three kinematic markers, we were able to get a better view on the

9   temporal and spatial variability of the movements across multiple aiming attempts.

10   **Primary saccade amplitude.** Primary saccade initiation and termination were

11   determined similarly as in previous studies of our lab (e.g., Helsen, Elliott, Starkes, &

12   Ricker, 1998): Saccade onset was the last point when at least 24 sequential gaze

13   coordinate samples (i.e., 100 ms) had an SD equal to or higher than 1°. The end of a

14   saccade (or fixation onset) was defined as the first of 24 gaze samples with a SD lower

15   than 1°. The primary saccade was considered only if it travelled at least 50% of the total

16   distance between the two targets. Its amplitude was calculated and is expressed relative to

17   the distance between the middle of both targets.

18   **Aiming movements with corrective saccades.** This variable was defined as the

19   percentage of aiming movements in which the primary saccade was followed by a

20   fixation and at least one consecutive corrective saccade. The calculation of corrective

21   saccades was done using the same SD criterion as for primary saccades.

22   **Data Analysis**

23   First, because the assumptions for parametric statistics were not met, the general

24   characteristics of all three groups were compared using a Kruskall-Wallis analysis of

25   variance (ANOVA; see Table 1). Then**,** a custom-written Matlab-script computed the

1   means and SDs for all abovementioned variables per trial. As the aim of this study was

2   not to compare the discrete with the cyclical aiming task, but rather participant groups'

3   performance within each task, the data were separated in two sets: one with all data for

4   discrete aiming and one for cyclical aiming. Hand movement variables were analyzed

5   using a 3 GROUP (young, active older, sedentary older) x 2 VISUAL CONDITION (free

6   vision, fixation) x 2 ID (3.4 bits, 4.4 bits) mixed-model ANOVA. Separate analyses were

7   performed on the discrete and cyclical aiming data. Due to the absence of saccades in the

8   fixation condition, variables concerning eye movements were calculated and analyzed

9   only for the free vision condition. Because the task consisted of a one-dimensional

10   horizontal aiming movement, only the horizontal eye movement data were taken into

11   account. Post-hoc tests (Tukey's honestly significant differences) were conducted when

12   appropriate. For all analyses, the significance level was set at $p < .05$. Due to the specific

13   focus of the study, only significant differences including a GROUP effect are presented.

14   **Results**

15   **Discrete Aiming**

16   **Hand movement time.** A main effect of GROUP [$F(2, 298) = 48.92, p < .01$]

17   indicated sedentary older adults needed more time to perform the aiming movements

18   (732 ± 98 ms) than young (615 ± 84 ms) and active older (619 ± 107 ms) participants

19   (see Figure 2A).

20   **Endpoint accuracy.** No main or interaction effects regarding the percentage

21   of target hits, undershoots or overshoots were observed.

22   **Peak velocity.** A significant GROUP effect [$F(2, 298) = 21.56, p < .01$]

23   revealed lower peak velocities in sedentary older adults (857 ± 142 mm/s) than in young

24   (1140 ± 163 mm/s) and active older (1121 ± 160 mm/s) adults (see Figure 2B).

1   **Relative distance of the primary submovement.** A main effect of GROUP

2   [$F(2, 298) = 26.87$, $p < .01$] indicated that sedentary older participants travelled relatively

3   shorter distances during their primary submovement ($80.7 \pm 8.2\%$) compared to young

4   ($87.2 \pm 7.5\%$) and active older ($88.3 \pm 7.7\%$) adults (see Figure 2C). The primary

5   submovement of sedentary older adults thus undershot the target to a greater extent.

6   **Relative duration of the primary submovement.** A significant GROUP

7   effect was also found for the relative duration of the primary submovement [$F(2, 298) =$

8   8.33, $p < .05$], signaling that sedentary older adults had relatively shorter primary

9   submovements ($52.6 \pm 9.1\%$) compared to young ($56.5 \pm 11.0\%$) and active older ($58.3 \pm$

10   10.0%) adults (see Figure 2D). In other words, sedentary older adults spent a greater

11   proportion of the hand movement time during the homing-in phase of the movement.

12   **Temporal and spatial variability.** Temporal variability at peak acceleration

13   appeared to be lower in the young compared to the older groups (both $p < .01$; see Figure

14   3A). Similar results were observed for peak velocity when comparing young controls to

15   active older ($p < .05$) and sedentary older adults ($p < .01$). At the end of the primary

16   submovement, however, the temporal variability was no longer significantly different

17   among groups. With respect to space, lower SDs were noticed for the relative distance

18   travelled up to peak acceleration in the young compared to the older groups (both $p < .01$;

19   see Figure 3B). These group differences became statistically nonsignificant at peak

20   velocity and at the end of the primary submovement.

21   **Primary saccade amplitude.** A main effect of GROUP [$F(2, 148) = 9.44$, $p <$

22     $.01$] revealed that young adults' primary saccade amplitude ($89.7 \pm 6.4\%$) was greater

23   than those of active ($81.1 \pm 7.4\%$) and sedentary ($82.3 \pm 7.8\%$) older adults (see Figure

24   4A).

1   **Aiming movements with corrective saccades.** A main effect of GROUP [F(2,

2   148) = 10.14, $p < .01$] indicated young adults performed fewer hand movements with

3   corrective saccades (32.5 ± 15.6%) compared to active (52.5 ± 19.3%) and sedentary

4   (51.2 ± 20.8%) older adults (see Figure 4B).

5   **Cyclical Aiming**

6   **Hand movement time.** No main or interaction effects regarding hand movement

7   time were observed in the cyclical aiming task. Figure 5A clearly shows all groups were

8   able to make the aiming movements within 500 ms on average, thereby respecting the

9   high pace of the auditory cues.

10   **Endpoint accuracy.** This strict time constraint resulted in a main effect of

11   GROUP concerning the percentage of target hits [F(2, 298) = 30.63, $p < .01$]: Young

12   adults' percentage of target hits (54.5 ± 12.8%) was higher compared to the active (42.7 ±

13   14.0%) and sedentary (40.1 ± 14.7%) older participants. In accordance with their high

14   endpoint accuracy, young adults had a lower percentage of movements resulting in a

15   target undershoot (22.5 ± 9.5%) compared to sedentary older adults (31.2 ± 10.4%), who

16   in turn made relatively fewer target undershoots than active older adults (37.9 ± 12.8%)

17   [F(2, 298) = 22.85, $p < .01$]. Sedentary older adults did make more target overshoots

18   (28.7 ± 10.9%) compared to both the young (22.9 ± 9.5%) and active older (19.4 ± 8.6%)

19   adults [F(2, 298) = 8.29, $p < .01$].

20   **Peak velocity.** As in the discrete aiming task, a main effect of GROUP was found

21   [F(2, 298) = 4.37, $p < .05$] showing sedentary older adults aimed with lower peak

22   velocities (1267 ± 174 mm/s) than young (1344 ± 142 mm/s) and active older (1380 ±

23   163 mm/s) adults (see Figure 5B).

1   **Relative distance of the primary submovement.** Interestingly, a significant

2   GROUP effect was found [$F(2, 298) = 10.57$, $p < .01$], indicating active older adults

3   travelled a relatively greater distance during their primary submovement ($99.0 \pm 4.7\%$)

4   compared to young ($96.6 \pm 4.7\%$) and sedentary older ($96.5 \pm 5.4\%$) adults (see Figure

5   5C).

6   **Relative duration of the primary submovement.** A main effect of GROUP

7   [$F(2, 298) = 3.93$, $p < .05$] showed that young adults used relatively less time to perform

8   their primary submovement ($71.9 \pm 11.2\%$) than sedentary older adults ($75.9 \pm 10.9\%$).

9   Post-hoc analysis revealed that active older adults ($72.9 \pm 9.1\%$) did not significantly

10   differ from young or sedentary older adults (See Figure 5D).

11   **Temporal and spatial variability.** Young adults had a lower temporal variability

12   at peak acceleration compared to active older adults ($p < .01$), who in turn had lower SDs

13   than sedentary older adults (also $p < .01$; see Figure 6A). Comparable results were found

14   at peak velocity: Young controls were more consistent than active older adults ($p < .01$),

15   who in turn had lower SDs than their sedentary counterparts ($p < .05$). As in the discrete

16   aiming task, all temporal differences became statistically nonsignificant at the end of the

17   primary submovement. Analysis of the spatial variability revealed that the young had

18   lower SDs compared to active and sedentary older adults at peak acceleration (both $p <$

19     $.01$) and at peak velocity ($p < .05$ and $p < .01$, respectively; see Figure 6B). Again, these

20   differences became statistically nonsignificant at the end of the primary submovement.

21   **Primary saccade amplitude.** A main effect of GROUP [$F(2, 148) = 7.68$, $p <$

22     $.01$] indicated the young adults' primary saccade travelled on average further ($91.6 \pm$

23   6.2%) compared to those of active ($85.5 \pm 4.1\%$) and sedentary ($84.7 \pm 6.9\%$) older

24   adults (see Figure 7A).

1   **Aiming movements with corrective saccades.** Contrary to the discrete aiming

2   task, no main effect of GROUP was observed concerning the use of corrective saccades.

3   **Discussion**

4   In this study, we examined differences in manual aiming behavior between young

5   controls and active and sedentary older adults. In an attempt to reveal the mechanism

6   responsible for these changes, two aiming conditions (discrete aiming vs. cyclical

7   aiming) were used. Furthermore, two visual conditions (free vision vs. fixation) were

8   included to determine the contribution of visual feedback during the task. In short, this

9   experiment enabled us to investigate the following three hypotheses: First, only sedentary

10   older adults were expected to adopt the traditional age-related movement adaptations in

11   the discrete aiming task. Second, by looking into the movement variability, we examined

12   whether an *increased noise-to-force ratio* could underlie these movement adaptations. On

13   the other hand, the recent hypothesis of the *play-it-safe strategy* would be supported by

14   sedentary older adults adapting their aiming movements to a greater extent when

15   confronted with higher accuracy constraints, and an increased amount of target

16   overshoots in the cyclical aiming task. Third, sedentary older adults were expected to rely

17   more on visual feedback during the aiming movements. This hypothesis would be

18   supported by a greater drop in the accuracy levels of sedentary older adults when eye

19   movements were prohibited.

20   **Only sedentary older adults adapt their discrete aiming movements.**

21   Compared to both other groups, sedentary older adults needed more time (see

22   Figure 2A) to perform accurate goal-directed movements in the discrete aiming task.

23   Their movements were characterized by slower (2B) and shorter-ranged (2C) primary

24   submovements, resulting in a relatively larger proportion of time spent in the homing-in

25   phase (2D). As hypothesized, these typical age-related movement adaptations (Ketcham

1   et al., 2002; Poston et al., 2009; Pratt et al., 1994; Walker et al., 1997) were thus only

2   found in the sedentary older adults, but not in the physically active older adults.

3   Moreover, for the majority of variables the differences between active and sedentary

4   older adults were more pronounced than between active older adults and young controls.

5   In one case active older adults even performed better than young controls (i.e., relative

6   distance of the primary submovement in the cyclical aiming condition; see Figure 5C),

7   underlining the impact of a physically active lifestyle on older adults' aiming

8   performance. This observation should not come as a surprise, as the beneficial influence

9   of a physically active lifestyle in old age has already been described comprehensively in

10   motor control literature. For instance, the age-related degradation in interlimb

11   coordination has shown to be attenuated in older adults with a history in gymnastics

12   (Capranica et al., 2004) and soccer (Cortis et al., 2009). Also, upper-limb proprioception

13   has been demonstrated to be only mildly affected in physically active older adults

14   compared to sedentary controls (Adamo et al., 2009). Besides a general effect of physical

15   activity level, Adamo and colleagues (2009) reported an even greater impact in older

16   adults specifically involved in upper-limb activities (e.g., needlework, drawing, playing

17   tennis, etc.). Taking into account the substantial role of proprioception in accurate

18   aiming, the latter study has two major consequences for the interpretation of our data.

19   First, the general effect of physical activity implies that a better conservation of

20   proprioception among active older adults could mediate the observed differences in

21   manual aiming performance between active and sedentary older adults. Second, the

22   specific impact of upper-limb training on proprioception suggests even greater

23   differences in aiming behavior could have emerged if our active subsample was limited

24   to older adults specifically involved in upper-limb activities. Future research may

25   therefore investigate whether this distinct impact of upper-limb training also applies to

1   manual aiming. To clarify how physical activity in general and upper-limb training in

2   particular may impact the age-related changes in manual aiming, we first shed some light

3   on the mechanism underlying the movement adaptations typically observed in older

4   adults.

5   **Evidence for both the *increased noise-to-force ratio* and the *play-it-safe strategy***

6   **hypotheses.**

7   Two possible mechanisms underlying the typical age-related changes in aiming

8   behavior were investigated. On the one hand, the theory of an *increased noise-to-force*

9   *ratio* (Walker et al., 1997) was explored by looking at the variability of the movements.

10   Although differences did not always reach the level of significance, sedentary older

11   adults generally exhibited the greatest temporal and spatial variability, whereas the lowest

12   variabilty was nearly always detected in young controls (see Figure 3 and 6). These data

13   not only demonstrate a general age-related increase in noise-to-force ratio, they also

14   suggest that maintaining a physically active lifestyle in old age may counteract this

15   increase. Interestingly, differences in movement variability between active and sedentary

16   older adults emerged particularly in the cyclical aiming task when sedentary older adults

17   could not apply the traditional movement adaptations to cope with their increased noise-

18   to-force ratios. Despite our relatively small sample sizes, distinct group differences were

19   observed particularly in early kinematic markers, as one would expect in the case of a

20   deteriorated ability to plan and tune muscular forces in the sedentary older adults.

21   On the other hand, Welsh and colleagues (2007) have proposed an alternative

22   hypothesis in which the age-related changes in aiming behavior are explained by a *play-*

23   *it-safe strategy* that is generally adopted by older adults to prevent costly target

24   overshoots. In line with this hypothesis, conditions in which the strategy cannot be

25   adopted due to a strict time constraint (e.g., cyclical aiming task) should result in an

1   increased number of target overshoots. If we look at the cyclical aiming data, we indeed

2   notice more target overshoots among sedentary older adults compared to the other

3   groups. This finding supports previous results in a proprioceptive aiming task at the lower

4   limbs (Boisgontier & Nougier, 2013) and suggests the observed movement adaptations

5   were indeed a successful way to prevent target overshoots. Interestingly, evidence for this

6   being a well-chosen strategy can also be derived from the cyclical aiming movement

7   data: The strict time constraint in this condition forced all participants to move the hand

8   very rapidly. Here, sedentary older adults proved to be physically able to move at the

9   speeds reached by young and active older adults in the discrete aiming condition. Based

10   on these results we can thus conclude that in the discrete aiming condition sedentary

11   older adults were physically able to move at similar speeds as young and active older

12   adults, but intentionally choose not to do so. In contrast, active older adults may not slow

13   down the initial pulse because their force control is not degraded to the same extent as

14   their sedentary counterparts.

15   Taken together, our data suggest that instead of one distinct mechanism, the

16   movement adaptations observed in sedentary older adults may be caused by a

17   combination of both increased noise-to-force ratios and the play-it-safe strategy. If

18   moving at the same speed as young controls, sedentary older adults' primary

19   submovements have a greater temporal and spatial variability due to increased noise-to-

20   force ratios (Christou & Carlton, 2001; Galganski et al., 1993). This high variability

21   results in a greater amount of target overshoots (Elliott et al., 2001; Engelbrecht et al.,

22   2003). When sufficient time is available, the movements are slowed down to prevent the

23   high energy cost associated with target overshoots. This finally results in slower and

24   shorter-ranged primary submovements with limited spatial variability. However, as can

25   be derived from the temporal and spatial variability of the movement (see Figures 3 and

1   6), maintaining high levels of physical activity may counteract the increase in noise-to-

2   force ratio among older adults, thereby decreasing the need to adopt a play-it-safe

3   strategy.

4   **Sedentary older adults do not rely more on visual feedback.**

5   Finally, it was also hypothesized that sedentary older adults depend more on

6   visual information for the control of their aiming movements. This sensory reweighting

7   would be supported by a steeper decline in endpoint accuracy among sedentary older

8   adults when eye movements were prohibited. As can be derived from the lack of a

9   significant GROUP x VISUAL CONDITION interaction on endpoint accuracy, the

10   fixation condition did not affect sedentary older adults' aiming performance to a greater

11   extent than any other group. This seems to imply sedentary older adults do not rely more

12   on visual feedback during manual aiming compared to young or active older adults.

13   However, the lack in significant interaction could also be due to the visual conditions

14   used in the experiment: In the fixation condition, peripheral vision was still available

15   possibly guiding the hand onto the target. To exclude the use of peripheral vision, future

16   experiments may add visual conditions that take away visual information of the cursor

17   position instead of only prohibiting eye movements.

18   To control the eyes effectively fixated the midline during the fixation condition,

19   eye movements were registered throughout the experiment. Though not specifically the

20   focus of our study, we noticed both active and sedentary older adults demonstrated

21   hypometric primary saccades in the free vision condition (see Figures 4 and 7), and a

22   higher occurrence of corrective saccades (see Figure 4). The latter was observed only in

23   the discrete aiming task, perhaps because the strict time constraint of the cyclical task

24   allowed less time for corrective saccades. These results are consistent with a recent study

25   of Rand and Stelmach (2011a) in which similar results of hypometric primary saccades

1   and greater amounts of corrective saccades were described among elderly participants

2   during two-segment manual aiming. One could therefore argue that the play-it-safe

3   approach may not be limited to the hand but also occurs in saccadic behavior, even in

4   active older adults. Future studies focusing on the coupling between eye and hand

5   movements may further clarify how this altered eye movement strategy contributes to

6   accurate manual aiming in old age.

7   **Conclusions**

8   The current study underlines the beneficial effect of a physically active lifestyle

9   on manual aiming performance in old age. In the discrete aiming task, active older adults

10   performed similar to young controls without modifying their aiming behavior, whereas

11   sedentary older adults adopted the traditional age-related movement adaptations.

12   Evidence for these movement adaptations being a well-chosen strategy was derived from

13   the cyclical aiming task data. However, slightly different from the traditional

14   interpretation, the idea was raised sedentary older adults adopted a *play-it-safe strategy* to

15   prevent costly target overshoots in the face of an *increased noise-to-force ratio*. Although

16   no causal inferences should be drawn here, it seems as if there is a strong link between

17   physical activity level and the preservation of an efficient manual control during discrete

18   aiming movements in older adults that deserves further attention.

References

Adamo, D. E., Alexander, N. B., & Brown, S. H. (2009). The influence of age and physical activity on upper limb proprioceptive ability. *Journal of Aging and Physical Activity, 17*(3), 272-293.

Adamo, D. E., Martin, B. J., & Brown, S. H. (2007). Age-related differences in upper limb proprioceptive acuity. *Perceptual and Motor Skills, 104*(3), 1297-1309.

Baecke, J. A., Burema, J., & Frijters, J. E. (1982). A short questionnaire for the measurement of habitual physical activity in epidemiological studies. *The American Journal of Clinical Nutrition, 36*(5), 936-942.

Binsted, G., & Elliott, D. (1999). Ocular perturbations and retinal/extraretinal information: The coordination of saccadic and manual movements. *Experimental Brain Research, 127*(2), 193-206.

Boisgontier, M. P., & Nougier, V. (2013). Ageing of internal models: from a continuous to an intermittent proprioceptive control of movement. *Age*, *35*(4): 1339-55. doi: 10.1007/s11357-012-9436-4

Capranica, L., Tessitore, A., Olivieri, B., Minganti, C., & Pesce, C. (2004). Field evaluation of cycled coupled movements of hand and foot in older individuals. *Gerontology, 50*(6), 399-406. doi: 10.1159/000080178

Chaput, S., & Proteau, L. (1996). Aging and motor control. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences, 51*(6), 346-355.

Christou, E. A., & Carlton, L. G. (2001). Old adults exhibit greater motor output variability than young adults only during rapid discrete isometric contractions. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 56*(12), 524-532.

Coats, R. O., & Wann, J. P. (2011). The reliance on visual feedback control by older adults is highlighted in tasks requiring precise endpoint placement and precision grip. *Experimental Brain Research, 214*(1), 139-150. doi: 10.1007/s00221-011-2813-x

Cortis, C., Tessitore, A., Perroni, F., Lupo, C., Pesce, C., Ammendolia, A., & Capranica, L. (2009). Interlimb coordination, strength, and power in soccer players across the lifespan. *Journal of strength and conditioning research, 23*(9), 2458-2466. doi: 10.1519/JSC.0b013e3181bc1b39

Elliott, D., Helsen, W. F., & Chua, R. (2001). A century later: Woodworth's (1899) two-component model of goal-directed aiming. *Psychological Bulletin, 127*(3), 342-357.

Engelbrecht, S. E., Berthier, N. E., & O'Sullivan, L. P. (2003). The undershoot bias: Learning to act optimally under uncertainty. *Psychological Science, 14*(3), 257-261.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47*(6), 381-391.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research, 12*(3), 189-198.

Galganski, M. E., Fuglevand, A. J., & Enoka, R. M. (1993). Reduced control of motor output in a human hand muscle of elderly subjects during submaximal contractions. *Journal of Neurophysiology, 69*(6), 2108-2115.

Proske, U., & Gandevia, S. C. (2012). The proprioceptive senses: their roles in signaling body shape, body position and movement, and muscle force. *Physiological reviews, 92*(4), 1651-1697. doi: 10.1152/physrev.00048.2011

Helsen, W. F., Elliott, D., Starkes, J. L., & Ricker, K. L. (1998). Temporal and spatial coupling of point of gaze and hand movements in aiming. *Journal of Motor Behavior, 30*(3), 249-259. doi: 10.1080/00222899809601340

Kadota, K., & Gomi, H. (2010). Implicit visuomotor processing for quick online reactions is robust against aging. *The Journal of Neuroscience, 30*(1), 205-209. doi: 10.1523/JNEUROSCI.2599-09.2010

Ketcham, C. J., Seidler, R. D., Van Gemmert, A. W., & Stelmach, G. E. (2002). Age-related kinematic differences as influenced by task difficulty, target size, and movement amplitude. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences, 57*(1), 54-64.

Lavrysen, A., Elliott, D., Buekers, M. J., Feys, P., & Helsen, W. F. (2007). Eye-hand coordination asymmetries in manual aiming. *Journal of Motor Behavior, 39*(1), 9-18. doi: 10.3200/JMBR.39.1.9-18

Lavrysen, A., Heremans, E., Peeters, R., Wenderoth, N., Feys, P., Swinnen, S. P., & Helsen, W. F. (2012). Hemispheric asymmetries in goal-directed hand movements are independent of hand preference. *NeuroImage, 62*(3), 1815-1824. doi: 10.1016/j.neuroimage.2012.05.033

Lavrysen, A., Heremans, E., Peeters, R., Wenderoth, N., Helsen, W. F., Feys, P., & Swinnen, S. P. (2008). Hemispheric asymmetries in eye-hand coordination. *NeuroImage, 39*(4), 1938-1949. doi: 10.1016/j.neuroimage.2007.10.007

Lyons, J., Elliott, D., Swanson, L. R., & Chua, R. (1996). Use of vision in manual aiming by young and older adults. *Journal of Aging and Physical Activity, 4*(2), 165-178.

Mathiowetz, V., Volland, G., Kashman, N., & Weber, K. (1985). Adult norms for the Box and Block Test of manual dexterity. *The American Journal of Occupational Therapy, 39*(6), 386-391.

1   Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh

2   inventory. *Neuropsychologia, 9*(1), 97-113.

3   Oxford Grice, K., Vogel, K. A., Le, V., Mitchell, A., Muniz, S., & Vollmer, M. A.

4   (2003). Adult norms for a commercially available Nine Hole Peg Test for finger

5   dexterity. *The American Journal of Occupational Therapy, 57*(5), 570-573.

6   Poston, B., Van Gemmert, A. W., Barduson, B., & Stelmach, G. E. (2009). Movement

7   structure in young and elderly adults during goal-directed movements of the left

8   and right arm. *Brain and Cognition, 69*(1), 30-38. doi:

9   10.1016/j.bandc.2008.05.002

10 Pratt, J., Chasteen, A. L., & Abrams, R. A. (1994). Rapid aimed limb movements: Age

11   differences and practice effects in component submovements. *Psychology and

12   Aging, 9*(2), 325-334.

13 Pratt, J., Dodd, M., & Welsh, T. (2006). Growing older does not always mean moving

14   slower: Examining aging and the saccadic motor system. *Journal of Motor

15   Behavior, 38*(5), 373-382. doi: 10.3200/JMBR.38.5.373-382

16 Rand, M. K., & Stelmach, G. E. (2011a). Adaptation of gaze anchoring through practice

17   in young and older adults. *Neuroscience Letters, 492*(1), 47-51. doi:

18   10.1016/j.neulet.2011.01.051

19 Rand, M. K., & Stelmach, G. E. (2011b). Effects of hand termination and accuracy

20   requirements on eye-hand coordination in older adults. *Behavioural Brain

21   Research, 219*(1), 39-46. doi: 10.1016/j.bbr.2010.12.008

22 Seidler-Dobrin, R. D., & Stelmach, G. E. (1998). Persistence in visual feedback control

23   by the elderly. *Experimental Brain Research, 119*(4), 467-474. doi:

24   10.1007/S002210050362

Voorrips, L. E., Ravelli, A. C., Dongelmans, P. C., Deurenberg, P., & Van Staveren, W.

A. (1991). A physical activity questionnaire for the elderly. *Medicine and Science*

in Sports and Exercise, 23(8), 974-979.

Walker, N., Philbin, D. A., & Fisk, A. D. (1997). Age-related differences in movement

control: adjusting submovement structure to optimize performance. *The Journals*

of Gerontology. Series B, Psychological Sciences and Social Sciences, 52(1), P40-

52.

Welsh, T. N., Higgins, L., & Elliott, D. (2007). Are there age-related differences in

learning to optimize speed, accuracy, and energy expenditure? *Human Movement*

Science, 26(6), 892-912. doi: 10.1016/j.humov.2007.04.004

Woodworth, R. S. (1899). The accuracy of voluntary movement. *Psychological Review,*

3, 1-119.

Wright, M. L., Adamo, D. E., & Brown, S. H. (2011). Age-related declines in the

detection of passive wrist movement. *Neuroscience Letters, 500*(2), 108-112. doi:

10.1016/j.neulet.2011.06.015

1 **Table Captions:**

Characteristic	Young	Old	
		Active	Sedentary
n	15	13	13
Male/female	6/9	8/5	6/7
Age (in years)	**23.5 ± 0.8 *****	63.9 ± 2.5	65.1 ± 3.6
Baecke score	7.8 ± 1.0	8.3 ± 1.2	**6.1 ± 0.9 *****
Oldfield score	82.1 ± 12.2	89.9 ± 12.7	90.9 ± 11.6
NHPT (in seconds)	**16.9 ± 2.1 *****	19.0 ± 1.8	19.5 ± 2.4
MMSE score	/	29.5 ± 0.7	29.4 ± 0.8

2
3 **Table 1: Participant Characteristics.** *Note*: Results are presented as *median*
4 *(interquartile range)* when appropriate. A Kruskal-Wallis one-way analysis of variance
5 was used to compare the group scores. Significant group differences are highlighted by
6 * and *** (in case $p < .05$ and $p < .01$, respectively). *Abbreviations*:   NHPT = Nine
7 Hole Peg Test; MMSE = Mini Mental State Examination. High Baecke scores indicate a
8 physically active lifestyle, low Baecke scores a rather sedentary lifestyle; Oldfield
9 scores indicate handedness (-100: extremely left-handed, +100: extremely right-
10 handed).
11

1   **Figure captions:**
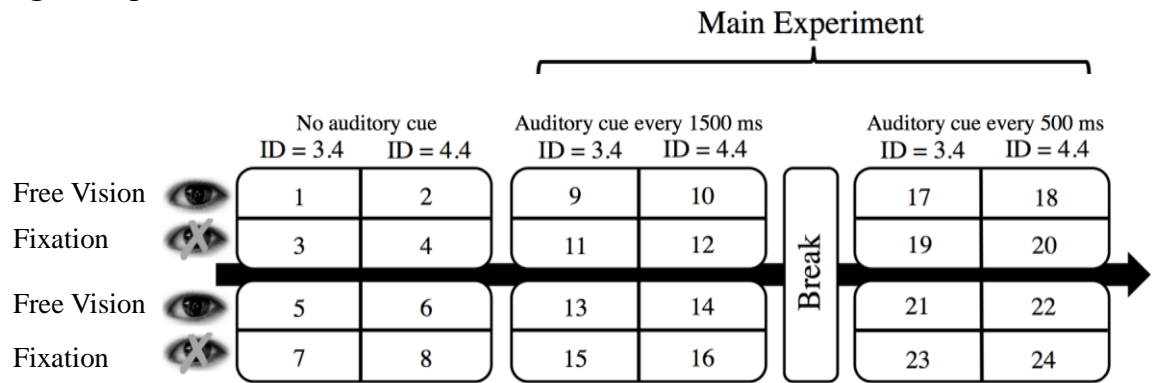
2
3   **Figure 1: Schematic overview of the experimental design.** The sequence of trials is
4   clarified by the increasing numbers and remained identical for all participants. Left:
5   familiarization, middle and right: main experiment, divided into discrete and cyclical
6   aiming (auditory cue every 1500 and 500 ms, respectively). Each trial of the main
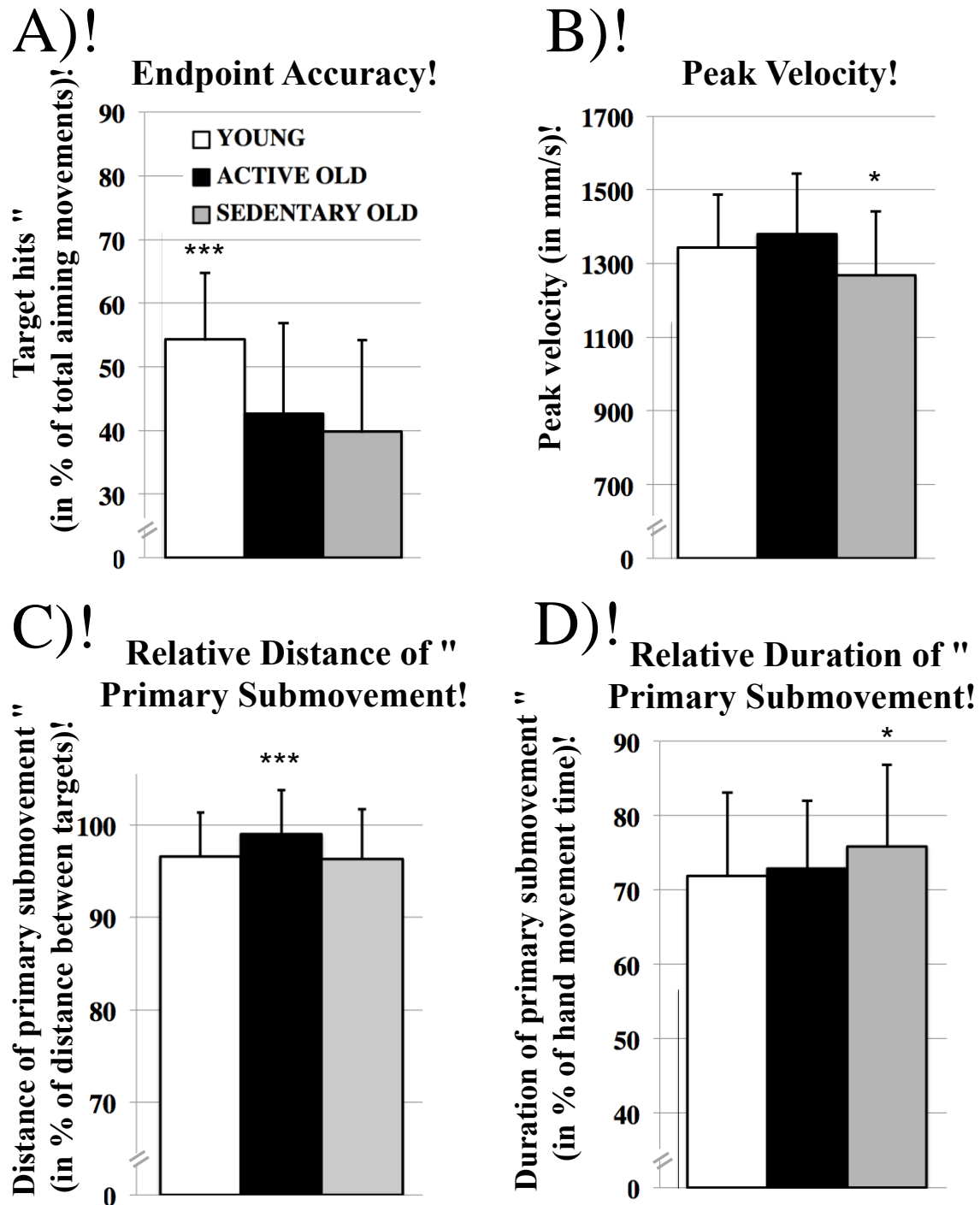7   experiment consisted of 25 aiming movements.
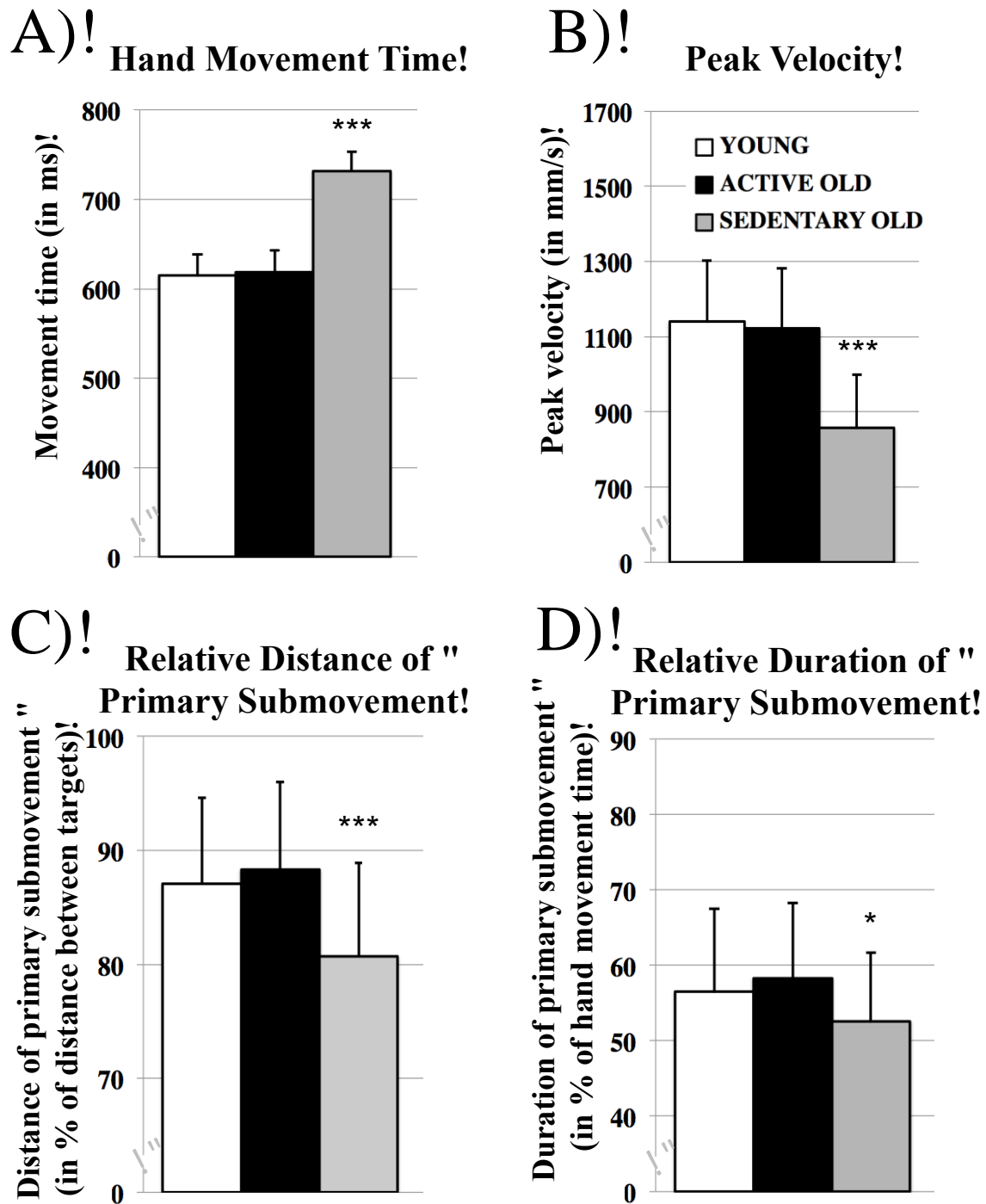
Figure 2: Hand movement results in the discrete aiming task. Comparison of mean group scores. Error bars represent standard deviations. (A) Hand movement time; (B) Peak velocity of the hand; (C) Relative distance travelled during the primary submovement; (D) Relative duration of the primary submovement. * $p < .05$. *** $p < .01$.

A)

B)
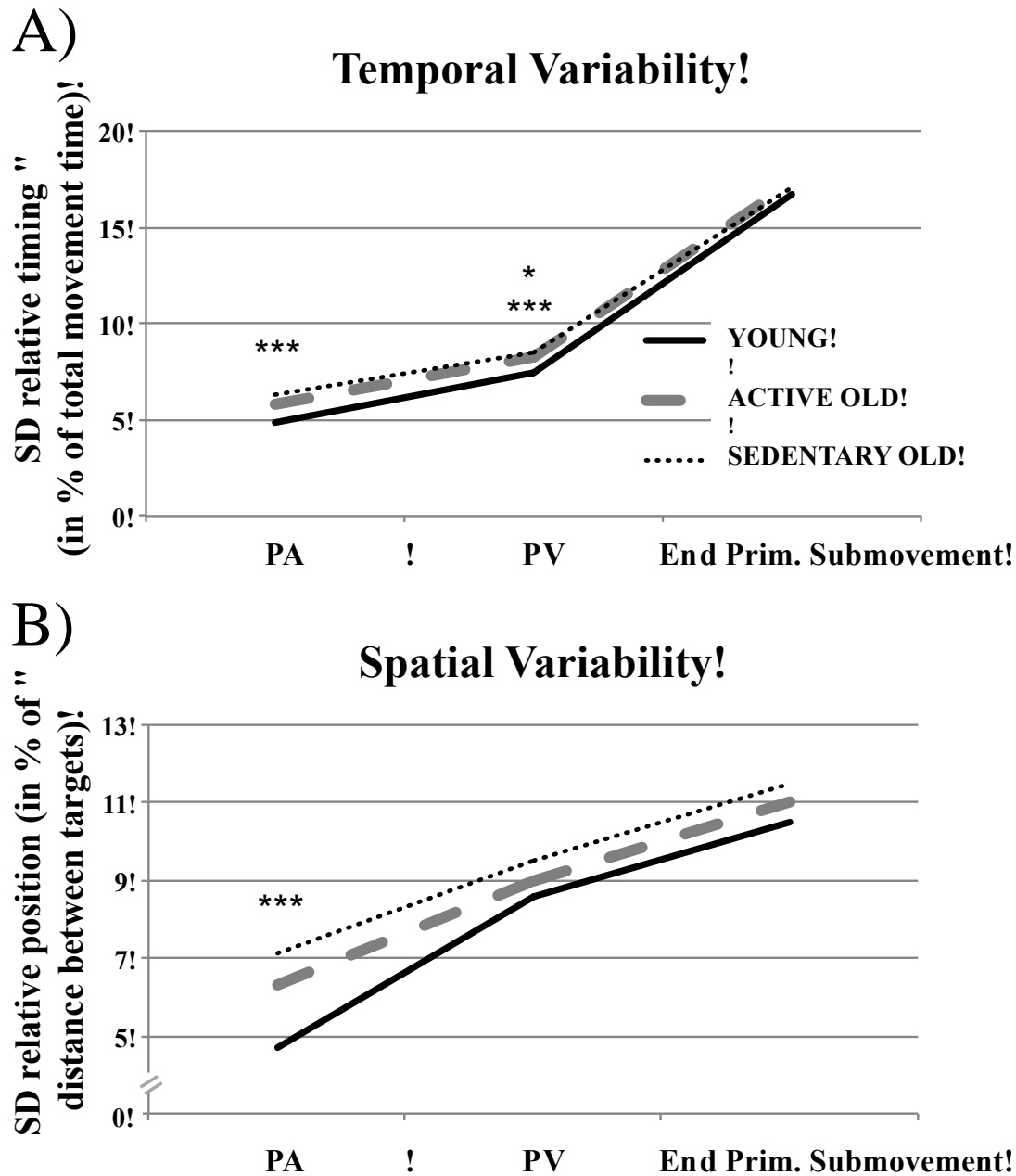
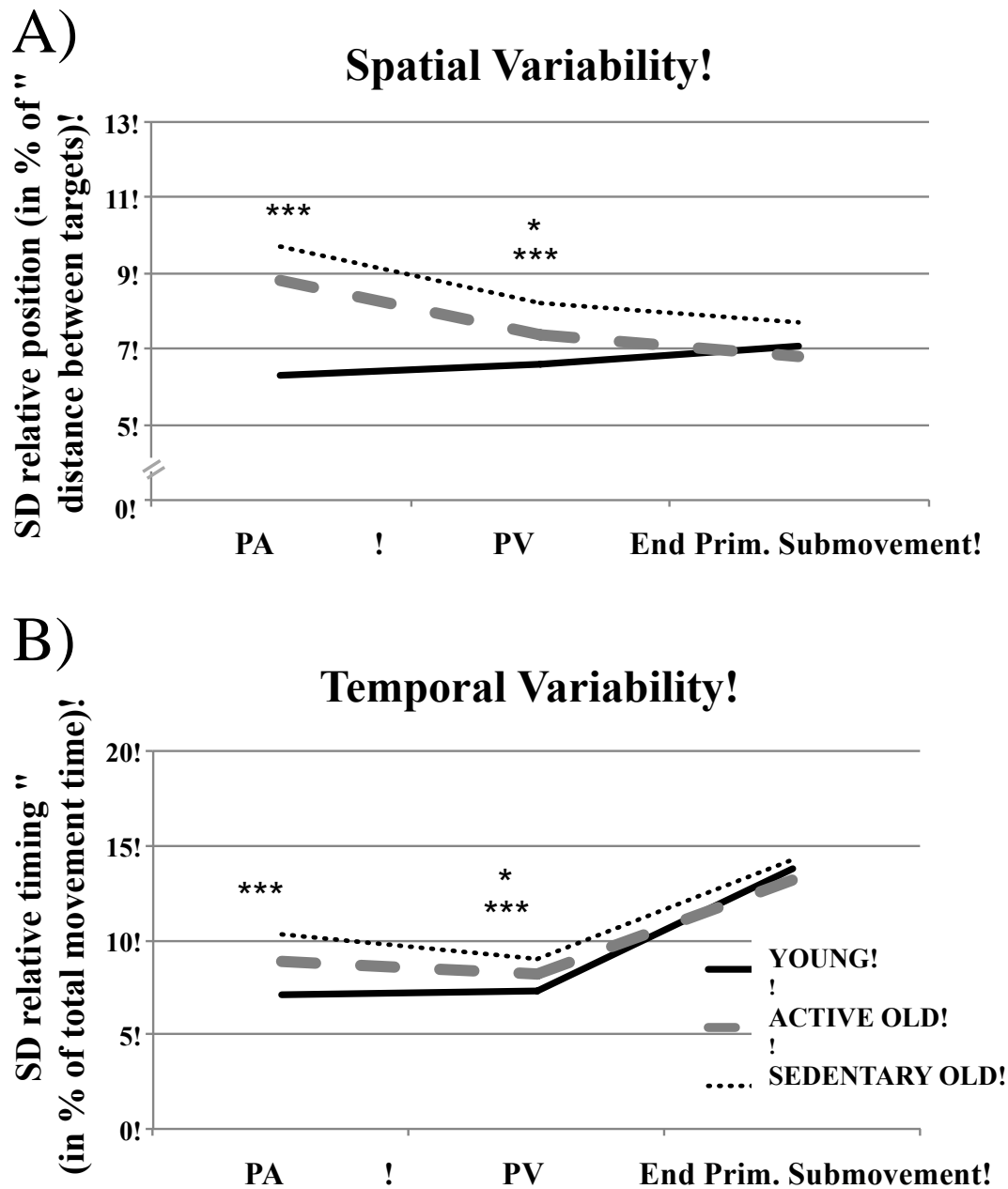Figure 3: Spatial (A) and temporal (B) variability of three kinematic markers in the discrete aiming task. *Abbreviations:* SD = standard deviation; PA = moment of peak acceleration; PV = moment of peak velocity; End Prim. Submovement = end of the primary submovement. * $p < .05$. *** $p < .01$.
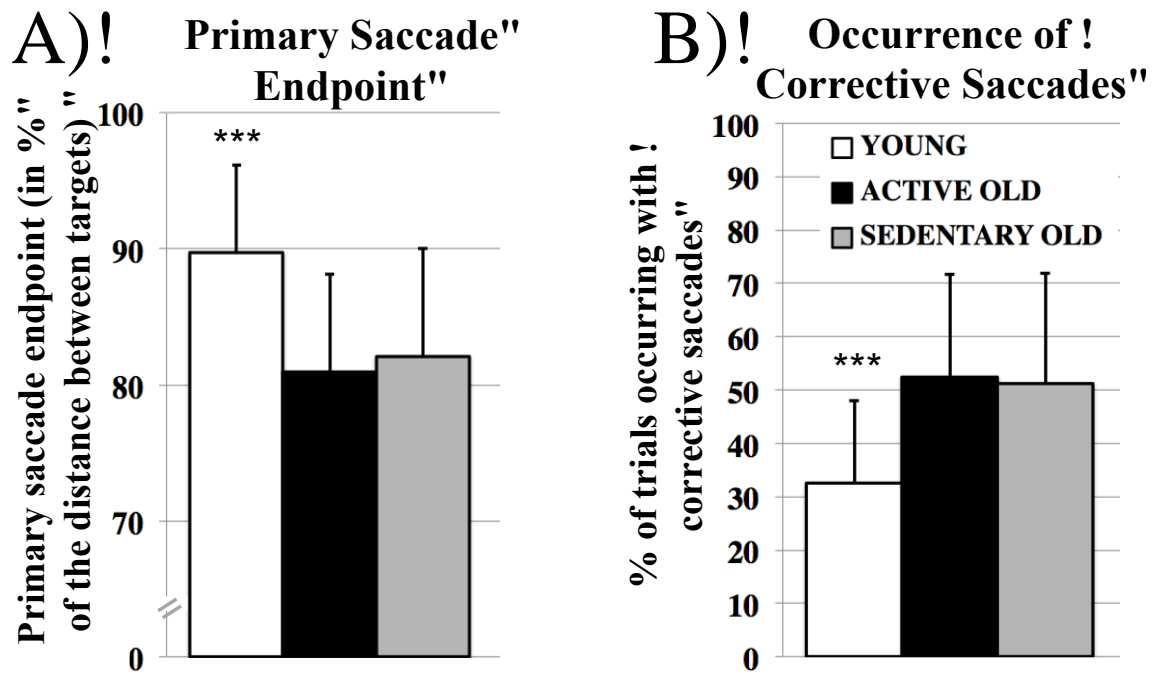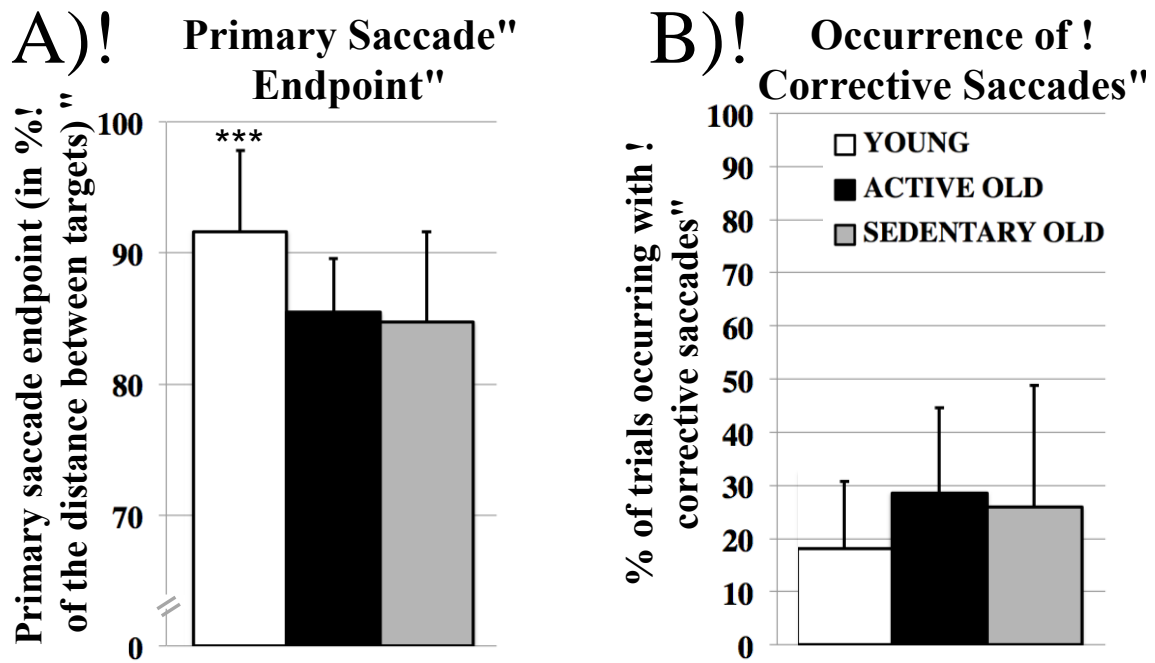
1
2 **Figure 4: Eye movement results in the discrete aiming task.** Comparison of mean
3 group scores. Error bars represent standard deviations. (A) Primary saccade amplitude;
4 (B) Proportion of aiming movements occurring with corrective saccades. * $p < .05$. *** p
5 $< .01$.

Figure 5: **Hand movement results in the cyclical aiming task.** Comparison of mean group scores. Error bars represent standard deviations. (A) Hand movement time; (B) Peak velocity of the hand; (C) Relative distance travelled during the primary submovement; (D) Relative duration of the primary submovement. * $p < .05$. *** $p < .01$.

A)

Spatial Variability!

B)

Temporal Variability!

Figure 6: Spatial (A) and temporal (B) variability of three kinematic markers in the cyclical aiming task. *Abbreviations:* SD = standard deviation; PA = moment of peak acceleration; PV = moment of peak velocity; End Prim. Submovement = end of the primary submovement. $* p < .05$. $*** p < .01$.

1
2 **Figure 7: Eye movement results in the cyclical aiming task.** Comparison of mean
3 group scores. Error bars represent standard deviations. (A) Primary saccade amplitude;
4 (B) Proportion of aiming movements occurring with corrective saccades. * $p < .05$. *** p
5 $< .01$.
6