Eye and hand movement strategies in older adults during a complex reaching task

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Abstract

The kinematics of upper limb movements and the coordination of eye and hand movements are affected by aging. These age differences are exacerbated when task difficulty is increased, but the exact nature of these differences remains to be established. We examined the performance of 12 older adults (mean age = 74) and 11 younger adults (mean age = 20) on a multi-phase prehension task. Participants had to reach for a target ball with their preferred hand, pick it up and place it in a tray, then reach for a second target ball and place that in the same tray. On half the trials (stabilising condition) participants were required to hold the tray just above the surface of the table with their non-preferred hand and keep it as still as possible. Hand and eye movements were recorded. Older adults took longer to complete their movements and reached lower peak velocities than the younger adults. Group differences were most apparent in the stabilising condition, suggesting that the added complexity had a greater effect on the performance of the older adults than the young. During pick-up, older adults preferred to make an eye movement to the next target as soon as possible, but spent longer fixating the current target during placement, when accuracy requirements were higher. These latter observations suggest that older adults employed a task-dependent eye movement strategy; looking quickly to the next target to allow more time for planning and execution when possible, but fixating on their hand and successful placement of the ball when necessary.

Key words: older adults, aging, prehension, reaching, eye-hand coordination, saccade

Introduction

Reaching out to pick up and move an object is a skill that develops in infancy, is utilised multiple times a day, and needs to be retained throughout the lifespan to enable independent living. Although there is some debate in the literature, it is generally accepted that in aiming or prehension tasks requiring a degree of accuracy and precision older adults take longer to complete their movements than younger adults, display a more asymmetric velocity profile; usually characterised by a lengthened deceleration phase, are more variable, and make more corrective movements at the end (Cooke, Brown and Cunningham 1989; Goggin and Stelmach 1990; Pratt et al. 1994; Weir et al. 1998). It is also evident that these differences between older and younger adults are exacerbated when task difficulty is increased e.g. target size decreased or target distance increased (e.g. Ketcham et al. 2002) or both hands are required (Stelmach et al. 1988). Older adults find interlimb coordination more difficult (Serrien et al. 2000), sometimes manifested by the production of a less synchronous movement (Stelmach et al. 1988), although not when synchrony was stressed in the task instructions (Coats and Wann 2012).

Most of the literature on discrete actions requiring the use of two hands concerns bimanual symmetrical movements where both hands perform the same task at the same time, or asymmetrical movements where the hands move different distances or to different targets. In both cases the hands tend to perform similar actions, albeit at different times, in different directions or to different targets. However, in everyday life we often perform a movement with one hand whilst the other is completing a different task, for example, using one hand to pour water from the kettle and the other to hold the cup. Given the prevalence of these types of task, it is important to examine how older adults perform them and whether they do so differently from their younger counterparts.

Aiming and prehension movements are historically regarded as consisting of two submovements; a primary impulse movement to bring the hand close to the target and a secondary control or ‘homing’ stage to make contact (Woodworth 1899). The former is generally considered to be ballistic and pre-programmed (open-loop), whilst the latter is under closed-loop control and utilises visual and proprioceptive feedback to correct any errors made during the movement. More recently this two-stage model has been updated to include the idea that kinaesthetic and visual information is gathered and processed throughout the movement (Spijker and Spellberg 1995; Prablanc et al. 1986; Komilis et al. 1993). Previous research has revealed that older adults tend to undershoot targets to a greater extent than young adults (Pratt et al. 1994; Coats and Wann 2011) and spend longer in the secondary submovement (Seidler-Dobrin and Stelmach 1998) but only when vision of the hand was removed (Coats and Wann 2011). This might reflect a more conservative compensatory strategy to deal with greater inherent movement variability (in part due to increases in neuromuscular noise with age), an inefficiency at using visual information (Seidler-Dobrin and Stelmach 1998), or the fact that older adults are more reliant on visual feedback (Coats and Wann 2011).

Given the role that vision plays in upper limb movements, particularly in older adults, it is important to investigate eye movements. Saccadic eye movements function to quickly move the fovea to specific locations in the visual field. Information on target location, distance, and size is then used to plan and produce a reaching movement. Eye-hand coordination studies have revealed that a saccadic eye movement towards a target usually precedes a hand movement towards the same target. In fact, Carnahan and Marteniuk (1991) and Helsen et al. (2000) found that the eyes generally fixated the target before the hand started to move towards it, to provide the system with visual information about target location to aid movement planning. Unsurprisingly, given the fact they are faster and usually initiated earlier, saccades always reached the target before hand movements did (Carnahan and Marteniuk 1991; Helsen et al. 2000).

While much of the lab-based research focused on aiming and prehension has examined single discrete movements to targets, many everyday actions are made up of multiple segments. With multiple sections to complete, the coordination of hand and eye movements becomes more complex. In such tasks, gaze typically arrives at each target before the hand, and departs for the next target at around the time the phase is complete (Flanagan and Johansson 2003). Target fixation until hand movement completion is known as gaze anchoring (Neggers and Bekkering 2000); utilised to allow visual feedback on hand and target simultaneously. However, in some instances, for example during Land and Hayhoe's (2001) multi-step tea-making task, participants moved their eyes away from the target object to the next target in the sequence before the hand reached the first target. The grasp itself was therefore not executed under visual feedback and open-loop reaching behaviour was utilised.

In general, the oculomotor literature suggests that the saccadic motor system is largely impervious to the usual effects of aging (Pratt et al. 2006; Abrams, Pratt and Chasteen 1998) at least in terms of saccade duration (Rand and Stelmach 2011). However, the coordination of hand and eye movements performed by older adults (particularly in multi-segment manual actions) is less well established. Previous research has shown that eye-hand coordination in older adults deteriorates as task complexity is increased in terms of cognitive load (Burke et al, 2014), and when a movement of the hand accompanies an eye movement older adults not only delay the start of the saccade (Warabi et al. 1986), but show increased gaze anchoring. Rand and Stelmach (2011) found that in a multi-segment aiming movement (moving a stylus to one target, stopping, and then to moving to another) all participants continued to fixate on the first target until after their hand arrived, only then making a saccade to the next target. This '$\text{hand}_{\text{offset}}$-to-$\text{eye}_{\text{onset}}$ dwell time' (gaze anchoring) was significantly longer for the older adults, suggesting either that the older adults had difficulty initiating an eye movement whilst their hand was still moving, or a conscious strategy to simplify the action. While prehension tasks might yield similar patterns of results, this has yet to be established. Reach-to-grasp movements are more complex in that, unlike aiming movements, they entail both a transport and grasp component. Using this more complex task could provide valuable insight into age related declines in the ability to coordinate multiple effectors.

We presented both young and older participants with a multi-phase prehension task. In one condition (baseline) participants had to place two objects (balls) into a pre-designated tray one at a time in a particular order. In the other condition (stabilising), participants completed the same task but were required to hold the tray and keep it steady throughout the movement. Gaze was free throughout and eye movements recorded. The purpose of the study was three-fold: to determine whether age affects performance on a multi-phase prehension task, to establish whether the age groups were differentially affected by the addition of the stabilising task, and to discover how eye movements are coordinated into the actions. It was hypothesised that both groups would be affected by the simultaneous stabilising task due to an increase in task difficulty, but the older adults to a greater extent. It was also hypothesised that given the findings of Rand and Stelmach (2011), and the reliance on visual information we found in previous studies (Coats and Wann 2011; 2012) the older adults would show increased $\text{hand}_{\text{offset}}$-to-$\text{eye}_{\text{onset}}$ dwell times.

Method

Participants

Twenty three participants took part in the study. Twelve (six female) were recruited from the University of Reading's School of Psychology Aging Panel and were remunerated £5 for their time. All were between seventy and eighty years of age (mean age = 73.75). The other eleven participants were students at the University of Reading who took part in the study on a voluntary basis or for credit as part of their undergraduate degree course (nine female, mean age = 20.18). All twenty three were right-handed (for ease of analysis) and had normal or corrected-to-normal eyesight. None had any overt movement problems. The study was approved by the University of Reading Ethics and Research Committee, and therefore performed in accordance with the ethical standards laid down in the 1964 declaration of Helsinki. Informed consent was obtained from all individual participants included in the study.

Apparatus

Participants were sat at a table on top of which were two trays and two balls. Balls were 2.5cm in diameter and the trays were 10×6×2.5cm in size. Inside each tray were two rings made from fimo™, into which the balls could be placed. The rings were 2.7cm in diameter with a hole of 10mm in diameter. They were shallow (5mm) so careful placement was required. When in the rings there was 2.5cm between the balls. The near tray was located 30cm to the left of the near ball, and the far tray was located 30cm to the left of the far ball. The trays were 14cm from each other as were the balls. The start point was located 8cm away from the edge of the table nearest the participant, and 19cm away from the line on which the near tray and ball were located (see Fig 1B).

Fig1 here

A projector and mirror were used to allow the balls and trays on the table to be lit from underneath (see Fig 1A). The surface of the table was an opaque sheet made from 6mm thick Plexiglas® and the mirror was angled underneath the surface in such a way that lights could be projected onto the surface underneath where the balls and trays were located using a Hitachi CP-X328 projector. A custom written LabVIEW program was used to control the lights.

Each participant's reaching movements were recorded by a Vicon 3D motion camera system which consisted of a data station, six infrared cameras running at 120Hz, and reflective markers (6.5mm in diameter). Markers were placed on the participant's reaching limb (nail of the index finger, nail of the thumb, knuckle of index finger, and wrist) and on the two balls and the two trays. The motion capture at the start of each trial was triggered by a +5V digital signal sent via a National Instruments data acquisition card controlled by the LabVIEW program. Capture ended after 7 seconds had elapsed. Eye movements were also recorded, using a high resolution Panasonic digital video camera (60Hz). This was attached to a miniature tripod which was placed on the far end of the table in front of the participants. The angle of viewing and extent of zooming was adjusted for each participant to ensure the eyes were visible throughout. The advantage of this more user-friendly technique over conventional eye-tracking is that it allows natural head and hand movements. The apparatus did not allow for precise spatial location of the eyes to be measured, but this was not required. The data from the camera were integrated with the Vicon system to ensure temporal synchronisation of the two data sources and allow simultaneous recordings of the hand and eye movements, which could then be analysed frame by frame along a time line to calculate the various time points of each movement. It should be noted that the difference in the sampling rate between Vicon and the camcorder means that hand events can be resolved to within ~8ms whereas gaze events can only be resolved to within ~17ms. X, Y and Z coordinates were exported from each marker and data were filtered using a low-pass Butterworth filter with a cutoff frequency of 10Hz and then underwent further analyses using Visual3D software (C-motion, USA). The time points of the eye movements were exported into an Excel file with the hand movement data for analysis. Calibration of the Vicon system was performed at the beginning of each testing session.

Procedure

The procedures for the two separate conditions to this experiment are similar but they are outlined separately below. The order of conditions was counterbalanced between participants. Before testing of each condition commenced all participants completed 2 practice trials to make sure they understood task instructions.

Baseline Condition

Participants started with their right hand on the start point, left hand on the table beside the start point, and fixated a point in the middle of the experimental set up. One of the trays was then lit up (triggering the start of video and motion capture) followed immediately by one of the balls (the go signal for participants). The participant was required to use their right hand to move to and pick up the lit ball using a precision grip (phase 1), and move it to the lit tray and place it in the left hand ring (phase 2). They then had to move to and pick up the other ball (phase 3) and place it in the right hand ring of the same tray (phase 4). During pick up and placement participants were not allowed to rest any part of the wrist or arm on the table. The order of trays and balls being lit up was the same for all participants and pseudo-randomised so participants never completed a reach identical to the previous one, and participants completed 12 trials in total (3 trials of each of the 4 different sequence types (see Figure 1B and C)). Participants were asked to move at a comfortable pace, accuracy instructions were not given.

Stabilising Condition

In this condition participants had to pick up the lit tray with their left hand and proceed to put the balls in the tray as before. Participants were told they should lift the tray at the start of the trial but instructions were no more specific than that. Participants picked up the tray using fingers and thumb by grasping the near and far edges to the left of centre. Again participants completed 12 pseudo-randomised trials in total, 3 of each sequence type (A,B,C,D). They were told to try and hold the tray as still as possible and keep it located above the location on the table from which they had picked it up. They only needed to lift it a few centimetres from the table top and were told they were not allowed to rest their left elbow on the table as this might help them to hold the tray steady. The root mean square error (RMSE) of the tray was calculated in all stabilising condition trials in two ways – over the duration of the whole trial (whole-trial task condition), and from when the right hand started to move to when its movement was complete (start-end task condition).

In order to determine the difference the prehension task made to tray stability, separate measures were taken of how still the participants could hold the tray whilst not carrying out the simultaneous reaching task. The RMSE of the tray marker was calculated in four different control trials, each lasting 7 seconds, designed to mirror the types of things participants would be doing in the actual stabilising task: 1) hold the tray, 2) hold the tray with a ball in it, 3) hold the tray but look at the right hand which is holding a ball, 4) hold the tray with a ball in it but look at the right hand which is holding the other ball. Performance on these could then be compared with tray stability during the stabilising condition and group differences examined.

Design

For most of the analyses the independent variables of interest were group (older and young) and task condition (baseline or stabilising). We also included sequence type (A,B,C,D) although this was not a variable of direct interest to us (we varied it to make sure participants weren't always completing the same movement each trial rather than because we were interested in its effects) and so collapse across it in figures. This produced a 2×2×4 design with each participant making reaches in both conditions in all sequence types.

The overall hand movement was split into various phases for analysis. The first movement refers to the movement of hand to the first ball, the second movement refers to movement of the hand with the first ball to the tray, the third movement refers to the movement of the hand from the tray to the second ball, and the fourth movement refers to the movement of the hand with the second ball returning to the tray. For each separate phase movement time, deceleration time and peak velocity were extracted from the data using the resultant of the X, Y and Z coordinates from the wrist marker. Velocity was calculated by taking the first derivative of the resultant position data for the wrist marker. For the overall movement time the start was defined as the start of the first phase and the end as the end of the fourth (final) phase. The start of the first phase was defined as when the participant moved faster than 5cm/s and end of the final phase as when the participant moved below 5cm/s. The start and end of all other phases were defined in the same way unless the velocity never crossed the 5cm/s threshold in which case they were defined as the absolute minima between neighbouring velocity profile peaks. Inter-phase intervals were obtained by calculating the time between the end of one phase and the start of the next to determine whether one group were delaying starting the next phase of the movement for longer than the other (perhaps indicating the use of extra time for planning and influencing the timing of eye movements). In the stabilising condition the time the tray was lifted was also calculated (again using the 5cm/s resultant velocity threshold) so it could be compared with the start of the movement of the right hand. Aperture closure time (phases 1 and 3) and ball final adjustment time (phases 2 and 4) were calculated to provide more information on the end of each movement phase, and further detail on planning and the use of feedback on hand position. Final adjustment time of the balls was determined by subtracting the time the hand stopped moving from the time the ball stopped moving (in both cases using the <5cm/s velocity threshold). The grip aperture was calculated by subtracting the signals of the finger marker from the thumb marker and calculating the resultant value. From this we could calculate the maximum grip aperture (MGA) and use this to determine aperture closure time (time of MGA to the time the aperture stopped getting smaller (<0cm/s velocity threshold)).

For eye movements, saccade onset and offset were determined by watching the video data frame by frame and marking frames where the eye movements were initiated and stopped. These were obvious and participants did not look back once they had made an eye movement. Saccade duration was measured by subtracting eye onset from eye offset for each eye movement. Differences between the hand and eye movements at various stages in the overall reach were also extracted. The difference between the times at which the eyes and hand movements were initiated/stopped was achieved by subtracting the time point at which the hand left/arrived from the time point at which the eyes left/arrived. Positive scores show that the eyes left or arrived at the target after the hand; negative scores that the eyes left/arrived first.

Given Land and Hayhoe's (2001) finding that the eyes usually moved away from the target object before the hand reached it so the grasp itself was not executed under visual feedback, we also examined whether the hands arrived at a ball or tray (wrist stopped moving) before or after the eyes moved to the next target ($Hand_{offset}$-to-Eye_{onset} dwell time). Wrist offset was subtracted from eye onset. Negative values represent the eyes moving away before the hand arrives, positive scores that the hand arrived before the eyes moved on (and pick up or placement carried out under visual guidance). In a few trials or parts of trials eye movements were difficult to identify so were not used to create means and therefore were not included in any analyses. This was the case for 3 young (two trials each) and 5 older (1-4 trials lost each) adults. Given the number of different ways one can determine movement end we also calculated this dwell time using the grip aperture data rather than the wrist (time at which aperture stops closing was subtracted from eye onset) for the reach-to-grasp phases (end of phase 1/1st ball pick up; and end of phase 3/2nd ball pick-up) for a more complete picture.

Intra-individual means for each dependent measure were derived from the 3 experimental trials performed in each sequence type in each condition (although, in addition to the eye movement data, for two of the participants two trials were lost due to missing markers or ambiguous velocity profiles). These means formed the basis for further statistical analysis using (unless otherwise stated below) a mixed ANOVA with a between subjects factor of group (young v older) and within subjects factors of task condition (baseline v stabilising) and sequence type (A,B,C,D). For tray stabilisation there were 8 levels of task (control1, control2, control3, control4, Sequence type A, B, C and D in the stabilising condition only). For final adjustment time, inter-phase interval and saccade duration a third within subjects factor (ball (2 levels), inter-phase interval (3 levels) and saccade (3 levels), respectively) was added to the mixed ANOVA. For time of tray lift only the stabilising condition trials were relevant so there was no condition factor. All significant interactions involving group were further explored using independent samples t-tests to examine group differences and paired samples t-tests to examine differences between conditions (alpha levels were reduced due to multiple comparisons). Other significant interactions are stated but not explored statistically as are of less interest to our research questions. For all dependent variables, when the sphericity assumption was violated values generated using the Greenhouse-Geisser correction are reported.

Results

Hand movements will be considered first, and then how eye movements are coordinated into actions. Velocity profile example trials produced by a younger adult (top row) and an older adult (bottom row) in both baseline (left column) and stabilising (right column) conditions are shown in Figure 2, with eye movements also marked.

Fig2 about here

Hand Movements

Tray Stabilisation

To explore any group differences in terms of how still the participants could hold the tray measures of tray stabilisation (RMSE) were taken during the stabilising condition of the experimental task and in four control tasks (See Table 1A for means). Findings were the same regardless of whether the whole-trial or start-end task condition was analysed. There was no significant main effect of group but a significant main effect of task was found [whole trial: $F(2.68,56.36) = 144.86$; $p < 0.001$, Start-End: $F(2.49,52.18) = 85.85$; $p < 0.001$]. Pairwise comparisons with Bonferroni corrections showed this was led by significant differences ($p<0.001$) between all the stabilising tasks and all the control tasks, but between none of the control tasks themselves or the stabilising tasks themselves. There was no interaction of task and group. The older adults were able to hold the tray as still as the young whether or not they had to carry out a simultaneous reach task.

Time of Tray lift

The time the right hand started to move was subtracted from the time of tray lift. Despite instructions both groups actually lifted the tray after starting the first hand movement but this time difference was much greater for the older adults (mean = 0.50s) than the younger adults (mean = 0.12s) [$t(15.80) = 2.97$; $p < 0.01$]. All participants had lifted the tray before they finished the first phase of the movement with their right hand (young mean = -0.66s. older mean = -0.61s), and all participants (bar two older adults) had lifted the tray before they reached peak velocity (young mean = -0.24s, older mean = -0.12s).

Movement Time

Overall movement time

Results for overall movement time can be seen in Figure 3a. There was a significant main effect of group [$F(1,21) = 6.65$; $p < 0.05$] with young adults completing the movement in less time than the older adults. There was a significant main effect of condition [$F(1,21) = 25.62$; $p<0.001$] with movements in the stabilising condition taking longer than those in the baseline condition. There was also a significant main effect of sequence type [F(3.63) = 16.48 ; p < 0.001] with movement time being shorter in type A reaches (mean = 3.459s) compared to the others (means: B=3.618s, C=3.685s, D=3.663s). A significant interaction between group and condition also emerged [F(1,21) = 8.95 ; p < 0.01]. The older adults took significantly longer to complete the movement than the younger adults in the stabilising condition (p<0.01) only. There was a significant increase in MT in the stabilising condition compared to the baseline one for the older adults (p<0.001) but not the younger ones. No further significant interactions emerged

First phase:

Results for each separate phase can be seen in Figure 3b. As with overall movement time there was a significant main effect of group for the first phase [F(1,21) = 6.15 ; p < 0.05] with young adults completing the movement in less time than the older adults. There was also a significant main effect of condition [F(1,21) = 20.92 ; p<0.001] with movements in the stabilising condition taking longer than those in the baseline condition. There was a significant main effect of sequence type [F(3,63) = 24.42 ; p < 0.001] with movement time being shorter in types A and B compared to C and D (means: A=782ms, B=779ms, C=894ms, D=883ms). A significant interaction between group and condition also emerged [F(1,21) = 8.63 ; p < 0.01]. The older adults took longer to complete phase 1 than the younger adults in the stabilising condition only (p<0.01). There was a significant increase in MT in the stabilising condition compared to the baseline one for the older adults (p<0.001) but not the younger ones after alpha level adjustment (p=0.043). No further significant interactions emerged.

Second phase:

The main effect of group proved significant [F(1,21) = 5.15 ; p < 0.05] with the older adults taking longer to complete the movement than younger adults. There was also a main effect of sequence type [F(3,63) = 37.0 ; p < 0.001] with type B movements (mean=821ms) being significantly longer than all others (means: A=723ms, C=742ms, D=733ms). There was no main effect of condition and no interactions.

Third and Fourth phases:

A main effect of group emerged [phase3: $F(1,21) = 7.85$; $p < 0.05$, phase 4: $F(1,21) = 4.90$; $p < 0.05$] with movements made by the older adults taking longer than those made by the younger adults. There was also a significant main effect of condition [phase 3: $F(1,21) = 6.08$; $p < 0.05$, phase 4: $F(1,21) = 12.18$; $p < 0.01$] with movements in the stabilising condition taking longer than those in the baseline condition. There was a main effect of sequence type [phase 3: $F(3,63) = 5.48$; $p < 0.01$, phase 4: $F(3,63) = 20.32$; $p < 0.001$] with movements of types A and B taking less time than movements of type C in phase 3 (means: A=742ms, B=738ms, C=790ms, D=764ms) and A, B and D taking less time than C in Phase 4 (mean: A=681ms, B=715ms, C=768ms, D=715ms). No significant interactions emerged for either phase.

Fig 3 here

Peak Velocity

Results for peak velocity can be found in Figure 3c.

First phase:

There was a significant main effect of group [$F(1,21) = 5.52$; $p < 0.05$] with the young adults reaching higher peak velocities than the older adults. There was also a significant main effect of condition [$F(1,21) = 7.04$; $p < 0.05$] with higher peak velocities in the baseline compared to stabilising condition. There was a significant main effect of sequence type [$F(3,63) = 342.55$; $p < 0.001$] with peak velocity being significantly higher in types C and D compared to A and B (means: A=669mm/s, B=650mm/s, C=944mm/s, D=949mm/s). No interactions emerged.

Second phase:

There was no significant main effect of group but there was a significant main effect of condition [$F(1,21) = 14.67$; $p < 0.01$] with peak velocities being higher in reaches in the baseline than the stabilising condition. There was also a significant interaction between group and condition [$F(1,21) = 5.07$; $p < 0.05$]. This was caused by the older adults reaching lower PVs than the younger adults in the stabilising condition (although this did not withstand alpha level adjustment ($p=0.034$) and the fact that velocity in the stabilising condition was much lower than at baseline for the older adults ($p<0.001$) only. There was also a main effect of sequence type [$F(3,63) = 44.06$; $p < 0.001$] (with peak velocity in type B and D movements being higher than in type A and C movements (means: A=728mm/s, B=798mm/s, C=718mm/s, D=775mm/s)) and a sequence type by condition interaction [$F(3,63) = 3.74$; $p < 0.05$]. No further significant interactions emerged

Third and Fourth phase:

A significant main effect of group emerged for Phase 3 [$F(1,21) = 12.18$; $p < 0.01$] with the younger adults reaching higher peak velocities than the older adults. There was a significant main effect of condition for both phases [Phase 3: $F(1,21) = 26.52$; $p < 0.001$; Phase 4: $F(1,21) = 24.04$; $p < 0.001$] with peak velocities being higher in reaches in the baseline than the stabilising condition. There was a significant main effect of sequence type for both phases [Phase 3: $F(1,21) = 19.30$; $p < 0.001$ (higher in type A and C compared to B and D. Means: A=864mm/s, B=805mm/s, C=877mm/s, D=803mm/s); Phase 4: $F(1,21) = 58.01$; $p < 0.001$ (highest in type C, lowest in type A, differences between all sequence types except B and D. Means: A=728mm/s, B=669mm/s, C=774mm/s, D=681mm/s] . No significant interactions emerged.

Proportion Deceleration time:

Due to the group differences in movement time the proportion of the movement spent decelerating is presented rather than absolute deceleration time. Results can be found in Figure 3D.

First phase:

No significant main effect of group emerged but there was significant main effect of condition [$F(1,21) = 21.36$; $p < 0.001$] with the proportion of the movement time spent decelerating being longer in reaches produced in the baseline condition than the stabilising one. There was a significant interaction between group and condition [$F(1,21) = 9.08$; $p < 0.01$]. The younger adults decelerated for more of the movement than the older adults in the stabilising condition and the reciprocal effect occurred in the baseline condition, but neither group difference withstood alpha level adjustment (baseline = 0.028, stabilising = 0.025). There was a decrease in the proportion of time spent decelerating in the stabilising compared to baseline condition, for the older adults only ($p<0.001$). No further main effects or interactions emerged (sequence means: A=0.565, B=0.563, C=0.563, D=0.587).

Second phase:

There was no main effect of group but there was a significant main effect of condition [$F(1,21) = 4.35$; $p < 0.05$] with the proportion of the movement time spent decelerating being longer in reaches produced in the baseline condition than the stabilising one. A significant interaction of group and condition emerged [$F(1,21) = 6.36$; $p < 0.05$]. You can see in Figure 3D that the younger adults spent a greater proportion of the phase decelerating compared to the older adults, and this difference was greater in the stabilising condition compared to the baseline one although just failed to withstand alpha level adjustment ($p=0.021$). There was also a marginally significant decrease in the proportion of time spent decelerating in the stabilising compared to baseline condition for the older adults ($p=0.018$) but not the younger adults. A main effect of sequence type also emerged [$F(3,63) = 26.63$; $p < 0.001$] with participants decelerating for more of the movement in sequence type D compared to all others and in C compared to B (means: A=0.608, B=0.595, C=0.620, D=0.646). No further significant interactions emerged

Third and Fourth phases:

For Phase 3 no significant main effect of group emerged but there was a significant main effect of condition [$F(1,21) = 4.84$; $p < 0.05$] with the proportion of the movement time spent decelerating being longer in reaches produced in the baseline condition than the stabilising one. For Phases 3 and 4 a significant main effect of sequence type emerged [Phase 3: $F(3,63) = 6.38$; $p < 0.01$ (longer in C compared to A and B. Means: A=0.588, B=0.583, C=0.613, D=0.599); Phase 4: $F(3,63) = 49.00$; $p < 0.001$ (longer in A compared to all the others, and in D compared to C. Means: A=0.665, B=0.616, C=0.597, D=0.614)]. No significant interactions emerged.

Aperture Closure Time (phases 1 and 3)

Means (and SDs) can be seen in Table 1C. A significant phase × condition × group interaction emerged [$F(1,21) = 9.11$; $p < 0.01$] so the two phases were examined separately. No main effects of group, sequence type or condition were found for either phase 1 or phase 3. A significant group × condition interaction emerged for phase 3 [$F(1,21) = 12.00$; $p < 0.01$] but not phase 1. This interaction was driven by the fact that the younger adults showed longer aperture closure times than the older adults at baseline ($p=0.023$) but there was no group difference in the stabilising condition. In addition, the older adults showed longer aperture closure times in the stabilising condition than they did at baseline ($p=0.018$) while condition had no significant effect on the younger adults. No further interactions emerged. Sequence type means: Phase 1: A=336ms, B=338ms, C=326ms, D=356ms, Phase 3: A=331ms, B=317ms, C=327ms, D=326ms.

Ball Final Adjustment time (phases 2 and 4)

Due to missing markers on the balls we only obtained ball data for 8 older and 10 younger adults. Although the ball adjustment time for the older adults (mean = 71ms, SD = 116ms) was longer than for the younger adults (mean = 39ms, SD = 61ms) there was no significant main effect of group. Likewise there was no significant main effect of condition although ball adjustment time was longer in movements in the stabilising (mean = 64ms, SD = 102ms) condition than the baseline (mean = 47ms, SD = 72ms). No main effect of ball emerged (1st ball mean = 57ms, SD = 92ms; 2nd ball mean = 52ms, SD = 89ms) and neither did a main effect of sequence type or any interactions (sequence type means: A=71ms, B=44ms, C=36ms, D=68ms).

Inter-phase intervals

Means (and SDs) can be found in Table 1B. No main effects of group, sequence type or condition emerged, and neither did any interactions. There was a significant main effect of inter-phase interval [$F(1.18,25) = 136.31$; $p < 0.001$] and pairwise comparisons with Bonferroni corrections showed this was driven by longer intervals between phases 2 and 3 (interval 2) than between phases 1 and 2 (interval 1) [$p<0.001$] or 3 and 4 (interval 3) [p<0.001] which were not significantly different from each other. Significant inter-phase interval × sequence type [$F(6, 126) = 3.91$; $p < 0.001$] and sequence type × condition [$F(3,63) = 2.76$; $p < 0.05$] interactions were found (sequence type means: A=178ms, B=185ms, C=167ms, D=190ms).

Eye Movements

Saccade duration

Saccade 1 refers to moving from the ball to the tray, saccade 2 refers to moving from the tray to the second ball, and saccade 3 from the second ball to the tray. Mean values can be found in Table 1D. Although saccade duration was longer for the older adults (89ms) than the young (69ms) no significant main effects of group, saccade or condition emerged, and nor did a significant group × condition interaction. A main effect of sequence type was found [$F(3,60) = 6.90$; $p < 0.001$] with saccades in sequence type C and D taking longer than type B (means: A=76ms, B=72ms, C=82ms, D=85ms), as was a saccade × sequence type interaction [$F(6,120) = 6.76$; $p < 0.001$].

Coordination of eye and hand movements

Eye-Hand Onset/Offset Timing (See Fig 4a)

Eye-$Hand_{onset}$1 (leave (with) 1st ball):

A significant main effect of group emerged [$F(1,21) = 4.56$; $p < 0.05$] with the older adults showing a greater hand lag compared to the younger adults. A significant main effect of condition was also found [$F(1,21) = 11.12$; $p < 0.01$] with hand lag being greater in the stabilising condition than the baseline one. No main effect of sequence type emerged and nor did any significant interactions. Sequence type means: A=-74ms, B=-73ms, C=-73ms, D=-67ms).

Eye-$Hand_{offset}$1 (arrive at tray):

A significant main effect of group emerged [F(1,21) = 5.11 ; p < 0.05] with older adults showing a larger hand lag compared to the younger adults. There was also a significant main effect of condition [F(1,21) = 14.30 ; p < 0.01] with hand lag being greater in the stabilising condition than the baseline one. A significant main effect of sequence type was found [F(1,21) = 18.40 ; p < 0.001] with hand lag being greater in sequence type B than the others (means: A=-717ms, B=-812ms, C=-741ms, D=-718ms). No significant interactions were identified.

Eye - $Hand_{onset}2$ (leave tray):

Although eye lag was greater for the older adults than the young the main effect of group just failed to reach levels of conventional significance [F(1,21) = 4.04 ; p = 0.058]. There was, however, a significant main effect of condition [F(1,21) = 28.06 ; p < 0.001] with eye lag being greater in the stabilising condition than the baseline one. There was a main effect of sequence type [F(3,63) = 26.81 , p < 0.001] driven by differences between all sequence types except between B and D. Eye lag was longest in C and shortest in A (means: A=125ms, B=167ms, C=236ms, D=176ms). A significant condition × sequence type interaction emerged [F(3,63) = 5.73, p < 0.01] as did a group × sequence type interaction [F(3,63) = 3.15, p < 0.05]. There were no group differences at baseline but eye lag was greater for the older adults than the young in all sequence types apart from A in the stabilising condition. No significant interaction between condition and group was identified.

Eye - $Hand_{offset}2$ (arrive at 2^{nd} ball):

There was no main effect of group but there was a significant main effect of condition [F(1,21) = 17.07; p < 0.001] with hand lag being greater in the baseline condition than the stabilising one. A main effect of sequence type [F(3,63) = 4.68; p < 0.01] emerged with eye lag being greater in sequence type A than C (means: A=-534 ms, B=-499ms, C=-477ms, D=-497ms). No significant interactions were identified.

Eye - $Hand_{onset}3$ (leaves (with) 2^{nd} ball):

A significant main effect of group emerged [$F(1,21) = 6.41$; $p < 0.05$] with the older adults showing a greater hand lag compared to the younger adults. There was also a significant main effect of condition [$F(1,21) = 24.63$; $p < 0.001$] with hand lag being greater in the stabilising condition than the baseline one. No main effect of sequence type or significant interactions emerged (sequence type means: A=-61ms, B=-51ms, C=-25ms, D=-46ms).

Eye - $Hand_{offset}$3 (arrive at tray):
A significant main effect of group emerged [$F(1,21) = 6.39$; $p < 0.05$] with the older adults showing a longer hand lag compared to the younger adults. There was also a significant main effect of condition [$F(1,21) = 36.87$; $p < 0.001$] with hand lag being greater in the stabilising condition than the baseline one. No significant main effect of sequence type or interactions were identified (sequence type means: A=-664ms, B=-700ms, C=-696ms, D=-672ms).

Fig 4 here

$Hand_{offset}$-to-Eye_{onset} dwell time (See Fig 4b)

1st Ball dwell time (eye leaves 1st ball – hand arrives at 1st ball):
A significant main effect of group emerged [$F(1,21) = 4.52$; $p < 0.05$] with the older adults moving their eyes away almost simultaneously as their hand arrived while the younger adults waited longer after their hand arrived before moving their eyes away from the ball. There was also a significant main effect of condition [$F(1,21) = 12.79$; $p < 0.01$] with the length of time after the hand arrived before the eyes moved away being longer in the baseline than stabilising task condition. A significant main effect of sequence type emerged [$F(2.24, 47.04) = 3.91$; $p < 0.05$] with a longer delay between hand arrival and eye onset in sequence type D compared to C (means: A=42ms, B=48ms, C=29ms, D=81ms). No significant interactions were found.

Tray dwell time (eye leaves tray – hand arrives at tray):

Positive values show the placement of the ball in the tray was always carried out under visual guidance. No significant main effect of group emerged although it was close [$F(1,21) = 3.75$; $p = 0.066$], but there was a main effect of condition [$F(1,21) = 33.32$; $p < 0.001$] with the length of time after the hand arrived before the eyes moved away being longer in the stabilising than baseline task condition. There was also an interaction of group and condition [$F(1,21) = 5.18$; $p < 0.01$]. Compared to the younger adults the older adults waited for longer after hand arrival before they moved their eyes away in the stabilising condition ($p=0.027$, although this group difference just failed to withstand alpha level adjustment) but not the baseline. Both groups waited for longer before moving their eyes away in the stabilising compared to the baseline condition (both groups $p<0.01$). A main effect of sequence type also emerged [$F(3, 63) = 12.57$; $p < 0.001$] as did a condition × sequence type interaction [$F(3,63) = 4.97$; $p < 0.01$]. The delay between hand arrival and the eye moving on was shorter in sequence type A than the rest (means: A=410ms, B=491ms, C=534ms, D=507ms). No further significant interactions emerged.

2nd Ball dwell time (eye leaves 2nd ball – hand arrives at 2nd ball):
The main effect of group was significant [$F(1,21) = 10.11$; $p < 0.01$] with the older adults moving their eyes away almost simultaneously as their hand arrived while the younger adults waited longer after their hand arrived before moving their eyes away from the ball. There was also a significant main effect of condition [$F(1,21) = 11.28$; $p < 0.01$] with the length of time after the hand arrived before the eyes moved away being longer in the baseline than stabilising condition. No main effect of sequence type emerged (means: A=69ms, B=56ms, C=71ms, D=52ms), and nor did any interactions.

$Grip_{offset}$-to-Eye_{onset} dwell time

Means (and SDs) are shown in Table 1E. Negative values show the eyes moved on before the grip aperture was closed on the object. During pick-up of the first ball the older adults showed a longer delay between moving the eyes on and subsequently finishing the reach movement by closing the aperture on the ball but this difference failed to reach levels of significance. For the second ball the main effect of group approached significance [$F(1,21) = 3.18$; $p = 0.089$] also with the time between eye onset and subsequent aperture closure being longer for the older than the younger adults. Significant main effects of condition were found [1st ball = $F(1,21) = 21.45$; $p < 0.001$; 2nd ball = $F(1,21) = 17.41$; $p < 0.001$], in both cases due to the fact that the time between eye onset and subsequent aperture closure was longer in the stabilising condition than the baseline. For the 2nd ball a main effect of sequence type emerged [$F(3,63) = 3.19$; $p < 0.05$] although there were no significant pairwise comparisons (means: A=-69ms, B=-90ms, C=-86ms, D=-55ms). No interactions were significant.

Discussion

The aim of this study was to examine how older adults performed compared to younger adults on a complex, multi-phase reaching task, whether the addition of a stabilising task with the non-dominant hand would detrimentally affect them to a greater extent, and how eye and hand movements were coordinated during the action.

Hand movements

When only the primary reaching task was required the older adults were able to complete the total movement in the same amount of time as the young adults. It was only when the additional stabilising task was added that their movement time increased such that they were no longer on a par with their younger counterparts. The same effect was found for the first phase. This increased movement time of the older adults in the stabilising condition was likely due to the fact that they did not lift the tray until well after they had started the first phase of the movement with their right hand, and the lifting motion thus interfered with the movement of the right hand causing an increase in movement time. The addition of the stabilising task increased task difficulty and had a greater effect on the older participants than the younger ones, in line with previous research (Ketcham et al. 2002) and as hypothesised. As the movement progressed through further segments the group differences remained apparent and could be seen in both baseline and stabilising conditions.

Peak velocities were higher in the baseline compared to stabilising condition regardless of movement phase. In terms of group differences, the younger adults reached higher peak velocities than the older adults until the final phase when the groups were equivalent. In the second phase the group differences were greater (although just failed to reach levels of significance after alpha level adjustment) in the stabilising condition due to a significant decrease in the peak velocity reached by the older adults compared to at baseline. Task complexity caused a reduction in peak velocity, especially for the older adults, reflecting either an inability to sustain baseline levels of performance or a change in strategy to cope with different task requirements. The older adults could have reduced the strength of muscle contractions, which would not only have reduced the variability of the right arm in terms of end point error during ball placement, but would also have caused slowing of the limb (Darling et al. 1989). There was no group difference in tray stabilisation, indicating that older adults could hold the tray as still as the younger adults once they had implemented their compensatory movement control strategy. Group differences disappeared as the movement progressed, indicating that given enough time the older adults will be able to act more like the young. This has implications for lab-based research where conclusions about aging are often made from one-movement actions.

Surprisingly, where differences in deceleration time between conditions were apparent (the first 3 phases) participants decelerated for proportionally more of the reach in the baseline condition compared to the stabilising one (although this was the case only for the older adults (not the younger) in the first two phases). This may be because participants reached lower peak velocities and/or took longer to complete each movement in the stabilising condition compared to baseline (and this was especially true for the older adults), and slower movements mean there is less need for corrective submovements and a lengthened deceleration phase. With regards to phase 1 the lifting of the tray might have delayed the time of peak velocity also. Interestingly, there was a trend towards the older adults spending less time decelerating than the younger adults in the first two phases, but only in the stabilising condition (Phase1 $p=0.025$, Phase 2 $p=0.021$). The younger adults might have utilised the deceleration portion of the movement to make their adjustments, whilst the older adults reached the tray as quickly as possible and then made their adjustments to the ball after arrival. This is in line with our previous findings (Coats and Wann, 2012).

The coordination of hand and eye movements

As mentioned in the Introduction, previous research has found that the saccadic motor system is largely resistant to the usual effects of aging (Pratt et al. 2006; Abrams, Pratt and Chasteen 1998). Our data support this, with no significant group differences in saccade duration, in line with the findings of Rand and Stelmach (2011). Any differences between the young and older adults in this study in terms of the onset or offset times of the eyes compared to the hands cannot simply be attributed to the elderly producing slower saccades.

Throughout the movement the eyes always arrived at the next target before the hand (see Fig 4a), which is unsurprising given the greater speed of eye movements, and is consistent with findings from previous research (Carnahan and Marteniuk 1991; Helsen et al. 2002). Visual information on target position is used to guide the hand to the correct location. On arriving at the second ball there were no group differences, probably because the older adults' eye lag when leaving the tray was greater than that of the young, and the young adults moved their hand faster. On arriving at the tray the hand lag was greater for the older adults than the young. This was due to both the greater movement time of the hand and a longer delay in the onset of the hand movement compared to the saccade when leaving the balls. The older adults may have needed more time to program the next phase of the movement, and so moved their eyes as early as possible to obtain the visual information on tray position necessary to plan and execute their movement. On leaving the tray the hand actually left before the eyes, although this was equivalent for both groups. This might reflect a desire to remain looking at the tray to check the ball stays in the ring, a hypothesis reinforced by the fact the eye lag was longer in the stabilising condition than the baseline, when the ball was more likely to roll out.

Given Land and Hayhoe's (2001) finding that the eyes usually moved away from the target object before the hand reached it, so the grasp itself was not executed under visual guidance, we examined whether the hands arrived at a ball or the tray before or after the eyes moved to the next target. It is clear that when picking up the ball the older adults moved their eyes away from it (to the tray) almost simultaneously as the hand arrived (wrist stopped moving). In contrast, the younger adults anchored their gaze for longer, performing the pick up under more prolonged visual guidance and moving on once their grasp was complete (aperture closed). Given the proposed greater reliance on visual feedback in older adults that we have found previously (Coats and Wann 2010; 2011) and the increased gaze anchoring found in the older adults in Rand and Stelmach's (2011) study, this was unexpected, and might reflect the idea that advance planning might be key for the older adults, who refrain from lingering on the target to monitor pick-up, but make a saccade to the next target as soon as possible to benefit from more time to utilise visual feedback on target position.

Both groups completed the placement of the ball in the tray under visual guidance as they moved their eyes away a considerable time after their wrist had stopped moving (in fact, they moved their hand away before they moved their eyes) but this delay was longer for older adults than young (although the group difference just failed to reach levels of significance ($p=0.06$)). The significant interaction showed that in the baseline condition the groups were equivalent, but in the stabilising one the older adults waited longer before moving their eyes to the next target (although this became only a trend after alpha level adjustment ($p=0.027$)). This longer gaze anchoring in the older adults is in contrast with the ball pick-up results and in line with findings from previous research (Rand and Stelmach 2011). Perhaps the arguably more complex placement task (in comparison with pick up), with its greater precision and accuracy requirements, necessitated greater visual monitoring of the ball, and this was especially so for the older adults in the stabilising condition when the task was at its most complex. This complexity theory is backed up by the fact that the gap between the end of one hand movement and start of the next (inter-phase interval) was longer at placement than pick-up. Our ball final adjustment times are also consistent with this explanation of a need for greater visual monitoring, especially in the older adults. The older adults spent almost twice as long (although group differences were not significant, perhaps because of the reduced n due to missing markers on the balls) adjusting the ball than the younger adults before leaving for the next phase, and these adjustments would presumably have required visual guidance.

Recent research with young adults has also found gaze behaviour changes depending on task demands. Safstrom et al. (2014) found two distinct gaze strategies in their aiming task in which participants moved a cursor to successively acquire visual targets, but had to refrain from moving to the next target until they had been in the current target zone for a required duration (hold-phase). Firstly, a predictive strategy where gaze moved to the next target before the cursor 'hold phase' ended, affording planning of the forthcoming cursor movement using visual feedback, or, secondly, a contrasting strategy where gaze was shifted with or just after the cursor, enabling exits to be foveated. Not only is gaze behaviour task dependent, but also dependent on the skill of the performer (Safstrom et al. 2014). It appears from our study that task demands might affect older adults differently from their younger counterparts. In this case, when placing an object (with large accuracy and precision requirements) older adults showed longer gaze anchoring, but when picking up an object they made a saccade to the next target as soon as possible (when the hand reached the current target). More research is needed, examining both spatial and temporal aspects of eye movements, to determine under what circumstances group differences are most apparent. We also concede that an eye-tracker with a higher sampling rate would be usefully employed in future studies to obtain not only a good idea of the group differences we find here, but a clearer idea of the absolute time differences between eye and hand movements.

In summary, age affects both the kinematics of prehension movements in multi-phase tasks and also the coordination of eye and hand movements. Older adults move more slowly than younger adults, reaching lower peak velocities and taking longer to complete the movement. Group differences were most apparent at the start of the movement and in the stabilising condition, suggesting that the added complexity of the stabilising task had a greater effect on the performance of the older adults than the young, and also that experiments examining only single-segment movements may not always reflect the whole picture. Differences between the young and older adults could be due to the way in which visual information is used to monitor either the hand or target upon approach and take off. It appears that where possible, the older adults prefer to make an eye movement to the next target as soon as they can, in order to benefit from the extended period of time in which to benefit from visual feedback of its location to aid their hand movement. When task requirements are most complex, however, such as when the precision and accuracy requirements around object placement are high, they prioritise this placement task and complete the movement under visual guidance, again implying that they rely on visual information to complete the task successfully. More research into the effects of age on spatial as well as temporal characteristics of eye and hand movements in multi-segment prehension tasks is necessary to determine exactly what task demands cause this change in strategy.

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References

Abrams RA, Pratt J, Chasteen AL (1998) Aging and movement: Variability of force pulses for saccadic eye movements. Psychol Aging 13(3):387

Burke MRF, Poyser C, Schiessl I (2014) Age-Related Deficits in Visuospatial Memory Are due to Changes in Preparatory Set and Eye-Hand Coordination. J Gerontol Series B: Psychol Sci and Soc Sci doi:10.1093/geronb/gbu027

Carnahan H, Marteniuk RG (1991) The temporal organization of hand, eye and head movements during reaching and grasping. J Mot Behav 23:109-119

Coats RO, Wann JP (2011) The reliance on visual feedback control by older adults is highlighted in tasks requiring precise endpoint placement and precision grip. Exp Brain Res 214(1):139-150.

Coats RO, Wann JP (2012) Reaching a better understanding of the control of bimanual movements in older adults. PloS one 7(10) e47222.

Cooke JD, Brown SH, Cunningham DA (1989) Kinematics of arm movements in elderly humans. Neurobiol Aging 10:159–165

Darling WG, Cooke JD, Brown SH (1989) Control of simple arm movements in elderly humans. Neurobiol Aging 10(2):149–157.

Flanagan JR, Johansson RS (2003) Action plans used in action observation. Nature 424(6950):769-771.

Fradet L, Lee G, Dounskaia N (2008) Origins of submovements in movements of elderly adults. J Neuroeng Rehab 5:28

Goggin NL, Stelmach GE (1990) Age-related differences in a kinematic analysis of precued movements. Can J Aging 9(4):371–385

Helsen WF, Elliott D, Starkes JL, Ricker KL (2000) Coupling of eye, finger, elbow, and shoulder movements during manual aiming. J Mot Behav 32(3):241-248.

Ketcham CJ, Seidler RD, Van Gemmert AWA, Stelmach GE (2002) Age-related kinematic differences as influenced by task difficulty, target size, and movement amplitude. J Gerontol B: Psychol Sci 57B:54–64.

Komilis E, Pelisson D, Prablanc C (1993) Error processing in pointing at randomly feedback- induced double-step stimuli. J Mot Behav 25:299-308.

Land MF and Hayhoe M (2001) In what ways do eye movements contribute to everyday activities? Vis Res 41:3559-3565

Neggers SFW, Bekkering H (2000) Ocular gaze is anchored to the target of an ongoing pointing movement. J Neurophysiol 83:639–51

Pellegrini AM, Andrade EC, and Teixeria (2004) Attending to the non-preferred hand improves bimanual coordination in children. Hum Mov Sci 23:447-360

Prablanc C, Pelisson D, Goodale MA (1986) Visual control of reaching movements without vision of the limb. 1. Role of retinal feedback of target position in guiding the hand. Exp Brain Res 62:293-302

Pratt J, Chasteen AL, Abrams R (1994) Rapid aimed limb movements: age differences and practice effects in component submovements. Psychol Aging 9(2):325–334

Rand MK, Stelmach GE (2011) Effects of hand termination and accuracy requirements on eye–hand coordination in older adults. Behav Brain Res 219(1):39-46

Säfström D, Johansson RS, Flanagan JR (2014) Gaze behavior when learning to link sequential action phases in a manual task. J Vis 14(4): 3

Seidler-Dobrin RD, He J, Stelmach GE (1998) Coactivation to reduce variability in the elderly. Mot Control 2:314–330.

Seidler-Dobrin RD, Stelmach GE (1998) Persistence in visual feed- back control by the elderly. Exp Brain Res 119:467–474

Serrien DJ, Swinnen SP, Stelmach GE (2000) Age-related deterioration of coordinated interlimb behavior. J Gerontol Series B: Psychol Sci and Soc Sci 55(5):P295-P303

Spijkers W and Spellerberg S (1995) On-line visual control of aiming movements? Acta Psychologica 90:333-348

Stelmach GE, Amrhein PC, Goggin NL (1988) Age differences in bimanual coordination. J of Gerontol Psychol Sci 43(1):18–23

Walker N, Philbin DA, Fisk AD (1997) Age-related differences in movement control: adjusting submovement structure to optimize performance. J Gerontol Series B: Psychol Sci and Soc Sci 52:40-52

Warabi T, Noda H, Kato T (1986) Effect of aging on sensorimotor functions of eye and hand movements. Exp Neurol 92:686–97

Weir PL, MacDonald JR, Mallat BJ, Leavitt JL, Roy EA (1998) Age- related differences in prehension: the influence of task goals. J Mot Behav 30(1):79–89

Woodworth RS (1899) The accuracy of voluntary movement. Psychol Rev 3(3, Suppl. 13):1–119

Yan JH, Thomas JR, Stelmach GE (1998) Aging and rapid arm movement control. Exp Aging Res 24:155-168

Figure Captions

Fig.1 Shows a 2D illustration of the experimental setup (A) and task layout (B and C). B shows sequence type A. The near tray (rectangle) was lit followed by the near ball. This ball was then placed in this tray followed by the far ball. Filled circles represent the balls, unfilled circles represent the rings into which balls were placed. C shows the other types of movements (referred to as sequence types B-D in the order displayed).

Fig.2 An example of a velocity profile for a trial produced by a younger adult (top row) and an older adult (bottom row) in both baseline (left column) and stabilising (right column) conditions. The start (unfilled squares) and end (black crosses) of each phase are marked. The vertical lines represent the onset (black line) and offset (grey line) of each saccade.

Fig.3 Shows the group × condition interaction for overall movement time (a), and the movement time (b), peak velocity (c), and proportion of the movement time spent decelerating (d) for all phases (Phase1-Phase4) for both groups in both conditions (B = baseline, S = stabilising). Lined bars represent the young adults; no lines the older adults. Error bars represent the standard error of the mean

Fig.4 (a) shows the average difference between start and end times of the hand and eye movements (Eye-Hand Onset/Offset Timing) for both groups in both conditions (B = baseline, S = stabilising). Positive scores show that the hand left before the eyes; negative scores that the eyes left/arrived before the hand. Lined bars represent the young adults; no lines the older adults. Grey shaded bars represent movements at the trays, unshaded at the ball pick up position. Error bars represent the standard error of the mean. (b) shows the $Hand_{offset}$-to-Eye_{onset} dwell time for both groups in both conditions. Positive scores show that the hand arrived before the eyes moved on (and pick up or placement was carried out under visual guidance). Negative values show the eyes moving away before the hand arrives.