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RESEARCH ARTICLE

Rachael D. Seidler-Dobrin · George E. Stelmach

Persistence in visual feedback control by the elderly[1]

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Abstract Young and elderly subjects performed aiming movements to a visual target with a manipulandum to determine whether the elderly reduce their reliance on visual feedback after extended practice. Reliance on visual feedback was assessed by performance on trials in which the cursor displaying arm movement was unpredictably extinguished. Movements were divided into two subcomponents: a primary, ballistic submovement and a secondary, corrective submovement. For both age groups, removal of visual feedback prior to practice resulted in a decrease in the distance covered in the primary submovement, an increase in the distance of the secondary submovement, and a decrease in endpoint accuracy. After extensive practice with the cursor present, the proportion of distance traveled with the primary submovement was again assessed under trial conditions in which the cursor randomly disappeared. Following practice, the young demonstrated that they were capable of extending the primary submovement distance closer to the target. In addition, primary submovement distance was unaffected by the removal of vision following practice. After practice the elderly did not show evidence of lengthening the primary submovement, and submovement distance and endpoint accuracy continued to be altered by the removal of vision. This suggests that, unlike the young, the elderly do not benefit from practice so that they can place a greater proportion of the movement under program control. Thus, on a relative basis, a greater proportion of their overall movement requires corrective adjustments.

Key words Aging · Feedback · Vision · Program control · Human

R.D. Seidler-Dobrin · G.E. Stelmach (✉)
Motor Control Laboratory, Arizona State University,
Tempe, Ariz., USA
e-mail: Stelmach@asu.edu, Fax: +1-602 965 8108

Introduction

It is well documented that increased age is accompanied by declines in motor skill performance (Spirduso 1982; Welford 1984; Seidler and Stelmach 1995, 1996a). One of the more prominent declines is an increase in movement duration as seen on a variety of tasks (Warabi et al. 1986; Brogmus 1991; Stelmach and Homberg 1993). In addition to documenting that movement slowing occurs with age, many researchers have begun to investigate the underlying mechanisms through detailed comparisons of movement kinematics between younger and older adults (Cooke et al. 1989; Darling et al. 1989; Pratt et al. 1994). This in turn allows the formulation of hypotheses regarding factors contributing to movement slowing.

The bulk of the investigations into alterations in control with increasing age have analyzed kinematics by dividing movements into an acceleration and a deceleration phase, with the instant of peak velocity being the division point. A common finding of these investigations is that the elderly have an extended deceleration phase in comparison with the young (Cooke et al. 1989; Darling et al. 1989). However, much motor control research has instead used a more natural division of movements between an initial, ballistic primary submovement and a corrective, secondary submovement(s) to explore the locus of motor control mechanisms (Woodworth 1899; Carlton 1980; Meyer et al. 1988). Recent work by Pratt et al. (1994) has investigated the effects of aging on the temporal and spatial characteristics of these two submovements. They found the incidence of corrective movements to be equally high for the young and the elderly, occurring in over 90% of the trials. In addition, the elderly subjects spent the same amount of time in the primary submovement as young subjects, but they did not cover as much distance. Thus, for a given aiming task, the young required only a small correction, while the elderly had to make a large corrective movement(s) in order to achieve the target. Performing a greater portion of the movement under feedback control as opposed

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[1] Some of this data have been presented in abstract form at the 1995 Society for Neuroscience conference, San Diego, and the 1996 Biomechanics and Neural Control of Movement conference, Ohio.

to programming control could explain much of the observed movement slowing and increased variability in the elderly.

With practice, young subjects in the investigation by Pratt et al. (1994) extended the length of the primary submovement and shortened the distance of the secondary submovement. In contrast, the elderly did not modify either submovement with practice. Since the young subjects propelled the limb a greater portion of the distance to the target in the primary submovement following practice, they required only a small corrective, secondary submovement. Such data make it reasonable to expect that young subjects are improving the motor program as a function of practice, such that reliance on feedback decreases. The elderly subjects in the investigation by Pratt et al. (1994) did not modify primary submovement distance with practice and continued to spend a greater amount of time in the secondary submovement than the young. This suggests that the elderly are not able to improve the initial ballistic phase of their movements and instead rely to a greater extent on feedback control. Since vision was present in the Pratt experiment, however, it was not certain how much of the movement was under visual guidance. A better test of programming capabilities would be to remove the subjects' view of the cursor.

Indeed, Haaland et al. (1993) have demonstrated that, upon the unexpected removal of visual information regarding arm position during movements, aiming-task performance of elderly subjects is impaired to a greater extent than that of young subjects. The elderly subjects increased movement duration and endpoint errors without vision to a greater extent than the young. This suggests that movement planning and organizational processes may be compromised with advanced age and that the elderly allocate more attentional resources for on-line monitoring than the young. This is further supported by the finding of Pohl et al. (1996) that the elderly make a greater number of movement corrections during a tapping task than the young, suggesting that more of the movement is under feedback control. These investigations did not provide extensive practice for the subjects, so nothing is known regarding whether the elderly modify visual reliance and movement structure as a function of practice. The purpose of this study was therefore to extend the primary and secondary submovement analysis in the assessment of whether visual reliance changes as a function of practice for both young and elderly adults.

Materials and methods

Subjects

Eight male and five female elderly subjects with a mean age of 71.7 ± 4.5 years were recruited from the community and paid $10.00 each for their participation, which took an average of 1 h. Four male and five female young subjects with a mean age of 27.0 ± 4.0 years were recruited from the Arizona State University campus. Their participation fulfilled undergraduate class experimentation requirements. The elderly were given a health-history questionnaire to exclude those who may have had a condition affecting their performance such as a recent history of stroke or arthritis. In addition, elderly subjects were given the Mini-Mental State test (Folstein et al. 1975) in an effort to exclude those with neurological disease or dementia. Minimum performance on the Mini-Mental test was 29 out of 30 possible points. All subjects were right-handed and all signed informed consent forms in accordance with human subjects policies.

Apparatus

The testing instrument was comprised of a lever, potentiometer, and personal computer. Subjects grasped the lever with their elbow placed over the pivot point. Lever rotations were produced by internal or external rotation of the subject's right shoulder and were represented in real time by corresponding left and right cursor movements on a computer monitor directly in front of the subjects. The cursor was a bright display 1 mm thick and 20 mm high. The home position was such that the forearm rested 30° counterclockwise from the sagittal plane, parallel with the floor. The target was achieved with an internal shoulder rotation of 50°. The target and home positions were not mechanical stops but consisted of two lines 2 mm thick, 60 mm high, and 5 mm apart on the monitor, with 200 mm between the target and home positions. None of the subjects indicated difficulty in viewing the display. To prevent visual monitoring of arm movements, a cover was placed over the arm and the lever. Data were sampled and stored from the potentiometer at 100 Hz.

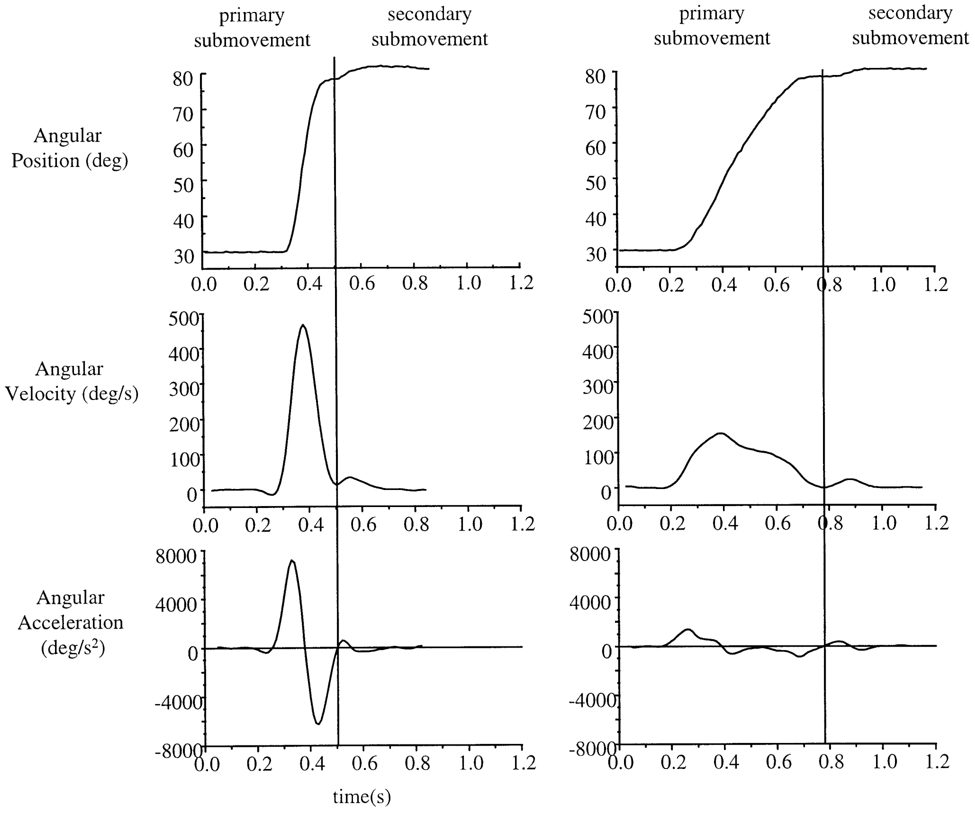
Procedure and design

Subjects were instructed to move as fast and as accurately as possible into the target upon hearing an auditory tone. Feedback of movement time and error direction was displayed on the monitor for 3 s following each trial. Although latency of response was not stressed, anticipation and no-response trials were omitted by repeating trials in which subjects did not achieve a reaction time (RT) between 100 and 1000 ms.

Subjects were provided with five explanation trials followed by an initial block of 40 trials (block 1). For this initial trial block, the cursor representing arm movement was extinguished upon the initiation of movement on ten of the trials (one randomly interspersed within every four trials). It was essential to randomize the condition presentation to ensure that subjects could not anticipate the trials without vision. The 4:1 ratio was chosen so that the subjects made their movements with the expectation that the cursor would be present. Subjects were instructed to make this movement as fast and as accurately as possible. In the subsequent trial block, subjects performed 100 trials in which visual feedback of lever movements was always available (block 2). Brief breaks were allowed as needed to minimize fatigue and maintain attention. The final trial block (block 3) consisted of 40 trials that were identical to those in block 1.

Data analysis

The angular position data were subjected to a residual analysis to determine the appropriate smoothing cut-off frequency (Winter 1990). All data were filtered at 6 Hz with a dual-pass Butterworth digital filter and differentiated to obtain angular velocity and acceleration data. As sampling was initiated upon target presentation rather than movement initiation, the following algorithm was used to determine movement onset: first, the point at which the velocity of movement exceeded 10% of the peak velocity was found (V_{10}). Then the algorithm worked backwards from V_{10} until the velocity amplitude had decreased by 10% of the peak amount. The time at this sample was marked as movement onset. As sampling was terminated when subjects remained stationary for 300 ms, the same algorithm was used in reverse to determine movement offset. The existence of secondary submovements was determined by an algorithm that searched for a positive acceleration value following peak velocity,



A. Young Subject

B. Elderly Subject

Fig. 1A, B Movement kinematics. Sample data from one young (**A**) and one elderly subject (**B**) is presented to illustrate the submovement parsing method. The *top trace* displays angular position versus time, the *middle trace* displays angular velocity versus time, and the *lower trace* displays angular acceleration versus time. The *vertical line*, drawn at the instant when acceleration is first positive after the deceleration phase, separates the primary submovement from the secondary submovement

as shown in Fig. 1. The parsing routine of Pratt and colleagues (1994; Pratt and Abrams 1996) was similar, except that their algorithm also searched for an inflection in the acceleration profile, signifying an increase in braking force. This was not included here, as Chua and Elliott (1993) have suggested that these fluctuations may be reflective of feedforward adaptations rather than discrete corrections. For trials in which there was a positive acceleration value following peak velocity, the instant at which acceleration exceeded zero was termed both the end of the primary submovement and the beginning of the secondary submovement. While it is acknowledged that multiple corrective submovements may occur, they were considered as one submovement for the purposes of this analysis. Trials not containing corrective submovements were excluded from mean calculations of secondary submovement amplitude and duration.

Performance differences between block 1 and 3 were analyzed with an Age (2) × Condition (2) × Practice (2) ANOVA with repeated measures on Practice (pre and post) and Condition (with or without visual information), with the alpha rate set at 0.05. The repeated measures were treated as multivariate to ensure a robust analysis.

Data from one of the young subjects was omitted due to mechanical errors during acquisition. Therefore, scores for eight young subjects and 13 elderly were included in the data analysis.

Results

Prepractice age differences with vision

Table 1 presents mean performance characteristics for all conditions. Figure 1 plots sample data for a young and an elderly subject prior to practice. There was no significant difference in the peak velocity amplitude; however, the time to peak velocity differed such that the elderly spent more time in the deceleration phase of the primary submovement than the young ($F_{(1,19)} = 4.81$, $P < 0.05$). Otherwise, prior to practice, performance was similar for the young and the elderly. There was no age group difference in the mean number of corrections performed per movement (1.13 for the young and 1.32 for the elderly). Both age groups propelled the limb the same distance in the primary submovement. There was a trend for the elderly to travel further in the secondary submovement than the young, with the young covering 2% of the total distance and the elderly covering 4% of their total distance in this phase of the movement ($F_{(1,19)} = 3.95$, $P = 0.06$). Despite the consistent slowing by the elderly throughout the movement, age differences for the duration of each submovement were not significant. Both age groups spent approximately 65% of the total duration in the primary submovement and 35% in the secondary submovement. The elderly tended to be less accurate in their movements than the young prior to practice; the young subjects hit the target on 52% (18) of the trials while the elderly only achieved the target on 42% (14) of the trials ($F_{(1,19)} = 3.25$, $P = 0.09$).

Prepractice age differences without vision

Both age groups were substantially affected by the elimination of visual information of arm position, as evidenced by the decrements in performance on trials without visual information (significant main effects for Condition). These declines in performance were roughly equal in magnitude for both groups. Removal of visual information produced differential effects on submovement distances. Without visual information, primary submovements became shorter by about 5% of the primary submovement distance ($F_{(1,19)} = 10.13$, $P < 0.01$) and secondary submovements increased by about 85% of the secondary submovement distance ($F_{(1,19)} = 11.75$, $P < 0.01$). There was no change in the number of corrections performed per movement.

Elimination of visual information resulted in substantial movement slowing; total movement duration increased by approximately 300 ms for both groups ($F_{(1,19)} = 75.09$, $P < 0.01$). This increase in total movement duration was a result of increases in both the primary submovement duration ($F_{(1,19)} = 139.97$, $P < 0.01$) and the secondary submovement duration ($F_{(1,19)} = 13.88$, $P < 0.01$). Both age groups were therefore spending 60% of the total duration in the primary submovement and 40% in the secondary submovement.

Elimination of vision of arm position resulted in an increase in constant, absolute, and variable endpoint errors for both age groups ($F_{(1,19)} = 4.07$, $P = 0.05$; $F_{(1,19)} = 33.41$, $P < 0.01$; $F_{(1,19)} = 108.47$, $P < 0.01$, respectively). In addition, subjects decreased their target hit rate from roughly 50–10% (significant main effect for Condition, $F_{(1,19)} = 79.40$, $P < 0.01$).

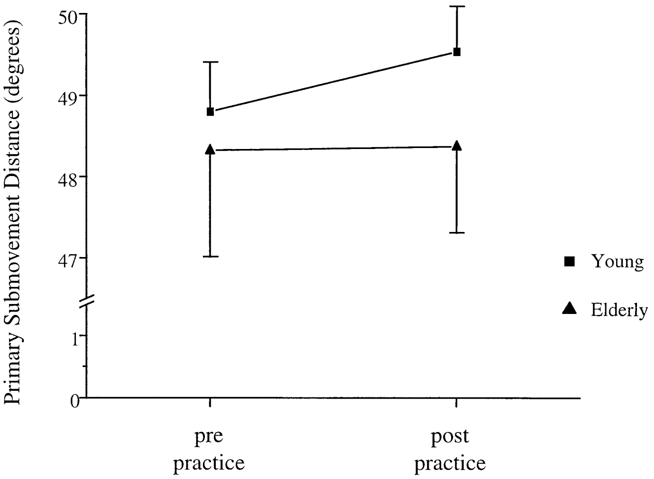


Fig. 2 Primary submovement distance. The young increased primary submovement distance as a function of practice with vision, while the elderly did not

Postpractice effects on age differences with vision

There were no significant changes in total distance for either age group with respect to prepractice. The elderly did not change the distance covered in the primary submove-

Table 1 Performance characteristics

	Prepractice				Postpractice			
	Young		Elderly		Young		Elderly	
	With vision	Without vision	With vision	Without vision	With vision	Without vision	With vision	Without vision
Primary submovement distance (deg)								
Mean	48.80	46.33	48.32	46.05	49.54	49.37	48.37	47.32
SD	(0.61)	(2.48)	(1.31)	(2.55)	(0.56)	(1.17)	(1.06)	(3.96)
Secondary submovement distance (deg)								
Mean	1.13	2.65	2.03	3.48	0.66	1.23	1.60	2.10
SD	(0.76)	(1.84)	(1.51)	(2.30)	(0.43)	(0.93)	(1.08)	(1.78)
Total movement distance (deg)								
Mean	49.94	48.98	50.35	49.54	50.20	50.60	49.96	49.42
SD	(0.24)	(1.79)	(1.70)	(1.94)	(0.46)	(1.63)	(0.25)	(4.25)
Primary submovement duration (ms)								
Mean	481	562	554	673	458	598	515	628
SD	(150)	(152)	(132)	(157)	(143)	(193)	(142)	(165)
Secondary submovement duration (ms)								
Mean	286	489	358	515	231	308	306	390
SD	(49)	(176)	(80)	(202)	(52)	(59)	(75)	(245)
Total movement duration (ms)								
Mean	769	1053	883	1137	691	908	775	914
SD	(184)	(268)	(140)	(205)	(167)	(171)	(166)	(262)
Constant endpoint error (deg)								
Mean	−0.08	−1.23	−0.37	−1.04	0.01	–.05	−0.04	−2.00
SD	(0.26)	(1.67)	(0.50)	(3.59)	(0.15)	(0.27)	(0.25)	(2.89)
Absolute endpoint error (deg)								
Mean	0.37	2.55	0.56	3.18	0.31	1.88	0.37	3.49
SD	(0.37)	(1.04)	(0.52)	(2.79)	(0.25)	(0.78)	(0.22)	(1.96)
Variable endpoint error (deg)								
Mean	0.59	2.70	0.64	3.21	0.53	2.19	0.64	2.32
SD	(0.49)	(1.40)	(0.26)	(1.28)	(0.30)	(0.92)	(0.24)	(1.10)
Target hit rate ratio								
Mean	0.52	0.12	0.42	0.08	0.53	0.18	0.54	0.06
SD	(0.18)	(0.12)	(0.14)	(0.10)	(0.22)	(0.07)	(0.13)	(0.09)

ment as a function of practice, while in contrast the young subjects propelled the arm a significantly greater proportion of the total distance with the primary submovement following practice (Age × Practice interaction: $F_{(1,19)} = 3.05$, $P = 0.09$), leaving them only 0.50° from the target, as shown in Fig. 2. Both age groups demonstrated a shortening in the distance traveled to the target with the secondary submovement following practice (practice main effect $F_{(1,19)} = 7.87$, $P = 0.01$). In addition, both groups reduced the mean number of corrections performed per trial ($F_{(1,19)} = 26.19$, $P < 0.001$) (0.95 for the young and 1.03 for the elderly).

The young and the elderly reduced total movement time as a function of practice by about 100 ms (significant main effect of Practice, $F_{(1,19)} = 16.34$, $P < 0.01$). Both the young and the elderly spent about 50 ms less in the secondary submovement with respect to prepractice (Practice main effect, $F_{(1,19)} = 28.77$, $P < 0.001$). Both the young and the elderly were therefore spending 65% of the total duration in the primary submovement and 35% in the secondary submovement following practice.

There were no significant declines in the magnitude of endpoint errors for either age group following practice with vision. The elderly subjects did, however, increase their target hit rate with vision following practice, while the young did not. This result produced a significant three-way interaction, because performance without vision did not follow the same trend, as discussed in the next section (significant Age × Condition × Practice interaction, $F_{(1,19)} = 7.41$, $P = 0.01$). The follow-up Age × Practice (with vision) contrast was significant at $F_{(1,19)} = 3.38$, $P = 0.08$, reflecting that the elderly subjects increased their target hit rate ratio as a function of practice, while the young did not demonstrate significant practice improvements. Thus, there was no age difference in target hit rate with vision following practice.

In summary, improvements as a function of practice on trials with vision were different for each age group. The elderly did not increase the distance covered with the primary submovement, while the young did. Nevertheless, both the young and the elderly decreased the duration of and the distance covered in the secondary submovement. In addition, only the elderly subjects increased target hit rate as a function of practice with vision, bringing them up to the same level as the young subjects.

Postpractice effects on age differences without vision

There were no significant effects between age group for visual condition on total distance following practice, similar to prepractice. The same group × time interaction that applied to primary submovement distance with vision applies here as well, such that the young increased primary submovement distance without vision while the elderly did not ($P = 0.09$). Although the three-way interaction was not significant, there was a trend for the young subjects to cover the same distance in the primary submovement regardless of whether they had visual information following practice while the elderly did not, as seen in Fig. 3. They increased the proportion of the total distance covered with the primary submovement from 93% to 99%. Following practice, both age groups continued to cover a greater distance in the secondary submovement upon the extinction of visual information.

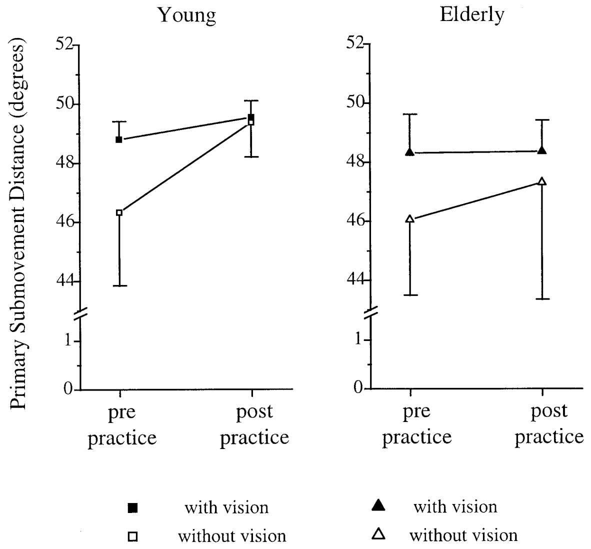


Fig. 3 Primary submovement distance and visual feedback reliance. Following practice, the young covered the same distance in the primary submovement regardless of whether they had visual information available. The elderly, meanwhile, were still affected by the removal of visual information following practice

The effect of removing visual feedback information on total movement time still existed but was reduced following practice for both groups. The increase in total movement duration as a result of removing vision was 300 ms prior to practice and was reduced to roughly 150 ms for both age groups following practice, resulting in a significant Condition × Practice interaction, $F_{(1,19)} = 6.22$, $P < 0.05$. This was due to the reduction in time spent in both the primary and the secondary submovement for both groups without vision following practice (significant Condition × Practice interactions: $F_{(1,19)} = 5.90$; $P < 0.05$, $F_{(1,19)} = 7.88$, $P = 0.01$, respectively). The young spent 65% of the total duration in the primary submovement following practice without vision and 35% in the secondary submovement, while proportions for the elderly were 70% and 30%, respectively.

The young subjects increased target hit rate without vision as a function of practice, while the elderly showed no significant change in performance (follow-up contrasts resulted in a borderline Group × Practice without vision effect, $F_{(1,19)} = 2.88$, $P = 0.10$). The same pattern of results was observed in the constant and absolute endpoint error data; the young subjects tended to decrease constant and absolute endpoint error without vision following practice while the elderly did not ($P < 0.10$). These endpoint accuracy measures thus support the hypothesis that, following practice, the young subjects are less reliant on visual information to achieve the target, while the elderly are not. Both age groups did demonstrate a reduction in variable error without vision, resulting in a significant Condition × Time interaction $F_{(1,19)} = 5.46$, $P < 0.05$)).

Discussion

Prior to practice, the young and the elderly subjects covered essentially the same distance in the primary submovement, although the elderly moved slightly slower. The proportion of the distance covered in the primary submovement was larger than that seen in other investigations (Abrams and Pratt 1993; Pratt et al. 1994); possibly reflecting the difference in parsing algorithms used. The general pattern of results does concur with those of other investigators, however. Since the primary submovement is assumed to reflect mostly the program-controlled portion of the movement, the lack of age difference in the distance covered suggests that, for unpracticed conditions, elderly and young adults program the movement endpoint in a similar fashion. The finding that both younger and older adults spend the same amount of time in the primary submovement supports the suggestion of Pratt et al. (1994) that both age groups seek feedback information at the same point in the movement. Despite the similarity in the primary submovement distance for the young and the elderly, the elderly spent a greater proportion of the primary submovement decelerating, suggesting that the details of this submovement are planned differently for the elderly than for the young. In addition, the elderly subjects traveled a greater distance and spent more time in the secondary submovement than the young prior to practice, suggesting that they were making either ineffective and/or multiple corrections. This result concurs with those of Pratt et al. (1994). The greater time spent in the secondary submovement by the elderly prior to practice would suggest a greater reliance on visual feedback than the young subjects. However, the elderly were not disrupted to a greater extent than the young when visual feedback was removed prior to practice. The longer secondary submovement prior to practice may instead reflect a decreased efficiency in using visual feedback information for the elderly, rather than a greater reliance on this information.

The observation of larger-amplitude and longer duration secondary submovements without vision concurs with the results of Pratt and Abrams (1996), who tested young adults on an aiming task without vision. The fact that corrections are made in the absence of vision may seem curious; it is likely, however, that subjects used proprioceptive information to guide these corrections. Proprioceptive information is not as accurate as visual feedback, which may explain the increase in amplitude and duration of these corrections.

The 100 practice trials provided in this investigation were sufficient to bring about changes in performance for both age groups, accompanied by changes in the underlying kinematics. The young subjects increased the distance traveled in the primary submovement following practice, similar to the findings of Pratt and colleagues (1994; Abrams and Pratt 1993). This implies that, with practice, the young extend the length of the primary submovement so that they have fewer adjustments to make in order to reach the target. While this change was small, it was quite consistent across subjects. The elderly, in contrast, did not increase the distance covered in the primary submovement, suggesting that they do not have the capability to alter their movement substructure following practice.

The elderly subjects tended to decrease total movement distance slightly following practice. This issue makes it difficult to compare the magnitude of relative changes in primary and secondary submovement distance between the young and the elderly. Accepting all trials into the analysis rather than only those that hit the target, however, provides a clearer picture of actual performance. Both the young and the elderly subjects in the current investigation decreased the distance covered in the secondary submovement as a function of practice. For the young subjects, this decrease in secondary submovement distance was accompanied by an increase in primary submovement distance, further supporting the notion that the young reduce reliance on feedback control following practice and preprogram a greater portion of the movement. They also concurrently demonstrated a reduced reliance on visual information following practice. The elderly subjects, in contrast, decreased secondary submovement distance and the number of corrections performed per trial without increasing primary submovement distance, suggesting that rather than decreasing reliance on feedback they were instead becoming more efficient at using feedback information and making more effective corrections. In addition, their performance was disrupted to a greater extent than that of the young subjects upon the extinction of visual information following practice.

Following practice, the young subjects increased the primary submovement distance and covered the same distance with it regardless of whether they had visual information, although they did move more slowly without vision. These results suggest that the young have improved their movement program.The elderly, however, covered less distance in the primary submovement without visual feedback than with visual feedback both pre- and post-practice. In addition, the young substantially decreased constant and absolute errors while increasing their target hit rate when tested without visual information following practice, while the elderly did not. These results imply, that following practice, the elderly maintain reliance on visual feedback while the young reduce reliance on visual information. These results concur with those of Haaland et al. (1993), who have shown the elderly to be more reliant on visual information than the young. Pohl et al. (1996) also suggested that the elderly are more reliant on feedback control, because they made a greater number of corrective movements during the performance of a tapping task than the young.

The elderly subjects' greater reliance on visual feedback appears to be related to impaired programming abilities. Much research has demonstrated that the elderly have a reduced capability to prepare movements and that they cannot maintain this preparation as well as young subjects (Gottsdanker 1980; Stelmach et al. 1987; Amrhein et al. 1991). This notion is further supported by the breakdown in antagonist EMG activity observed during aiming movements for the elderly (Darling et al. 1989). These authors reported that antagonist activity was either not present or was improperly timed such that it overlapped extensively with the primary agonist burst. Seidler and Stelmach (1996b) have also demonstrated irregularities in EMG patterns for the elderly; the elderly did not time antagonist inhibition such that it preceded the initiation of the agonist burst to the same extent that the young subjects did. The elderly also coactivated their muscles for a greater portion of the movement than the young. Coactivation that occurs early in the movement may be responsible for the shortened primary submovement in the elderly.

Shortened primary submovements may also reflect a conservative strategy for the elderly, due to the inherent increase in variability, making it difficult to predict the location of the endpoint of the primary submovement. It is well established that movements for the elderly are more variable and jerkier than those of the young (Cooke et al. 1989; Darling et al. 1989; Seidler and Stelmach 1995). Increased movement variability has been suggested to be related to the neuromuscular changes that occur with age (Cooke et al. 1989; Darling et al. 1989; Galganski et al. 1993; Booth et al. 1994). Specifically, motoneuron death occurs with increasing age (Campbell et al. 1973; Oda 1984; Kanda and Hashizume 1989). Some of the muscle fibers that were previously innervated by these motoneurons are reinnervated by the remaining motoneurons. These newly grouped motor units produce greater force, due to the greater number of muscle fibers per motor unit. Thus the elderly are left with less-refined control over force gradation than the young. Indeed, Galganski et al. (1993) have demonstrated that the elderly exhibit greater force variability per force ratios than the young at varying percentages of maximal force. This increased variability may reduce the precision of movement endpoint prediction in the elderly. Thus they may choose to always undershoot the target and then attempt to correct for errors due to increased movement variability.

Impaired sensory processes may also contribute to the elderly not modifying submovement distance as a function of practice. Recent work by Sainburg et al. (1995) has demonstrated that patients with peripheral sensory neuropathy are unable to update their internal model in the performance of an arm-aiming task. The well-documented declines in proprioception with aging (Skinner et al. 1984; Stelmach and Sirica 1986) may prevent elderly subjects from updating their movement plan for the initial, ballistic phase of the movement. As a result of this inflexibility, they would be unable to alter the length of the submovement.

The young and the elderly subjects in this investigation were equally reliant on visual feedback prior to extensive practice. The young were able to increase the distance covered in the primary submovement as a function of practice, but the elderly were not. Following practice, the elderly maintained their reliance on visual feedback, while the young decreased their dependence on it. This relationship between the proportion of the total movement distance that is covered with the primary submovement and the level of reliance on visual feedback has not been previously demonstrated. Overall, the results imply that young subjects are capable of improving the programmed portion of an aiming movement following practice, while the elderly are not. This requires the elderly to make corrective adjustments, causing them to be slower than the young on maximal speed-aiming tasks.

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References

Abrams RA, Pratt J (1993) Rapid aimed limb movements: differential effects of practice on component submovements. J Mot Behav 25:288–298

Amrhein PC, Stelmach GE, Goggin NL (1991) Age differences in the maintenance and restructuring of movement preparation. Psychol Aging 6:451–466

Booth WF, Weeden SH, Tseng BS (1994) Effect of aging on human skeletal muscle and motor function. Med Sci Sport Exerc 556–560

Brogmus GE (1991) Effects of age and sex on speed and accuracy of hand movements and the refinements they suggest for Fitts' Law. In: Proceedings of the Human Factors Society 35th Annual Meeting. Human Factors Society, Santa Monica, CA, pp 208–212

Campbell MJ, McComas AJ, Petito F (1973). Physiological changes in aging muscles. J Neurol Neurosurg Psychiatry 36:174–182

Carlton LG (1980) Movement control characteristics of aiming responses. Ergonomics 23:1019–1032

Chua R, Elliott D (1993) Visual regulation of manual aiming. Hum Mov Sci 12:365- 401

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 10:149–157

Folstein MF, Folstein SE, McHugh PR (1975) Mini-Mental State, a practical method for grading the cognitive state of patients for the clinician. J Psychosom Res 2:189–198

Galganski ME, Fuglevand AJ, Enoka R (1993) Reduced control of motor output in human hand muscle of elderly subjects during submaximal contractions. J Neurophysiol 69:2108–2115

Gottsdanker R (1980) Aging and the use of advance probability information. J Mot Behav 12:133–143

Haaland KY, Harrington DL, Grice JW (1993) Effects of aging on planning and implementing arm movements. Psychol Aging 8:617–632

Kanda K, Hashizume K (1989) Changes in properties of the medial gastrocnemius motor units in rats. J Neurophysiol 61:737–746

Meyer DE, Abrams RA, Kornblum S, Wright CE, Smith, JEK (1988) Optimality in human motor performance: ideal control of rapid aimed movements. Psychol Rev 95:340–370

Oda K (1984) Age changes of motor intervention and acetylcholine receptor distribution on human skeletal muscle fibers. J Neurol Sci 66:327–338

Pohl PS, Winstein CJ, Fisher BE (1996) The locus of age-related movement slowing: sensory processing in continuous goal-directed aiming. J Gerontol 51B:94–102

Pratt J, Abrams RA (1996) Practice and component submovements: the roles of programming and feedback in rapid aimed limb movements. J Mot Behav 28:149–156

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

Sainburg RL, Ghilardi MF, Poizner H, Ghez C (1995) Control of limb dynamics in normal subjects and patients without proprioception. J Neurophysiol 73:820–835

Seidler RD, Stelmach GE (1995) Reduction in sensorimotor control with age. QUEST 47:386–394

Seidler RD, Stelmach GE (1996a) Motor control. In: Encyclopedia of gerontology, vol 1. Academic Press, San Diego

Seidler RD, Stelmach GE (1996b) EMG Patterns: age differences in a speed- constrained, self-initiated task. Soc Neurosci Abstr 22:1638

Skinner HB, Barrack RL, Cook SD (1984) Age-related decline in proprioception. Clin Orthop 184:208–211

Spirduso WW (1982) Physical fitness in relation to motor aging. In: Mortimer JA, Pirozzolo FJ, Maletta GJ (eds) The aging motor system. Prager, New York, pp120–151

Stelmach GE, Homberg V (1993) Sensorimotor impairment in the elderly. Kluwer Academic, Norwell, MA

Stelmach GE, Sirica A (1986) Aging and proprioception. Age 9:99–103

Stelmach GE, Goggin NL, Garcia-Colera A (1987) Movement specification time with age. Exp Aging Res 13:39–46

Warabi T, Noda H, Kato T (1986) Effect of aging on sensorimotor functions of eye and hand movements. Exp Neurol 92:686–697

Welford AT (1984) Between bodily changes and performance: some possible reasons for slowing with age. Exp Aging Res 10:73–88

Winter DA (1990) Biomechanics and motor control of human movement, 2nd edn. Wiley, New York

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