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Journal
Psychology and Aging, 8(4)

ISSN
0882-7974

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Publication Date
1993-12-01

DOI
10.1037/0882-7974.8.4.617

Peer reviewed

Psychology and Aging
1993, Vol. 8, No. 4, 617-632

0882-7974/93/$3.00

Effects of Aging on Planning and Implementing Arm Movements

Kathleen Y. Haaland, Deborah L. Harrington, and James W. Grice

In Experiments 1 and 2, aiming movements were performed with and without visual feedback in young and elderly adults. The initial (acceleration and deceleration phases) and secondary movement components were analyzed. Although deceleration phase accuracy decreased without visual feedback in both age groups, accuracy diminished as movement amplitude increased only in the elderly. This suggested that the elderly were more dependent on visual feedback to modify motor programs for longer duration movements. Velocity also increased less with increasing amplitude and target size in the elderly, which was related to impaired preprogramming (acceleration phase) and implementation (deceleration phase) of higher forces. This conclusion was confirmed directly in Experiment 2 because only the deceleration phase was affected by the removal of visual feedback of arm position when availability of visual information could not be predicted before movement.

It is well established that normal aging is accompanied by a slowing in movement. The reasons for this slowing have been attributed to both peripheral and central changes (Welford, 1984), although the importance of central explanations has been emphasized (Salthouse, 1985). Many cognitive processes that affect the formulation of a plan for an action appear to be diminished in elderly adults. Stimulus encoding, response programming, and response selection have been shown to slow with advancing age by some (Light & Spirduso, 1990; Stelmach, Goggin, & Garcia-Colera, 1987; Waugh & Barr, 1982), but not others (Goggin & Stelmach, 1990; Larish & Stelmach, 1982). These discrepancies point to the incomplete understanding of aging and cognition in movement. One reason for this void is that relatively few studies have examined how the aging process affects the implementation of an action plan. Slow movements in elderly adults may be caused by a deterioration in some aspect(s) of central processing that is (are) ongoing during response implementation (Harrington & Haaland, 1991a).

One approach to identify mechanisms supporting slowing with aging rests on an analysis of the implementation of the movement; this approach proposes that movements are composed of two components that differ in their reliance on sensory information (Keele, 1986). In a simple aiming movement, the initial ballistic component transports the limb to the vicinity of the target. This component has been separated into an acceleration phase and a deceleration phase. The acceleration phase is less dependent on sensory feedback and more reflective of preprogramming (MacKenzie, Marteniuk, Dugas, Liske, & Eickmeier, 1987). The secondary component involves corrective movements to hit the target endpoint. This component is considered closed-loop because programming occurs on-line, and the movements are slow and sensory dependent. The dichotomy between open- and closed-loop components of aiming is not absolute because the initial component sometimes can be modified by changes in visual information during the movement (Goodale, Pelisson, & Prablanc, 1986; Prablanc, Pelisson, & Goodale, 1986), although the limits of this have not been specified.

Although several researchers have reported longer aiming movement times in elderly individuals (Stelmach, Goggin, & Amrhein, 1988; Stelmach et al., 1987), detailed analyses of the movement trajectory have not been conducted to specify the reasons. Warabi, Noda, and Kato (1986) found that although reaction times (RTs) were longer in elderly subjects regardless of movement amplitude, the peak velocity of the initial movement component did not differ among the age groups. Although they concluded that changes in the secondary component explained the slowing in the elderly subjects, they did not perform analyses of the secondary movement or examine the accuracy of each movement component. This latter point is especially problematic because it obscures the potential reasons for slower movements in the elderly subjects. Specifically, if the elderly participants did not come as close to the target by the end of the initial component, the longer duration of the secondary component could have been caused by a greater remaining distance to travel, which would point to aging effects specific to the initial component. Goggin and Stelmach (1990) found that elderly subjects did not show as great an increase in peak velocity between short and long movements, which suggested that open-loop processing may be compromised in normal aging, perhaps because of the subjects' difficulty scaling movements as the movement context changed. Although Goggin and Stelmach did not analyze the pattern of the trajectory (i.e., the relative

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This work was supported by the Medical Research Service, Department of Veterans Affairs, and the National Institute of Aging Grant AG02049 awarded to Philip Garry, director of the New Mexico Aging Process Study at the University of New Mexico. We would like to thank Philip Garry for allowing us to examine the elderly subjects in his study. We also thank Lee Stapp and Shannon O'Brien for their technical assistance and Asenath La Rue for her helpful comments on this article.

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duration of the acceleration vs. deceleration phase) to test this hypothesis, others (e.g., Cooke, Brown, & Cunningham, 1989) have found that elderly subjects' deceleration phase was consistently longer than young subjects' but that these group differences were greater for shorter, not longer, amplitude movements.

In the two experiments reported in this article, we addressed these issues by examining whether aging would differentially affect the acceleration and deceleration phases of the initial component and the secondary component. We predicted that the velocity and/or accuracy of the acceleration phase of the initial movement would be diminished in elderly subjects if the ability to preprogram or implement a program for action deteriorates with age. The availability of visual feedback during movement was also manipulated. If a plan for an action is deficient in elderly individuals, then they should show even greater impairments in the absence of arm position information because they will have to rely on their preprogrammed responses. Because these predictions may vary depending on the type of visual information available during movement (i.e., arm position, target location, or both), we examined these factors in Experiment 2. We also investigated the effect of visual feedback on the acceleration and deceleration phases of the initial movement when the availability of feedback was not predictable.

Experiment 1

Results of a study by Warabi et al. (1986) suggested that the removal of visual feedback had similar effects on simple aiming movements in young and elderly adults. However, neuropsychological models of cognitive functioning in elderly individuals predict otherwise. Specifically, Parkinson's disease (PD) may serve as an accelerated model of normal aging because of parallel motor slowing, neurotransmitter changes, and reductions in the size of the substantia nigra in these two groups (McGeer, McGeer, & Suzuki, 1977; Mortimer, 1988; Pujol, Junque, Vendrell, Grau, & Capdevila, 1992). Flowers (1976) reported that in PD there were changes in the open-loop but not the closed-loop component of aiming movements and that elimination of visual feedback impaired performance more in the PD patients than in normal control subjects. These findings may be attributable to either deficits in PD patients completely preprogramming a movement prior to initiation (Harrington & Haaland, 1991a), using other sources of sensory feedback during movement to modify the motor program, or both. If aging is a less extreme version of the deficits observed with PD, the acceleration phase of the aiming movement should deteriorate with aging more than the deceleration phase or the secondary component, especially with the removal of visual information.

In Experiment 1 we also examined the influence of movement amplitude and target size on response planning and implementation. We predicted that elderly subjects would evidence greater difficulty increasing their movement velocity with increases in amplitude (Goggin & Stelmach, 1990). If this is attributable to problems in scaling movements, the proportion of the initial movement that is occupied by the acceleration phase should change with amplitude differently for elderly subjects. Similar predictions should hold for increases in target width because in young adults, velocity increases and the duration of the deceleration phase decreases as target size increases (MacKenzie et al., 1987).

Method

Subjects

Thirteen young and 11 elderly right-handed volunteers were obtained from the University of New Mexico and the New Mexico Aging Process Study (Garry, Goodwin, Hunt, Hooper, & Leonard, 1982). These subjects did not have any medical diagnosis that would compromise peripheral functioning (e.g., arthritis). The sex distribution varied significantly across the two groups, with 62% women in the young group and 9% women in the elderly group.[1]

Table 1 shows the demographic and cognitive variables. Tests of general information, visuospatial skills, and visuomotor skills were administered to all subjects to better assess their general cognitive functioning. There were no significant differences in performance between the two groups on the Information subtest of the Wechsler Adult Intelligence Scale–Revised (WAIS–R; Wechsler, 1981) and on a nonspeeded test of visuospatial skills, Line Orientation (Benton, Hamsher, Varney, & Spreen, 1983). The elderly group performed more poorly on the Block Design subtest of the WAIS–R, which is a speeded test of visuospatial skills that requires the manipulation of blocks.

Apparatus

The subject sat in front of a video monitor with her or his chin placed in a chin rest. A computer data tablet was situated on a table directly in front of the subject. A horizontal track was mounted on the data tablet with a handle and tablet stylus attached to the track. When the subject gripped the handle, horizontal movements were detected by the computer sampling the data tablet. The tablet's maximum sampling rate of 110 coordinate pairs per second was used both for recording the subject's movements and for updating the display of the subject's position on the video monitor. A one-to-one correspondence existed between the subject's movement of the handle and the movement of the position dot on the monitor. The monitor was also used to display the start and the target circles.

In order to improve the signal-to-noise ratio for analysis, we smoothed position data over five successive data points by calculating the position change between two data points separated by three intervening data points. These calculations overlapped, such that differences were calculated between Points 1 and 5, Points 2 and 6, Points 3 and 7, and so on. We used these position calculations to analyze the data.

RT was defined as the interval between the imperative stimulus (target appearance) and when velocity of the arm movement exceeded 20 mm/s. Three different components of the movement were separated: the ac-

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[1] The findings from Experiment 1 were not likely caused by the greater percentage of men in the elderly group because men usually attain higher velocities and forces than women (Phillips, Bruce, Newton, & Woledge, 1992), and our velocity findings (see Figure 1) replicate previous findings on aging in a study in which there were no sex differences (Goggin & Stelmach, 1990). One study (York & Biederman, 1990) has shown no differences in errors between elderly men and women, suggesting that our differences in error patterns with age cannot be explained by sex differences. In the same study, elderly men demonstrated greater increases in movement time (MT) as the movements' index of difficulty (ID) increased. By contrast, when we analyzed our MT findings as a function of ID (see Figure 4), we did not find such aging effects. These findings argue against gender explanations for the aging effects observed in Experiment 1.

Table 1
Demographic Characteristics and Cognitive Status of Young and Elderly Subjects

	Experiment 1				Experiment 2			
	Young		Elderly		Young		Elderly	
Variable	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Age	25.0	7.0	60.0	2.0*	19.5	1.7	71.7	4.1*
Education	13.4	0.3	12.4	0.8	12.9	1.2	14.2	4.1
Information[a]	21.0	3.0	19.5	6.0	17.9	5.2	22.8	3.9*
Block Design[a]	41.2	8.0	27.2	10.2*	40.7	7.2	28.2	7.3*
Line Orientation[b]	26.6	3.3	25.3	3.6	25.2	3.2	25.3	2.5

[a] Raw score from the Wechsler Adult Intelligence Scale–Revised (Wechsler, 1981). [b] Mean number correct (Benton, Hamsher, Varney, & Spreen, 1983).
* $p < .01$.

celeration phase of the initial component, the deceleration phase of the initial component, and the secondary component. The acceleration phase began at the end of the RT interval and ended when peak velocity was reached. Deceleration began at the end of the acceleration component but required additional constraints to establish its termination. Visual inspection of velocity curves in pilot subjects revealed three profiles indicative of an end to the deceleration component: (a) velocity dropped back to noise level (i.e., less than 12 mm/s); (b) velocity leveled out to a plateau above noise level (i.e., less than a 10% change over a 100-ms interval); or (c) velocity increased again, entering a second acceleration phase. All three criteria were applied to the data, and the first one to be satisfied determined the end of the deceleration component. The secondary movement began at the end of the deceleration phase and ended when velocity was less than 12 mm/s.

Average velocity was the mean velocity over a given time interval (e.g., acceleration phase). Absolute error was defined as the distance from the edge of the target to the location of the hand because instructions were to hit the target rather than the "center" of the target. Absolute error, average velocity, and the total distance traveled were measured at the end of the acceleration phase, the deceleration phase, and the secondary movement.

Procedure

At the beginning of a trial, the start circle and the dot indicating the subject's arm position were displayed on the monitor. The subject initiated the trial by moving his or her right arm to the start circle, which was located on the far left of the data tablet. When the stylus entered the start circle, a 50-ms auditory tone was presented. After a variable delay of 1–2 s (in 100-ms increments), the start circle was removed from the screen, and a target circle was displayed either 40 mm (3°), 100 mm (7°), 200 mm (14°), or 300 mm (20°) to the right. When the target circle was displayed, the subject immediately moved his or her arm to the target as quickly and as accurately as possible.

On visual trials, feedback of the arm position was available throughout the trial. On nonvisual trials, feedback of the arm position was removed 200 ms after target onset (i.e., imperative stimulus) for a duration of 1,100 ms. Therefore, visual feedback was extinguished before movement onset because average RT ranged from 309 to 407 ms. Visual feedback was not available from before the onset of the movement throughout the entire initial component, which averaged 648 ms for the young group and 748 ms for the elderly group.

A trial ended when a subject entered the target and remained in the target for 1 s or 3 s after the imperative stimulus, whichever came first. Trials were excluded if the RT was less than 150 ms, but the number of trials eliminated was less than 1% in all conditions and for both groups.

Design

The presence or absence of visual feedback, movement amplitude (40, 100, 200, and 300 mm), and target width (3, 5, 10, and 20 mm) were manipulated in a factorial design. Practice trials consisted of one trial for each of the 32 conditions. Experimental trials were blocked for each of the 32 conditions such that subjects received 10 consecutive trials of a particular condition. The order of the 32 conditions was randomized across subjects. All 32 conditions were presented once and then were followed by a second random presentation of the 32 conditions. Hence, there were 20 trials per condition and a total of 640 experimental trials. For each of the dependent measures, the mean of 20 trials for each of the 32 conditions was analyzed. The aiming task took no more than 2 h to complete.

Results

Analyses of variance (ANOVAs) with repeated measures tested the effects of age group (young, elderly), visual feedback (feedback, no feedback), amplitude of movement (40, 100, 200, and 300 mm), and target width (3, 5, 10, and 20 mm) separately for each dependent measure. Whenever appropriate, the tests of effects involving amplitude and target width were adjusted for heterogeneity of variance using the Huynh–Feldt corrected significance values. The focus of the hypotheses were on the effect of age group and the interactions with age group. Therefore, we report the main effects and the first-order interactions for the within-subjects variables and only the second-order interactions involving age group.[2] The slopes (*b*) were analyzed for follow-up tests involving movement amplitude and target width because we were primarily interested in the linear effects of these variables. Unless otherwise stated, the probability levels were

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[2] In preliminary analyses, the potential influence of practice or fatigue on aging was examined in repeated measures analyses of variance, in which all dependent measures were analyzed as a function of block. Although there were small improvements across blocks in the speed and accuracy of aiming, none of these changes differed between the age groups. In addition, fatigue or practice explanations of the data from Experiment 1 are not consistent with the velocity findings from the elderly group (see Figure 1), which replicated another study (Goggin & Stelmach, 1990) that contained more practice trials but fewer experimental trials.

Table 2
Effects of Movement Amplitude on the Initiation and Implementation of Movements in Elderly and Young Subjects

	Young				Elderly			
Variable	40	100	200	300	40	100	200	300
Reaction time	330	321	311	319	378	359	366	368
Average velocity								
Acceleration phase	112	195	319	421	98	162	261	352
Deceleration phase	94	169	270	354	82	142	225	302
Secondary component	7	12	18	22	8	17	23	27
Movement time								
Acceleration phase	160	215	268	297	179	241	309	352
Deceleration phase	257	371	455	520	296	441	556	619
Secondary component	412	540	572	615	431	571	581	599
Absolute error								
Acceleration phase	20	57	117	178	20	60	120	181
Deceleration phase	2	5	8	11	2	7	11	15

Note. All values are based on group means. Reaction times and movement times are expressed in milliseconds, average velocity is expressed in millimeters per second, and absolute error is expressed in millimeters.

less than or equal to .05. Multiple follow-up analyses were conducted without adjustment of alpha level because of small sample sizes, so the results must be interpreted with this in mind.

Reaction Time

Table 2 and Table 3 show that RT was slower in the elderly group, $F(1, 22) = 8.52$, $MS_e = 50{,}293$, but that this age group difference was the same regardless of visual feedback, amplitude, and target width. RT was slightly slower without visual feedback, $F(1, 22) = 42.42$, $MS_e = 752$ (visual mean = 335 ms, $SE = 9$; nonvisual mean = 349 ms, $SE = 9$). The significant amplitude effect, $F(3, 66) = 7.42$, $MS_e = 1{,}236$, reflected longer RTs for the shortest amplitude movement. RT decreased as target width increased, $F(3, 66) = 56.74$, $MS_e = 432$. There also was a Target Width × Amplitude interaction, $F(9, 198) = 2.02$, $MS_e = 496$. Follow-up analyses showed that RTs decreased with increases in amplitude, but only for the largest target width, $F(1, 23) = 12.36$, $MS_e = 0.01$ (3 mm, $b = -.03$; 5 mm, $b = -.01$; 10 mm, $b = -.02$; and 20 mm, $b = -.08$). Furthermore, the effect of target width differed across the amplitudes, $F(3, 69) = 3.00$, $MS_e = 0.01$, such that it had less of an effect on the smaller amplitude movements (40 mm, $b = -.06$; 100 mm, $b = -.08$; 200 mm, $b = -.12$; and 300 mm, $b = -.11$).

Initial Movement Time: Percentage Devoted to the Acceleration Phase

There was no difference between the young and elderly groups in the percentage of the initial movement that was devoted to the acceleration phase. On the average, acceleration movement time was approximately 38% of the total initial movement time. This varied somewhat with movement amplitude, $F(3, 66) = 8.22$, $MS_e = 18$, and target width, $F(3, 66) = 12.76$, $MS_e = 8$, such that the percentage devoted to the acceleration phase was greater for shorter (39%) than longer (37%) distances and greater for larger (39%) than smaller (37%) target widths. However, this was found in both the young and the elderly groups. No other effects were significant.

Initial Movement Component: Average Velocity

Acceleration phase. There was no overall difference between the age groups in average velocity during the acceleration velocity. It was faster when visual feedback was available, $F(1, 22) = 9.77$, $MS_e = 3{,}181$ (visual mean = 248, $SE = 13$; nonvisual mean = 235, $SE = 11$), but did not vary with age group because there was no reliable Group × Visual Feedback Condition interaction. Velocity of the acceleration phase was higher with increases in amplitude, $F(3, 66) = 474.53$, $MS_e = 6{,}178$, and target width, $F(3, 66) = 72.03$, $MS_e = 364$. However, amplitude and target width interacted $F(9, 198) = 2.76$, $MS_e = 367$, indicating that average velocity increased with amplitude similarly for all target widths, but increases in velocity with target width were less for the shortest and longest amplitude movements, $F(3, 69) = 4.00$, $MS_e = 0.01$ (40 mm, $b = .09$; 100 mm, $b = .11$; 200 mm, $b = .14$; and 300 mm, $b = .07$). In addition, age group interacted with amplitude, $F(3, 66) = 4.74$, $MS_e = 6{,}158$, and with target width, $F(3, 66) = 5.47$, $MS_e = 364$. Panels A and B in Figure 1 show that average velocity increased more with amplitude in the young group than in the elderly group, $F(1, 22) = 4.99$, $MS_e = 0.05$. In addition, for the two largest movement amplitudes, the elderly subjects produced lower velocities than did the young group: 200 mm, $F(1, 22) = 4.60$, $MS_e = 4{,}382$; 300 mm, $F(1, 22) = 3.90$, $MS_e = 7{,}335$, $p = .06$. The same pattern of effects was found for changes in velocity with increases in target width. The effect of target width was greater for the young group than for the elderly group, $F(1, 22) = 11.60$, $MS_e = 0.34$. The elderly subjects produced lower velocities in the acceleration phase than the young for the two largest target widths: 10 mm, $F(1, 22) = 4.10$, $MS_e = 3{,}157$, $p = .055$; 20 mm, $F(1, 22) = 4.76$, $MS_e = 3{,}314$. These interactions could not be attributed to differences between the age groups in the

Table 3
Effects of Target Width on the Initiation and Implementation of Movements in Elderly and Young Subjects

	Young				Elderly			
Variable	3	5	10	20	3	5	10	20
Reaction time	334	323	316	309	385	366	363	357
Average velocity								
Acceleration phase	248	253	264	282	210	215	217	230
Deceleration phase	209	214	222	241	180	185	187	199
Secondary component	16	16	16	12	20	19	19	16
Movement time								
Acceleration phase	241	240	334	224	274	270	271	266
Deceleration phase	425	414	397	367	493	490	481	449
Secondary component	821	642	432	246	795	667	445	275
Absolute error								
Acceleration phase	98	96	92	86	100	98	95	88
Deceleration phase	9	8	6	3	13	12	10	8

Note. All values are based on group means. Reaction times and movement times are expressed in milliseconds, average velocity is expressed in millimeter per second, and absolute error is expressed in millimeters.

total distance traveled during the acceleration phase because there were no main effects of age group or interactions of group with target width or movement amplitude for distance traveled in the acceleration phase.

Finally, there was a Visual Feedback × Amplitude interaction, $F(3, 66) = 7.01$, $MS_e = 630$, showing that the effect of the amplitude was greater with visual feedback ($b = 1.13$) than without feedback ($b = 1.05$). Visual feedback did not interact with target width, and there were no second-order interactions involving visual feedback and age group. Hence, the aging effects depicted in Panels A and B of Figure 1 cannot be attributed to differences between elderly and young adults in the use of visual information during the acceleration phase of the movement.

Deceleration phase. The findings for the deceleration phase were similar to those of the acceleration phase, except that velocity during the deceleration phase was not influenced by visual feedback in either the young group or the elderly group. Velocity increased with amplitude, $F(3, 66) = 432.62$, $MS_e = 4{,}853$, and target width, $F(3, 66) = 73.2$, $MS_e = 312$, but there were no overall differences between the two groups. However, age group interacted with target width, $F(3, 66) = 5.49$, $MS_e = 312$, and amplitude, $F(3, 66) = 3.28$, $MS_e = 4{,}853$. Panels C and D of Figure 1 show that amplitude had less of an effect on velocity in the elderly group than in the young group, $F(1, 22) = 3.45$, $MS_e = 0.04$, $p = .077$. Although there were trends for the elderly subjects to produce lower deceleration velocities than the young subjects, especially for the larger amplitude movements, age group comparisons at each amplitude did not reach statistical significance. Velocity also increased with target width more in the young subjects than in the elderly subjects, $F(1, 22) = 9.60$, $MS_e = 0.38$. However, the elderly subjects produced lower deceleration velocities than the young subjects only for the largest target width: 20 mm, $F(1, 22) = 4.58$, $MS_e = 2{,}303$. Although the total distance traveled during the deceleration phase was somewhat greater in the young subjects ($M = 87.7$, $SE = 0.9$) than in the elderly subjects ($M = 84.5$, $SE = 1.2$), $F(1, 22) = 4.93$, $MS_e = 40{,}963$, this did not vary with target width or movement amplitude, suggesting that distance traveled cannot explain the velocity effects detailed earlier.

Secondary Movement Component: Average Velocity

There were no age group differences in the percentage of trials with secondary movements, but for both groups this percentage was greater in the nonvisual condition (young, $M = 70\%$, $SD = 7\%$; elderly, $M = 77\%$, $SD = 10\%$) than in the visual condition (young, $M = 58\%$, $SD = 8\%$; elderly, $M = 58\%$, $SD = 8\%$). Although there were no main effects of age group, the average velocity of the secondary movement increased as target width increased, $F(3, 66) = 14.61$, $MS_e = 49$, and as movement amplitude increased, $F(3, 66) = 145.75$, $MS_e = 72$. Figure 2 shows that the visual feedback condition had no effect on the velocity of secondary movements for young subjects, whereas the removal of visual feedback of arm position altered the velocity patterns in elderly subjects. This observation was confirmed by the significant Age Group × Visual Feedback × Amplitude interaction, $F(3, 66) = 5.10$, $MS_e = 39$, for the secondary movement component. This interaction, however, was attributable to differences between the groups in the total distance traveled during the secondary movement. Specifically, the Group × Visual Feedback × Amplitude interaction for total distance traveled during the secondary movement, $F(3, 66) = 2.75$, $MS_e = 3{,}657$, indicated a trend for elderly subjects to move a greater distance than the young subjects as amplitude increased, but only in the nonvisual condition, $F(1, 22) = 3.43$, $MS_e = 0.19$, $p < .08$. This suggests that these velocity findings were attributable to differences between the age groups in the nonvisual condition in the distance traveled, which was directly related to their less accurate initial movement component (see the next section).

Finally, there was a significant Amplitude × Target Width interaction, $F(9, 198) = 2.27$, $MS_e = 19$. Follow-up analyses showed that average velocity decreased as target width increased

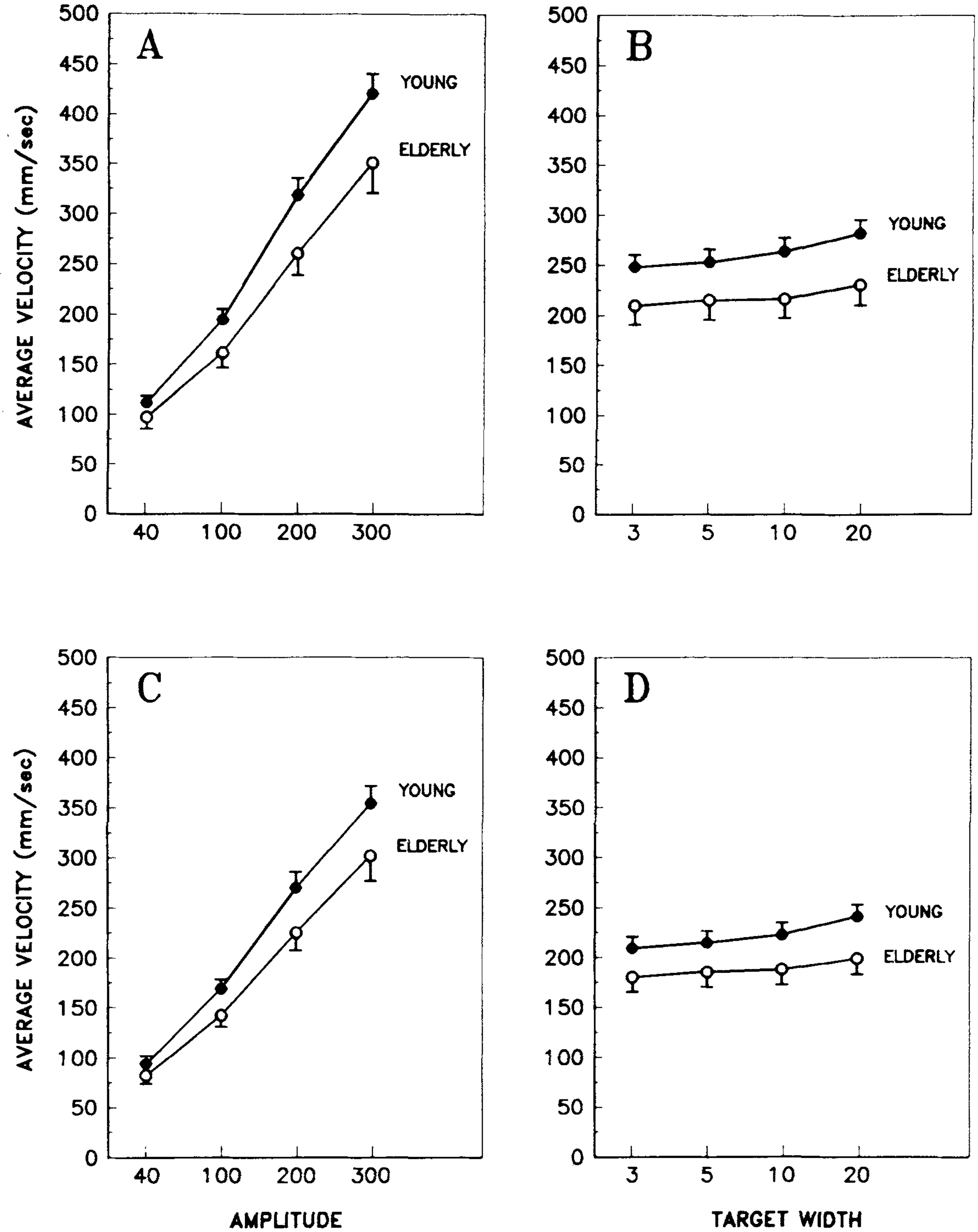

Figure 1. Average velocity as a function of amplitude and target width. (The acceleration phase is depicted in Panels A and B, and the deceleration phase is depicted in Panels C and D.)

at all amplitudes: 40 mm, $b = -.02$, $F(1, 23) = 32.5$, $MS_e = .00$; 100 mm, $b = -.02$, $F(1, 23) = 31.43$, $MS_e = .00$; and 200 mm, $b = -.02$, $F(1, 23) = 13.3$, $MS_e = .00$, except for the longest (300 mm, $b = .01$). Furthermore, there were significant differences among target widths in the effect of amplitude, $F(3, 69) = 4.36$, $MS_e = .00$, such that amplitude has somewhat less of an effect on velocity for smaller target widths (3 mm, $b = .06$; 5 mm, $b = .06$; 10 mm, $b = .07$; and 20 mm, $b = .07$).

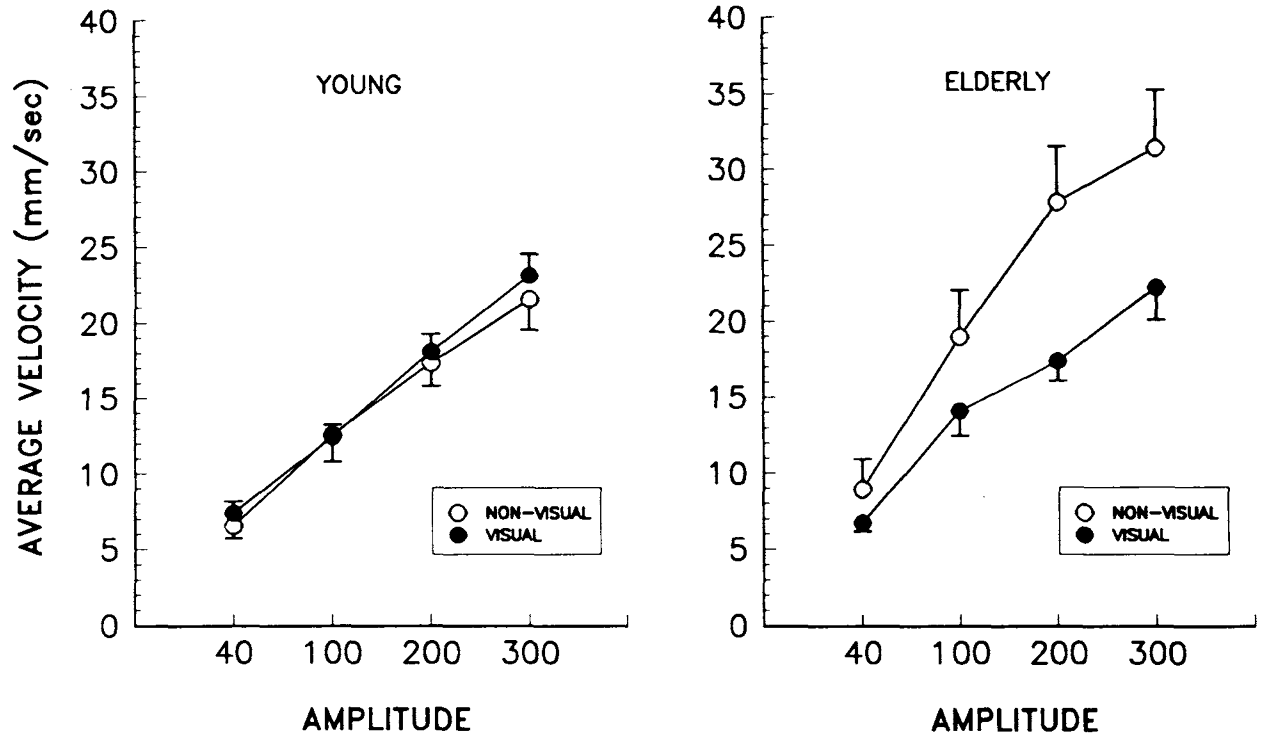

Figure 2. Secondary movement average velocity. (Velocity is plotted as a function of group, movement amplitude, and visual feedback. The mean distances traversed for each amplitude during the secondary component for the young subjects were 8, 13, 18, and 23 mm in the visual condition and 11, 19, 26, and 32 mm in the nonvisual condition; for the elderly subjects, the mean distances were 9, 17, 22, and 28 mm in the visual condition and 14, 25, 38, and 43 mm in the nonvisual condition.)

Initial Movement Component: Accuracy

Acceleration phase. In contrast to the velocity results, absolute error at the end of the acceleration phase was not affected by visual feedback. Absolute error increased with amplitude, $F(3, 66) = 4{,}281.59$, $MS_e = 21{,}685$, and decreased as target size increased, $F(3, 66) = 314.66$, $MS_e = 1{,}758$.[3] These relationships did not vary as a function of visual feedback or age group, suggesting that the precision of the movement at the end of the acceleration phase was similar in the two groups and was independent of visual feedback. No other significant effects were found.

Deceleration phase. Accuracy in the deceleration phase was poorer when visual feedback was not available, $F(1, 22) = 42.42$, $MS_e = 91$, when movement amplitude was larger, $F(3, 66) = 76.12$, $MS_e = 47$, and when target width was smaller, $F(3, 66) = 127.53$, $MS_e = 12$ (see footnote 3). Figure 3 suggests that accuracy at the end of the deceleration phase was lower when visual feedback was absent but that it varied with changes in movement amplitude only in the elderly group. This observation was confirmed by the Age Group × Visual Feedback × Amplitude interaction, $F(3, 66) = 7.58$, $MS_e = 13$. Planned comparisons revealed that in the young group, the effect of amplitude was the same in the visual and nonvisual conditions, whereas in the elderly group accuracy deteriorated more with increases in amplitude when visual feedback was absent than when it was available, $F(1, 10) = 19.87$, $MS_e = .00$. There were no age group differences in the slopes of amplitude for the visual condition, but the elderly subjects showed a steeper slope than did the young subjects in the nonvisual condition, $F(1, 22) = 7.29$, $MS_e = .00$. Furthermore, movement precision deteriorated with the removal of visual feedback more in the elderly subjects than in the young subjects at the two largest amplitude movements: 200 mm, $F(1, 22) = 6.93$, $MS_e = 25$; 300 mm, $F(1, 22) = 8.45$, $MS_e = 26$. Nonetheless, for all movement amplitudes, absolute error was still greater in the nonvisual condition for the young group, $F(1, 12) = 48.12$, $MS_e = 18$, and the elderly group, $F(1, 10) = 18.32$, $MS_e = 179$. These findings suggest that movement precision in both age groups was dependent on visual feedback during the deceleration phase. However, accuracy for longer amplitude movements deteriorated more in the absence of visual feedback only in the elderly group. As noted

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[3] The effect of target width on absolute error reflected a difference in the error criterion rather than a true increase in error relative to the center of the target. When error was calculated from the target center rather than the edge of the target, absolute error did not decrease with target width. For the acceleration phase, the young group had values of 99.5, 98.5, 97, and 96 for 3-, 5-, 10-, and 20-mm targets; the elderly group had values of 101.5, 100.5, 100, and 98 for 3-, 5-, 10-, and 20-mm targets. For the deceleration phase, the young group had values of 10.5, 10.5, 11, and 13 for 3-, 5-, 10-, and 20-mm targets; the elderly group had values of 14.5, 12.5, 15, and 18 for 3-, 5-, 10-, and 20-mm targets.

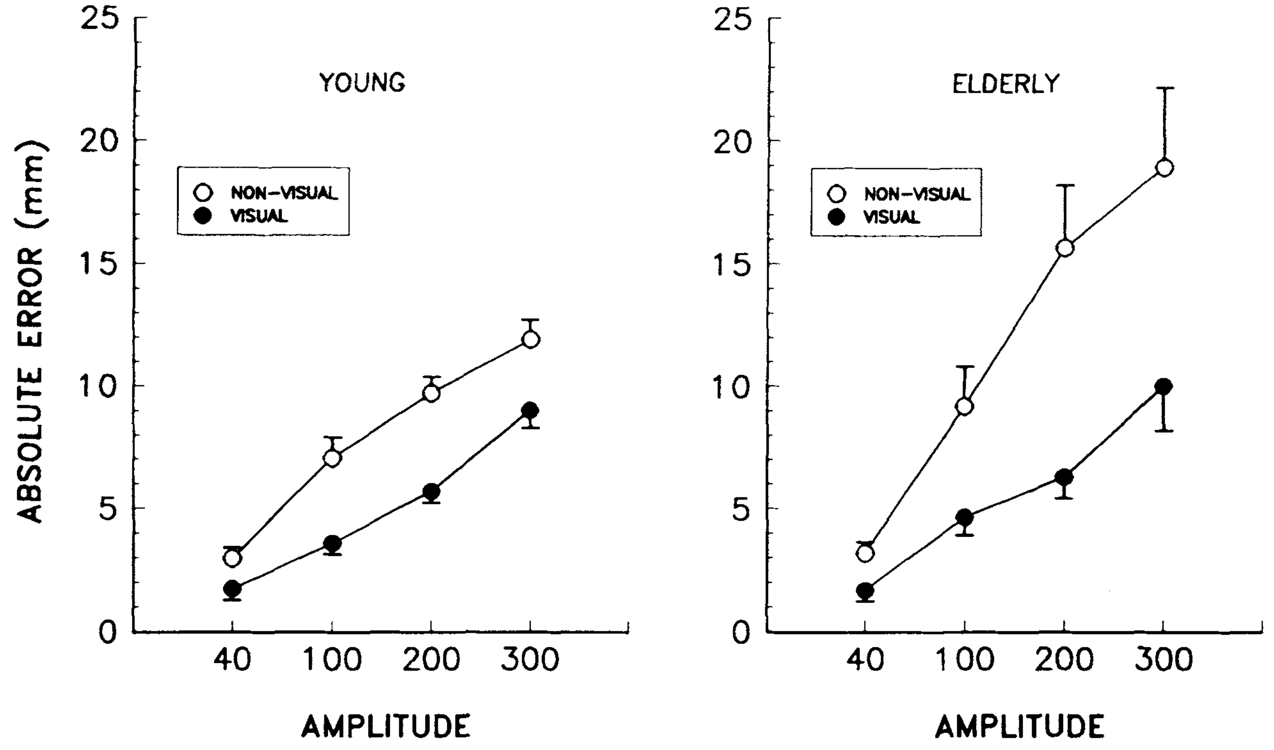

Figure 3. Absolute error for the deceleration component. (Error is plotted as a function of group, movement amplitude, and visual feedback conditions.)

previously, the total distance traveled during the deceleration phase did not vary as a function of group and therefore could not explain these results.

There also was a Visual Feedback × Target Width interaction, $F(3, 66) = 10.29$, $MS_e = 11$, showing that movements became increasingly more accurate as target size increased, especially in the nonvisual condition, $F(1, 23) = 23.04$, $MS_e = .00$ (visual, $b = -.27$; nonvisual, $b = -.46$). This effect was the same for both age groups. Finally, there was an Amplitude × Target Width interaction, $F(9, 198) = 7.62$, $MS_e = 9$, which showed that the effect of target width on movement precision was less for the shorter movement amplitudes, $F(3, 69) = 21.51$, $MS_e = .00$ (40 mm, $b = -.01$; 100 mm, $b = -.02$; 200 mm, $b = -.03$; and 300 mm, $b = -.03$). Similarly, amplitude had the smallest effect on movement precision when targets were large, $F(3, 69) = 13.52$, $MS_e = .00$ (3 mm, $b = .04$; 5 mm, $b = .04$; 10 mm, $b = .04$; and 20 mm, $b = .02$). No other significant effects were found.

Secondary Movement Component: Accuracy

We analyzed only the main effects for absolute error at the end of the secondary movement because there were many cells in which no subjects showed errors. Absolute error was greater in the elderly group, $F(1, 22) = 5.58$, $MS_e = 2$ (young, $M = 0.04$ mm, $SE = 0.04$; elderly, $M = 0.30$ mm, $SE = 0.12$). The effect of visual feedback condition could not be examined because feedback was always available at the end of the movement. No other main effects were significant.

Discussion

RTs in the elderly subjects were slower than in the young subjects, which is a common finding in the literature on aging (Salthouse, 1985). However, variations in movement amplitude and target width had similar effects on RT in both age groups, suggesting that the elderly subjects used advance information about these characteristics of the movement. Some researchers contend that latencies can be additive even if generated from central sources (e.g., Bashore, Osman, & Heffley, 1989), but we could not specify in this study the aspects of central processing that may be diminished.

The elderly subjects showed less of an increase in both acceleration and deceleration velocity with increases in movement amplitude and target width. This finding is in agreement with previous data (Goggin & Stelmach, 1990) and is likely attributable to the elderly group's greater difficulty attaining the higher forces required for high-velocity movements.

The availability of visual feedback affected both the planning and the implementation of movements. RTs were shorter, acceleration velocity was faster, and deceleration absolute error was less when visual feedback was available in both the young and the elderly groups. Clearly, prior knowledge of whether visual information would be available during movement affected preprogramming. Although changes in the acceleration and the deceleration phases when visual feedback was removed suggest that these components normally involve closed-loop processing, these findings also could be indicative of differences in programming prior to movement because the availability of visual feedback was predictable. If response implementation depends on the construction of a motor program (Rosenbaum, Kenny, & Derr, 1983), the slower acceleration velocities and greater deceleration error in the nonvisual condition may be attributable to preprogramming the movement differently during the RT interval when subjects knew visual feedback would not be available (Zelaznik, Hawkins, & Kisselburgh, 1983).

Finally, the accuracy of the deceleration phase and the accuracy and velocity of the secondary movement were diminished in elderly subjects. Although absolute error at the end of the deceleration phase was greater in the nonvisual condition for both age groups, larger amplitude movements were especially inaccurate when visual feedback was removed only in elderly subjects. If the deceleration component depends on preprogramming, this finding suggests that elderly individuals' movement plan is either incomplete or imprecise, particularly for large-amplitude movements, which are also longer and require more planning. Alternatively, the greater impairment of elderly subjects when visual feedback was removed may suggest that they have deficits in on-line processing and that these deficits are more apparent for larger amplitude movements in which a larger proportion of the movement is devoted to the deceleration phase. These accounts are not mutually exclusive and are discussed later.

Velocity increases in the secondary movement component with greater amplitude movements were also larger in the absence of visual feedback in elderly subjects, but this effect was attributed to the greater distance moved by elderly subjects. Elderly subjects were also less accurate at the end of the secondary component, despite the fact that visual information was available at the end of the movement, even on nonvisual trials. These results do not appear to be attributable to deficits in elderly subjects' use of visual feedback to alter the movement because they were as proficient as the young subjects in using visual information during the deceleration phase. Rather, because absolute error was small, these findings may reflect a slight decline in visual acuity with aging.

Experiment 2

The main purpose of the second experiment was to test directly the effect of visual feedback on the acceleration and deceleration phases of the initial movement, independent of preprogramming processes. We did this by randomizing the visual and nonvisual feedback conditions such that prior to movement initiation, subjects did not know whether they would perform the movement in the presence or absence of visual information. If the acceleration and deceleration phases are not entirely preprogrammed, the removal of visual information during the movement should affect its speed, accuracy, or both. Despite the absence of age group differences on the acceleration phase as a function of visual feedback in Experiment 1, such differences could emerge in this experiment if elderly subjects are less effective in constructing a program for movements when visual feedback is not predictable. Second, to directly test whether there were age group differences in the use of visual feedback during the secondary movement component, we did not provide visual feedback during the entire movement on nonvisual trials in Experiment 2. Finally, we were also interested in whether elderly subjects would rely more on visual feedback during the initial phases of movement when visual information about the target location, rather than the arm position, was removed. Short-term memory for spatial information appears to be diminished in elderly subjects (Till, Healy, Cunningham, & Bourne, 1990), which would suggest that the removal of target location, but not hand position, information should have more adverse effects on movements in elderly subjects.

A single amplitude and target width was examined as the effect of these variables on performance as a function of aging were addressed in Experiment 1. To eliminate the possibility that subjects would simply memorize the end location of the movement, we randomly varied the starting position of the movement.

Method

Subjects

Fifteen young and 15 elderly volunteers were obtained from the same populations as in the first experiment. There were 47% women in the young group and 53% women in the elderly group. Table 1 shows that there were no differences between the age groups in educational level or performance on the Judgment of Line Orientation Test. The elderly group performed better on the WAIS–R Information subtest but worse on the WAIS–R Block Design subtest. In addition, the WAIS–R Digit Symbol subtest, a measure of visuomotor processing speed, was administered. As expected, elderly subjects performed worse than did the young subjects on this test, $F(1, 28) = 54.88$, $MS_e = 5{,}824$, $p < .001$ (elderly mean = 42.2, $SD = 9.8$; young mean = 70.1, $SD = 10.8$).

Apparatus and Procedure

The same apparatus was used and the procedures were similar to those used in Experiment 1, with the following exceptions: After the stylus entered the start circle, there was a variable delay of 0.5–1.5 s (in 100-ms increments) before the start circle moved to the right. The amplitude of all movements was 175 mm, and the target width was 5 mm. There were four different start positions for the movements (i.e., at the subject's midline and 25, 50, and 75 mm to the right of midline) in each of the visual feedback conditions. Visual and nonvisual trials were randomized. On visual trials, feedback on the arm position and the target were available throughout the trial. On the nonvisual trials, feedback on either the arm position (no-arm-position feedback) or the target location (no-target-location feedback) was removed at the end of the RT interval and remained off for the duration of the movement.

Design

The three different feedback conditions (visual, no arm position, and no target) and the four start position combinations were completely randomized. The 24 practice trials consisted of 2 trials in each of the 12 feedback condition and start position combinations. For each feedback condition of the experimental trials, 10 trials were presented at each start position such that there were 40 trials per feedback condition and a total of 120 experimental trials.

Results

ANOVAs with repeated measures tested the effects of age group (young, elderly), visual feedback condition (visual feedback, no arm position, no target location), and the interaction separately for each dependent measure. Planned comparisons involving significant feedback condition effects contrasted the control condition (visual) with each of the nonvisual conditions. Table 4 shows the means for each dependent measure as a function of age group and visual feedback condition. Probability levels were always less than or equal to .05.

RT

Table 4 shows that RTs tended to be slower in the elderly subjects, but this effect was not statistically reliable ($F < 1.0$). This table also shows that there was no reliable effect of visual feedback condition on RT for either age group, which we expected because this information was not predictable.

Initial Movement Time: Percentage Devoted to the Acceleration Phase

There was no difference between the young and elderly subjects in the percentage of the initial movement that was devoted to the acceleration phase. Acceleration movement time was about 40% of the total initial movement time in both age groups. This varied, however, among the visual feedback conditions, $F(2, 56) = 4.59$, $MS_e = 36.9$. Planned comparisons showed that there was no difference between the visual (40.2%) and the no-arm-position feedback (41.1%) conditions but that the acceleration phase occupied less of the total initial movement time in the no-target-location condition (38.8%) than in the visual condition, $F(1, 29) = 6.28$, $MS_e = 19.8$. The Age Group × Visual Feedback Condition interaction was not significant ($F < 1.0$).

Initial Movement Component: Average Velocity

Acceleration phase. Acceleration velocity was not significantly different between the age groups ($F < 1.0$), and there was no interaction between age group and visual condition. Acceleration velocity did change as a function of the visual feedback condition, $F(2, 56) = 15.14$, $MS_e = 7{,}163$. Planned comparisons showed no significant difference between the visual and the no-arm-feedback conditions, but acceleration velocity was slower in the no-target-location condition than the visual feedback condition, $F(1, 29) = 16.43$, $MS_e = 5{,}963$.

Deceleration phase. In the deceleration phase, there were no significant effects of age group, visual feedback condition, or their interaction.

Secondary Movement Component: Average Velocity

The young group made more secondary movements, regardless of visual feedback condition ($M = 84\%$, $SE = 3\%$) than the elderly group ($M = 67\%$, $SE = 4\%$). However, there was no effect of visual feedback condition or an Age Group × Condition interaction for the percentage of secondary movements. As the data in Table 4 suggest, the velocity of the secondary movement was higher in the elderly subjects than in the young subjects, $F(1, 28) = 13.39$, $MS_e = 49{,}150$, across all visual feedback conditions. Because the distance traveled during the secondary movement was similar between the two age groups, this could not account for the finding. In addition, Table 4 shows that secondary movement velocity varied among the feedback conditions, $F(2, 56) = 10.44$, $MS_e = 12{,}883$, such that in the visual feedback condition, velocity was lower than in the no-arm-position condition, $F(1, 29) = 20.01$, $MS_e = 13{,}399$, and in the no-target-location condition, $F(1, 29) = 6.84$, $MS_e = 7{,}942$. There was no significant interaction between age group and visual feedback condition.

Initial Movement Component: Accuracy

Acceleration phase. The accuracy of the movement at the end of the acceleration phase was similar among the age groups, but it varied among the visual feedback conditions, $F(2, 56) = 5.02$, $MS_e = 5{,}455$. Planned comparisons showed no differences in

Table 4

Effects of Visual Feedback Condition on the Initiation and Implementation of Movements in Elderly and Young Subjects

	Young			Elderly		
Variable	Visual	No arm	No target	Visual	No arm	No target
Reaction time	379	380	384	405	404	407
Average velocity						
Acceleration phase	223	225	214	241	245	237
Deceleration phase	207	205	202	225	227	226
Secondary component	27	39	33	42	49	45
Movement time						
Acceleration phase	323	292	303	303	291	292
Deceleration phase	475	439	495	455	403	464
Secondary component	554	752	563	364	515	518
Absolute error						
Acceleration phase	104	108	110	104	105	106
Deceleration phase	9	24	11	13	22	16
Secondary component	0.4	12	1	3	17	7

Note. All values are based on age group means. Average velocity is expressed in millimeters per second, movement time is expressed in milliseconds, and absolute error is expressed in millimeters.

absolute error between the visual and the no-arm-position conditions, but errors were higher in the no-target-location condition than in the visual feedback condition, $F(1, 29) = 10.45$, $MS_e = 4{,}873$. These condition effects were similar between the age groups.

Deceleration phase. Similar findings were obtained for accuracy in the deceleration phase. There were no reliable age group differences or an Age Group × Feedback Condition interaction. However, absolute error changed as a function of the visual feedback condition, $F(2, 56) = 35.02$, $MS_e = 7{,}556$. Planned comparisons showed that accuracy was higher in the visual feedback condition than in the other two nonvisual conditions: no arm position, $F(1, 29) = 56.11$, $MS_e = 8{,}541$; no target location, $F(1, 29) = 7.83$, $MS_e = 2{,}971$.

Secondary Movement Component: Accuracy

At the end of the secondary movement, the elderly subjects were less accurate than the young subjects, $F(1, 28) = 4.84$, $MS_e = 22{,}579$. In addition, absolute error varied among the visual feedback conditions, $F(2, 56) = 52.44$, $MS_e = 5{,}241$, such that error was less in the visual condition than in the two nonvisual conditions: no arm position, $F(1, 29) = 75.08$, $MS_e = 6{,}556$; no target location, $F(1, 29) = 21.59$, $MS_e = 950$. The effects of visual feedback condition on absolute error were the same for both age groups.

Discussion

The principal finding from Experiment 2 was that when subjects could not preplan a movement, the removal of arm position information did not have any impact in either age group on the speed or the accuracy of the acceleration phase. This suggests that the reduced acceleration velocity in Experiment 1 with the removal of arm position feedback was attributable to subjects preprogramming the movement differently. By contrast, the removal of target location information reduced the accuracy and the speed of the acceleration phase in both age groups. This indicates that movements can be modified on-line during the acceleration phase when information is removed that is normally used to perform the movement. Hence, the acceleration phase does not appear to rely entirely on open-loop processing. These results differ from another study by Jacobson and Goodale (1991), which found that if visual feedback (i.e., arm position and target) was removed unpredictably, young subjects performed on all trials as though visual feedback was never available. In our study, both types of feedback were never removed simultaneously. Therefore, some type of visual information was always available, which would make a strategy of entirely relying on preprogramming inefficient.

The second main finding was that secondary movements were less accurate in the elderly subjects, perhaps because they made fewer secondary movements. However, their higher number of errors in the secondary movement was also accompanied by higher velocity movements, which may suggest a speed–accuracy trade-off. The third finding was that movements in the elderly subjects were not disrupted more than in the young subjects by the removal of target location information. This was surprising, but it might have been attributable to the large amount of practice subjects had with a single-amplitude movement. Specifically, elderly subjects may be able to effectively compute the distance of the movement, relying on this information to perform the movement rather than an internal representation of the target location. Although distance and location information tend to be correlated, there is evidence that they involve different processes (Abrams & Landgraf, 1990). The manipulation of several movement amplitudes would provide a better test of this hypothesis.

General Discussion

Planning and Response Implementation in Young Adults

Visual Feedback

Clearly, advanced knowledge about whether visual information will be available affects preprogramming (i.e., RT) and implementation of the early phase (i.e., acceleration) of a simple aiming movement. However, in both experiments, the accuracy of the deceleration component and the speed and accuracy of the secondary movement were diminished when arm position feedback was unavailable after the movement began. Because similar findings were obtained regardless of the predictability of visual input, it appears that the deceleration phase of the movement involves some degree of closed-loop processing. It is not likely that proprioceptive feedback of arm position could compensate for the lack of visual feedback of arm position in the acceleration but not the deceleration phase because proprioceptive compensation was possible in Experiment 1, yet abolishing visual feedback of arm position decreased acceleration velocity in that paradigm. These findings more likely reflect the independence of the acceleration phase, but not the deceleration phase, from visual feedback of arm position. This conclusion is consistent with the finding that the percentage of the initial movement devoted to the acceleration phase was not altered by the removal of arm position feedback in either experiment.

These results also suggest that all forms of visual information do not have the same impact. In contrast to removal of arm position feedback, target removal affected most velocity and error measures across all phases of the movement (see Experiment 2). The removal of target location, but not arm position, changed the acceleration phase. This finding suggests that the acceleration phase is not entirely open-loop because the removal of some kinds of visual information during the movement can alter the movement trajectory. Other researchers have arrived at the same conclusion on the basis of somewhat different manipulations (Goodale et al., 1986; Prablanc, Echallier, Komilis, & Jeannerod, 1979). Although knowledge of the target location *prior* to movement can provide extraretinal target location information (e.g., eye position or efference copy of the motor signals sent to the eye muscles) that can be used during the movement if the target is turned off, ongoing target location input also appears to be integrated on-line with the initial motor program and with the feedback of arm position to further update and improve aiming movements. In our study, the removal of arm position feedback had detrimental effects during later phases of the movement, suggesting that integration of this information with internal sources of information (e.g., efference copy) typically occurs during the deceleration phase.

Movement Amplitude and Target Width

The construction of a plan for movement was also influenced by the characteristics of the movement, suggesting that the action plan normally considers the goal of the movement (Jacobson & Goodale, 1991; Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987). The duration of planning is longer when greater endpoint precision is required and when the distance to travel is short. The latter finding may be attributable to subjects only partially preprogramming longer movements because they can complete the programming during movement without any undue delays, a strategy that is less effective for shorter movements (Harrington & Haaland, 1991b).

In general, parallel effects of movement amplitude and target width were obtained for the acceleration and deceleration phases of the movement. The velocity of both the acceleration and the deceleration phases was faster for longer amplitude movements and for wider targets. Our results were in agreement with previous research (MacKenzie et al., 1987; Marteniuk et al., 1987) and likely relate to the planning and/or generation of larger forces necessary to achieve higher velocities as the movement context changes because velocity is directly related to the amplitude of the muscle contraction (Freund & Budingen, 1978), which is reflective of force. Movement accuracy in both the acceleration and deceleration phases was also less for larger amplitude, higher velocity movements. This has been attributed to the greater variability in force production for faster and larger amplitude movements, which results in larger endpoint variability (Darling & Cooke, 1987; Meyer, Abrams, Kornblum, Wright, & Smith, 1988).

The Effect of Aging on Planning and Response Implementation

Visual Feedback

The elderly subjects took longer to preprogram movements (Salthouse, 1985), but only in Experiment 1, in which the movement context changed. More important, RTs changed similarly for both age groups when the availability of visual feedback was predictable. Elderly subjects were also able to preprogram normally movements that varied in amplitude and target size, regardless of the visual feedback condition. This indicates that the use of advance information to construct a plan of action is not diminished with aging (Goggin & Stelmach, 1990; Larish & Stelmach, 1982). Moreover, in both experiments the effect of removing visual feedback on the acceleration phase was the same in both age groups, suggesting that the elderly subjects' ability to implement the initial phases of an aiming movement is intact, regardless of whether they have advance knowledge about the availability of visual feedback during movement. However, later phases of the aiming movement (e.g., the deceleration phase and secondary movement), which were altered by the removal of visual feedback, were affected by normal aging in Experiment 1.

Although others have reported no differential aging effect on the speed of response implementation when visual feedback was removed (Warabi et al., 1986), they did not examine spatial accuracy. In Experiment 1, both groups showed a reduction in movement precision during the deceleration phase when visual feedback of arm position was removed. However, accuracy was diminished equally at all amplitudes in the young group, whereas it was more marked at the two largest amplitude movements in the elderly group. Hence, the elderly subjects were more dependent on visual feedback of arm position to control the accuracy of long-amplitude movements. One possible explanation for these results is that elderly individuals have difficulty preprogramming longer duration movements. Similar to patients with Parkinson's disease (Harrington & Haaland, 1991a), elderly subjects may have deficits in constructing an action plan for the entire movement when movements are longer. The action plan for these movements may require more extensive planning; therefore, greater deficits may reflect a less complete or less accurate initial program that requires more modification during the deceleration phase. When visual feedback of arm position was available, elderly subjects were as accurate as young subjects in the deceleration phase, suggesting they were able to use on-line visual feedback effectively, even for larger amplitude movements. Although elderly subjects did not show greater errors in the deceleration phase in Experiment 2 in the absence of visual feedback, this was likely caused by their extensive practice with a single-amplitude movement such that they learned across many trials to construct an accurate plan that did not require modification.

An alternative interpretation of these findings on aging is that elderly adults might have adopted a different strategy than young adults in terms of the amount of emphasis placed on spatial versus temporal precision. Fitts (1954) discovered that average movement time (MT) could be estimated by a logarithmic trade-off between the distance (D) and spatial precision or target width (W) of rapid aimed limb movements, that is, MT $= A + B\log_2(2D/W)$, where A and B are constants. The $\log_2(2D/W)$ was referred to as the index of difficulty (ID) of an aimed movement, and, relative to other functions (see Meyer et al., 1988),[4] it is a better approximation of MT for spatially constrained movements, such as in our task. We performed post hoc analyses of our MT and error data in terms of the ID levels to test this explanation.

Figure 4 shows the findings for total MT, initial MT,[5] and secondary MT. The best fitting slopes of the logarithmic function in the visual (left panel) and nonvisual (right panel) conditions were parallel between the two age groups for all movement components. Moreover, there was no effect of visual feedback condition on the slopes for any movement component in either age group, suggesting that the removal of visual feedback did not alter subjects' strategy for producing movement speed. Although the absence of an effect of visual feedback on the secondary movement contrasts with previous findings (Meyer et al., 1988), this is likely attributable to the poor fit of the loga-

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[4] Meyer, Abrams, Kornblum, Wright, and Smith's (1988) square-root function was applied in post hoc analyses of the data in Experiment 1; however, the regression lines did not fit the data for any movement component as closely as did Fitts's (1954) logarithmic function.

[5] The data from the acceleration and deceleration phases were not plotted because the post hoc analyses of these phases were identical to those of the initial movement time (IMT) component. In addition, the graph of the IMT allowed for a direct comparison between our findings and those of others.

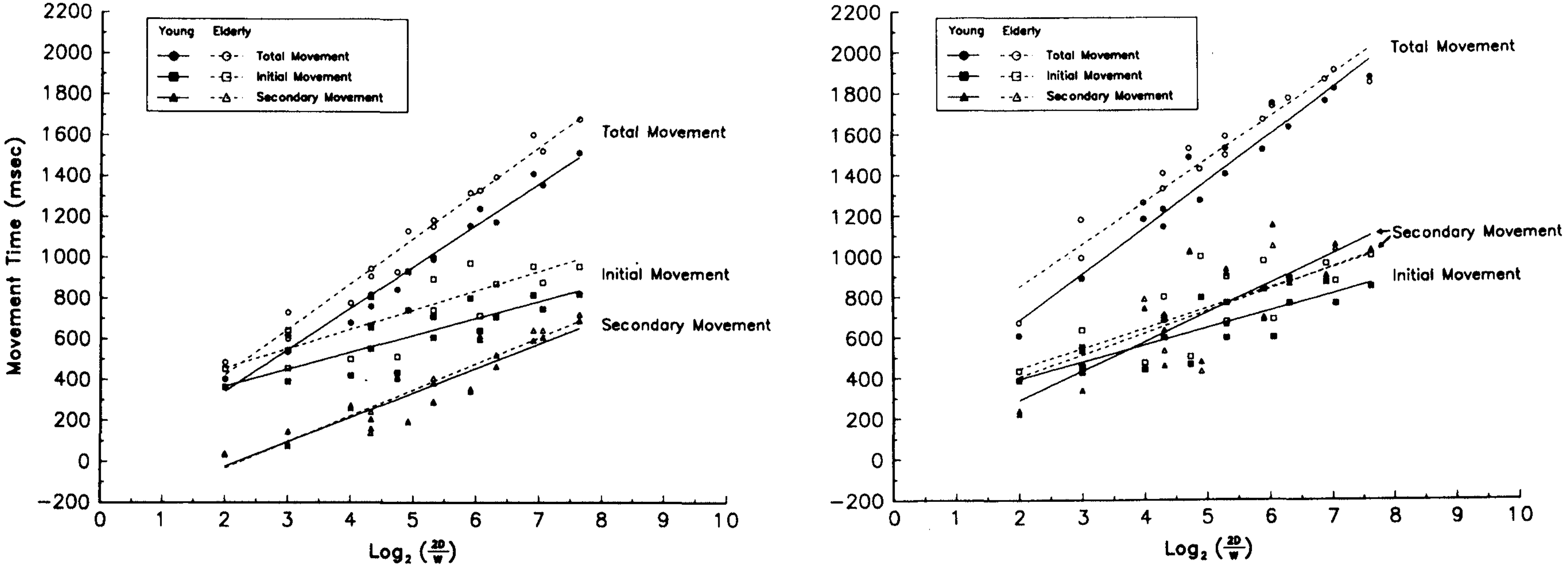

Figure 4. Movement time (MT) as a function of index of difficulty (ID). (The left and right panels depict the MT in the visual and nonvisual conditions, respectively. The graphs plot total MT [TMT], initial MT [IMT], and secondary MT [SMT]. In the visual condition, the log functions for the young group are as follows: TMT = −63 + 204$\log_2$[2D/W], r^2 = .98; IMT = 202 + 84$\log_2$[2D/W], r^2 = .72; and SMT = −266 + 120$\log_2$[2D/W], r^2 = .87. The log functions for the elderly group are as follows: TMT = −22 + 224$\log_2$[2D/W], r^2 = .98; IMT = 267 + 95$\log_2$[2D/W], r^2 = .64; and SMT = −289 + 129$\log_2$[2D/W], r^2 = .86. In the nonvisual condition, the log functions for the young group are as follows: TMT = 226 + 227$\log_2$[2D/W], r^2 = .95; IMT = 226 + 84$\log_2$[2D/W], r^2 = .66; and SMT = 1 + 144$\log_2$[2D/W], r^2 = .66. The log functions for the elderly group are as follows: TMT = 431 + 208$\log_2$[2D/W], r^2 = .94; IMT = 244 + 100$\log_2$[2D/W], r^2 = .60; and SMT = 187 + 108$\log_2$[2D/W], r^2 = .52. D = distance; W = width.)

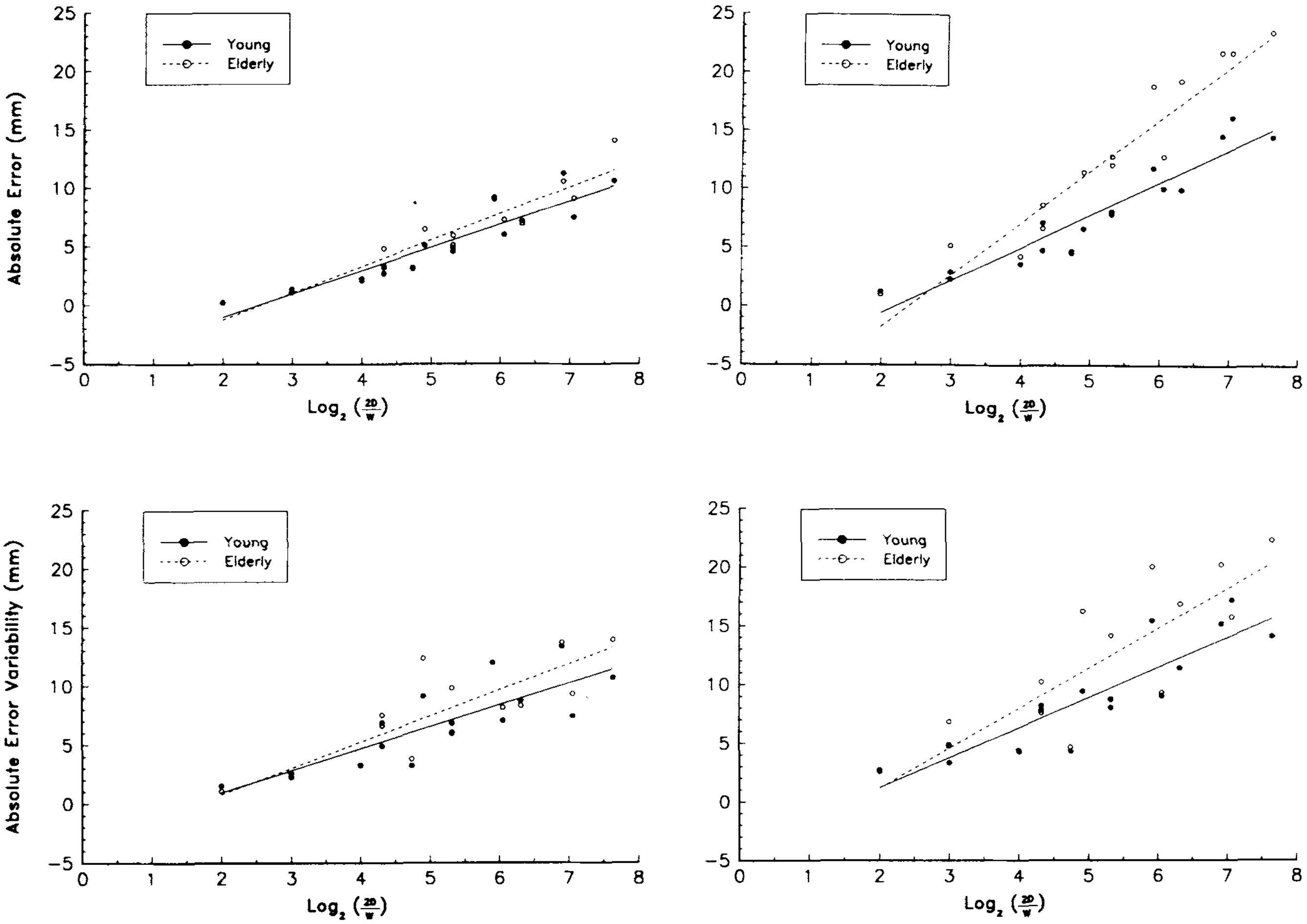

Figure 5. Absolute and error variability at the end of the deceleration phase as a function of index of difficulty (ID). The top left and right panels depict the absolute error [AE] in the visual and nonvisual conditions, respectively. In the visual condition, the log functions for the young and elderly groups are as follows: AE = $-4.97 + 1.97\log_2[2D/W]$, $r^2 = .86$, and AE = $-5.76 + 2.26\log_2[2D/W]$, $r^2 = .88$, respectively. In the nonvisual condition, the log functions for the young and elderly groups are as follows: AE = $-6.19 + 2.79\log_2[2D/W]$, $r^2 = .90$, and AE = $-10.67 + 4.44\log_2[2D/W]$, $r^2 = .88$, respectively. The bottom left and right panels depict the standard deviation of absolute error [AE_{SD}] in the visual and nonvisual conditions, respectively. In the visual condition, the log functions for the young and elderly groups are as follows: $AE_{SD} = -2.75 + 1.86\log_2[2D/W]$, $r^2 = .69$, and $AE_{SD} = -3.62 + 2.22\log_2[2D/W]$, $r^2 = .71$, respectively. In the nonvisual condition, the log functions for the young and elderly groups are as follows: $AE_{SD} = -3.92 + 2.55\log_2[2D/W]$, $r^2 = .79$, and $AE_{SD} = -5.65 + 3.39\log_2[2D/W]$, $r^2 = .71$, respectively. D = distance; W = width.)

rithmic function in the nonvisual condition, especially for the elderly group. Thus, with visual feedback deprivation, secondary movement duration did not correspond closely to the ID, perhaps because of subjects' spatial uncertainty about their arm position (Meyer et al., 1988), which is not taken into account in current theories of speed–accuracy trade-off. As for the accuracy of movements, the top two panels of Figure 5 show that the logarithmic function conformed well to the absolute error at the end of the initial movement in both the visual and nonvisual conditions. In the top left panel, the best fitting slope of the logarithmic function in the visual condition was parallel between the two age groups, whereas the top right panel shows that the elderly subjects were more affected by movement difficulty in the absence of visual feedback, $F(1, 22) = 5.64$, $MS_e = 2.86$. This parallels our findings of an Age Group × Amplitude × Visual Feedback Condition interaction. However, the removal of visual feedback increased the effect of ID level on absolute error in both age groups, $F(1, 22) = 31.42$, $MS_e = 0.85$, which is consistent with other work (Wallace & Newell, 1983). In summary, it does not appear that the elderly subjects simply adopted a different strategy for the relative amount of emphasis placed on speed versus accuracy because if this were true, changes in MT with variations in ID should also have differed between age groups in the nonvisual condition.

However, another possibility is that the elderly subjects' greater error at the end of the deceleration phase could have been caused by a greater "neuromotor" noise-to-force ratio, which caused them to adopt a different strategy when moving to targets with a higher ID (Meyer et al., 1988). This hypothesis was not supported when we examined the variability in absolute error as a function of ID.[6] The bottom left and right panels of Figure 5 show that although the logarithmic function fit the error variability data moderately well, no age group differences were found in the slopes of these functions for the visual or nonvisual condition. Visual feedback deprivation did, however, increase the effect of ID level on error variability in both age groups, $F(1, 22) = 13.00$, $MS_e = 0.80$. Hence, age group differences in neuromotor noise do not appear to be an adequate explanation of our findings.

Movement Amplitude and Target Width

Although elderly subjects were able to preplan normally when advance information was provided about amplitude and target width, in Experiment 1 increases in acceleration and deceleration velocity with increasing movement amplitude and target size were not as great for the elderly group. One explanation for these findings is that elderly individuals have more difficulty implementing movements that are less sensory dependent. This interpretation was not supported because the Age Group × Amplitude and the Age Group × Target Width interactions for acceleration and deceleration velocity did not vary as a function of visual feedback.

Another explanation is that elderly individuals do not scale movements so that velocity is comparable across a range of movement amplitudes (Cooke et al., 1989; Goggin & Stelmach, 1990). However, this explanation was not supported in our study because the percentage of the initial movement devoted to the acceleration phase did not differ between the age groups, suggesting that the scaling of different amplitude movements, and hence the coordination of the acceleration and deceleration phases, was not compromised by aging.

A more likely explanation for the velocity findings is that elderly people are not as able to plan or generate the forces necessary to produce velocities that are comparable to those of the young for larger amplitude movements (Bruce, Newton, & Woledge, 1989; Phillips, Bruce, Newton, & Woledge, 1992), which is consistent with force production deficits in Parkinson's disease (Stelmach, Teasdale, Phillips, & Worringham, 1989). Elderly people's inability to achieve the higher velocities of young people is likely attributable to difficulty generating stronger muscle contractions (Freund & Budingen, 1978). It is not clear whether this finding is associated with central and/or peripheral factors. Changes in voluntary force have been attributed to muscle atrophy, changes in muscle composition, and/or failure to fully activate the available muscle (Bruce et al., 1989; Phillips et al., 1992). However, evidence of greater discontinuities in the trajectory of force in elderly individuals as movement complexity increases (Vrtunski & Patterson, 1985) also suggests that central factors may be influential.

Conclusion

Results of these studies suggest that elderly individuals are able to use advance information about a movement's characteristics to preprogram an action. However, the planning and generation of force to implement higher velocity movements is compromised with aging. Furthermore, these same movements pose additional difficulty for elderly people when visual feedback is not available, but only during phases of the movement in which there is a greater reliance on integrating visual information with internal information about the movement. Similar findings have been described in Parkinson's disease (Flowers, 1976; Harrington & Haaland, 1991a), but not other brain-damaged groups with cognitive–motor deficits (Harrington & Haaland, 1991b), suggesting that Parkinson's disease may serve as a model of accelerated aging (Mortimer, 1988). Results of this research also demonstrate that a kinematic analysis of the movement can provide important information to better specify the reasons for slowing with aging. Future studies should examine the impact of aging on the on-line modification of movements.

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[6] Variability of absolute error at the end of the deceleration phase was also analyzed as a function of group, visual feedback, amplitude, and width. There was no significant group effect, and group did not interact with any other factor. This indicates that the Group × Visual Feedback × Amplitude interaction for absolute error cannot be explained by increased intertrial variability, which ostensibly reflects greater neuromotor noise.

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Received February 5, 1993
Revision received June 6, 1993
Accepted June 15, 1993 ■