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Age-Related Differences in Movement Control: Adjusting Submovement Structure To Optimize Performance

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In this experiment older and younger adults were compared on their ability to position a cursor with an electromechanical mouse. Distance of the movement, size of the target, and relative emphasis on the speed or accuracy of the movement were manipulated. The study was designed to isolate and evaluate the effects of age-related differences in the noise-to-force ratio, perceptual feedback efficiency, strategy differences, and the ability to produce force as explanations for age-related differences in movement control. This was done by using two types of movement tasks and by analyzing movement performance according to stages of movement. The study showed that all four factors, when isolated, are significantly different for the two age groups. However, in the task component where all factors could simultaneously affect performance, the age-related difference in performance was less than the difference in either the measure of noise-to-force ratio or perceptual efficiency. Analysis of the submovement structure revealed how older adults compensated for the greater noise and less perceptual efficiency by adjusting the velocity and number of submovements. These findings are discussed in light of the optimized submovement model.

RESEARCH on movement control has consistently documented two age-related differences in making simple ballistic movements. First, older adults take longer than younger adults to make movements. Second, older adults spend a greater proportion of time than younger adults in the deceleration, or "homing" phase, of movement. To date, however, these differences have not been fully explained. Four factors have been hypothesized as causes of these differences. These factors suggest that, relative to younger adults, older adults: (1) have higher levels of motor noise; (2) have less efficient perceptual feedback systems; (3) use different strategies, for example, are more conservative or error-averse; and (4) are unable to produce sufficient force to make very rapid movements. Researchers have had difficulty in isolating the specific contribution of each of the four factors, as each factor could explain the two performance differences mentioned above. This study will experimentally isolate and evaluate the age-related effects of each factor.

After experimentally isolating the effects of the four factors on performance, the next step is to begin to build a model of performance that incorporates these factors and can explain overall performance levels. In this article we will use the optimized submovement model of Meyer and his colleagues (Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Meyer, Smith, Kornblum, Abrams, & Smith, 1990) as the theoretical basis for proposing such a model.

We begin with a description of the theory and methods used to support previous research on each of the four factors hypothesized as important causes of age-related differences in movement control. Next, we will provide an overview of the optimized submovement model (Meyer et al., 1990). We then present an experiment in which we control for the effects of each factor on a cursor-positioning task through new combinations of experimental techniques. We present the results for each factor in isolation as well as in relation to overall performance levels. Finally, we discuss the experimental results in the context of the optimized submovement model, which we propose as the basis for an integrated theoretical framework for explaining age-related differences in movement control.

Factors Posited as Causes of Age-Related Differences in Movement Performance

Factor 1: Increased noise-to-force ratio. — A primary explanation for age-related slowing in movement is based on two assumptions about motor noise. The first assumption is that there is noise in the motor system. Noise is defined as random, unintentional error that occurs during the transmission of the signal to the muscles that control the movement. This means that even if one plans and programs a correct set of muscle forces for a movement, error can occur due to noise that is inherent in the system (e.g., Fitts, 1954). A second assumption is that noise increases with the amplitude of the force. Rapid movements that require greater muscle force will be accompanied by more noise or error in movement.

Noise-related explanations for movement slowing (e.g., Welford, 1981) suggest that with age, the noise-to-force ratio increases. This means that when an older adult produces a force, the noise associated with the resulting movement is greater than when a younger adult produces that same force. Given this assumption, older adults produce slower movements than younger adults. Given greater levels of motor noise, they move more slowly in order to maintain the same level of movement accuracy as younger adults.

Factor 2: Less efficient perceptual feedback. — Research has also suggested that older adults may be less efficient in their visual processing system than are younger adults (e.g., Cremer & Zeef, 1987; Verillo & Verillo, 1985). This lack of efficiency in processing visual information could lead to slower movement times by making the visually guided feedback mechanism involved in closed-loop movements less efficient for older adults.

Factor 3: Strategy differences. — This explanation for slower movement times among older adults suggests that older adults plan slower movements because they are more "error averse" or conservative than younger adults (e.g., Goggin & Stelmach, 1990). In all movement tasks, people deal with a tradeoff between speed and accuracy. As the force or resulting speed of a movement increases, the probability of the movement ending at the planned location decreases. For each movement task, a person must decide how to optimize performance on speed and accuracy. Whether one decides to have faster but less accurate movements, or slower but more accurate movements, depends on an individual's strategy, which in turn is primarily determined by the nature of the payoff constraints. In studies of the speed-accuracy tradeoff, the tradeoff is manipulated by rewards being placed differentially on speed and accuracy. Older adults could produce slower movements because they emphasize accuracy more than do younger adults.

Factor 4: Ability to produce force. — In any experiment on age-related differences in movement control, one possible explanation for the observed differences is the inability of the older group to produce the same amount of muscle force as the younger group. The inability to produce the same amount of force in a set of muscles would explain slower movement times if the older adults cannot generate the amount of force used by younger adults in making the movement. This can be examined by requiring older subjects to emphasize force in their movement production.

Explaining Overall Performance: The Optimized Submovement Model

Isolating and describing the relationship between these four possible factors and age-related differences in movement control is a necessary but not sufficient step. Questions will remain about overall movement control, including the relative importance of the four individual factors and their interactions. Both methods and a theoretical base are needed to develop a broader explanatory model. The introduction of sophisticated equipment for movement recording and computational algorithms for parsing movement has allowed movement substructure to be analyzed in great detail (e.g., Jagacinski, Repperger, Moran, Ward, & Glass, 1980; Wright & Meyer, 1983). One important outgrowth of this work has been the understanding that movement is often more than the combination of an acceleration and a deceleration phase.

The newer theoretical models are based on early work provided by the impulse-variability model of Schmidt, Zelasnik, Hawkins, Frank, and Quinn (1979). According to this model, the parameters of pulse amplitude and movement duration are programmed for a movement, and vary with distance of the movement and width of the target. The model assumes that there is neuromuscular noise which causes the actual values of pulse amplitude and time to fluctuate, with the amount of noise directly related to the value of the parameters. Schmidt and colleagues demonstrated that there is a linear relationship between the force of a movement and the error associated with the endpoint of movement (the standard deviation of the distance of movement).

A theoretical outgrowth of the impulse-variability model is the optimized submovement model of Meyer and his colleagues (e.g., Meyer et al., 1988, 1990).The theory's major components have direct applications to understanding age-related differences, because they make predictions about the nature of submovement structure within the execution stage of movement.

The basic tenet of the optimized submovement model is that people adjust to movement tasks of different difficulty by adjusting the underlying submovement structure, both in terms of the speed of an individual submovement, and in the number of submovements that will be required. Faced with any movement task, a person could take several approaches. First, one could make a very slow movement (using low force), and one's chance of hitting the target would be almost 100%, as noise is low. There would be a high degree of accuracy, but long movement times. On the other hand, one could use maximum force, making movement time very short, but the chance of hitting the target would be very small. Of course, in most movement tasks, more than one force (submovement) can be generated in the movement. One could, therefore, make a fast movement that has a certain probability of hitting the target, and if the target is missed a secondary (or tertiary) corrective submovement could be made.

The optimized submovement model has shown that in brief movements, subjects adjust the force of a movement (and the subsequent accuracy of the submovement) and the number of submovements to produce optimal performance in a task. While the model does not directly address age-related differences in movement control, it does provide a framework for understanding how older adults may compensate for increases in motor noise in the system. Specifically, the model suggests that under conditions of increased motor noise, one optimizes performance by increasing the number of submovements made and/or by decreasing the velocity of the individual submovements.

As a starting point for a broader explanatory model of age-related differences in movement control, the optimized submovement model holds promise for two reasons. First, if increased motor noise or slower perceptual feedback are important determinants of performance, it provides a framework for understanding how older adults may compensate for these difficulties. Second, the methodological focus on submovement structure promoted by the model supports a finer-grained analysis of movement control, which may be particularly important in understanding age-related differences in performance. To investigate the utility of this model for explaining age-related differences in movement performance, in this study we will analyze movement according to its submovement structure.

Summary

The primary purpose of this study is to isolate the component motor, perceptual, and cognitive processes to assess their roles in age-related differences in movement control. To do this, two different types of movement tasks will be performed, an "accuracy-constrained" task and a "no-accuracy constraints" task. Both tasks will consist of using a mouse to position a cursor on a computer screen. The accuracy-constrained task consists of having subjects make movements *into* a target area. In the accuracy-constrained task, distance of movement, target width, and penalty condition will be varied. This task will allow us to isolate stages of movement, the penalty condition variable will allow us to investigate age-related differences in error aversion, and we will be able to analyze the submovement structure of the movements. The second task, no-accuracy constraints, consists of having subjects make a single movement *toward* a target point with no accuracy constraint placed on the movement. This task will be used to judge the noise-to-force ratio for the two age groups, and, by comparison with the maximum velocities from the accuracy-constrained task, will determine if the ability to produce force plays a role in age-related difference in performance on the accuracy-constrained task. By using this task at the end of the experiment, we also will reduce any age-related practice differences and get a measure unconfounded by learning effects. Finally, we will be able to determine how any differences in the four factors combine to produce overall age-related differences in the execution stage of movement.

METHOD

Subjects

Sixteen older and 16 younger right-handed adults participated in this experiment. One group consisted of older adults between the ages of 65–75 (mean age of 70.19), recruited from a subject pool of older adults who had either responded to a newspaper advertisement or been contacted through local organizations. The younger subjects were recruited from the psychology subject pool at the Georgia Institute of Technology and from the surrounding community. They ranged in age from 18–28 (mean age of 21.94). Student participants were given course credit or $7.00 per hour; all other participants were paid $7.00 per hour for their participation in the study. In addition, the highest performer in both age groups was given an additional $50 reward.

For both age groups, tests of perceptual and cognitive abilities, and questionnaires on reported overall health, drug usage, and years of education were administered. All subjects were taking no more than one drug rated as causing more than minimal effects on attention (Giambra & Quilter, 1988) and had 20/40 near and far visual acuity (corrected or uncorrected). The means and standard deviations of the remaining measures are reported in Table 1.

Apparatus

The experiment was run on Epson Equity Plus computers with 400 pixels per inch Microsoft two-button bus mice. The mice were placed at the subject's discretion on the table, with the left-hand button being used for the experiment. Mouse resolution was 400 pixels per inch in movement resolution and 5 ms time resolution. The resolution of the 12-inch monochrome monitors and VGA graphics allowed a maximum screen dimension of 480 × 640 pixels. The screen resolution was approximately 24 pixels per centimeter. Subjects were seated in 1.5 m wide by 1.5 m deep cubicles in which the display screens and computers were situated upon a desktop. On either side of the computer there was an additional 61 cm of desktop for mouse movement and the subjects were allowed to place the mouse for movement by either hand. The subjects viewed the display from approximately 60 cm. The cursor was approximately 0.7 cm × 0.7 cm. The home box was approximately 1.5 cm × 1.5 cm and appeared 0.05 cm from the left hand side of the screen. The target boxes were of four different sizes (4 × 4, 8 × 8, 16 × 16, and 32 × 32 pixels), and appeared at five different

Table 1. Means and Standard Deviations (*SD*) of the Age, Years of Education, Health Rating, and Ability Tests for the Two Age Groups

	Younger Adults			Older Adults		
	Mean	(*SD*)	Range	Mean	(*SD*)	Range
Age	21.94	(2.69)	18–28	70.19	(3.02)	66–75
Years of college education*	2.63	(1.41)	0–5	5.19	(2.54)	2–11
Health rating[a]*	1.69	(0.95)	1–4	1.81	(1.05)	1–5
Vocabulary test[b]*	16.94	(6.02)	7–27	24.44	(8.62)	9–36
Number series[c]*	14.19	(3.67)	8–20	9.00	(5.15)	3–17
Reverse digit span[d]*	11.44	(1.63)	7–14	9.31	(3.18)	4–14
Digit symbol substitution[e]*	71.44	(12.69)	50–92	53.06	(10.90)	42–81
Simple reaction time[f]*	258	(21.47)	222–297	341	(55.37)	262–482
2-item choice reaction time[f]*	345	(44.29)	297–468	565	(130.41)	360–760
4-item choice reaction time[f]*	358	(46.41)	299–485	601	(123.00)	390–821
7-item choice reaction time[f]*	400	(62.53)	314–563	726	(186.59)	444–1042

[a]Self-rated on a 5-point scale, 1 = excellent, 5 = poor.
[b]Out of 36 questions.
[c]Out of 20 questions.
[d]Out of 14 questions.
[e]Out of 100 questions.
[f]In milliseconds.
*$p < .05$, 28 df, significant differences between the two age groups.

distances from the center of the home box (100, 200, 300, 400, or 500 pixels).

Movement Recording

The computer began recording mouse movements once the cursor was located within the home box and the left mouse button was pressed. Movement recording ended when the mouse button was released. During recording, a record of the x and y coordinates of the cursor was written every 5 ms. The total time during which the mouse button was depressed was later parsed into composite segments of initiation, execution, and verification times. Further information on the parsing of total movement times is contained in the section on Movement Parsing.

Design

The primary experimental task (accuracy constrained task) used a mixed factorial design. The grouping variable was age, either young or old. The within-subjects variables were target distance (D = 100, 200, 300, 400 or 500 pixels), target width (W = 4, 8, 16 or 32 pixels), and penalty (P = −4, −8, −16 or −32 points). For the second experimental task (no accuracy constraints task) there was the grouping variable of age and the within-subjects variable of movement distance (20, 100, 180, 260, 340, 420, 500, 580 pixels). Penalty and target width did not apply to this task.

Subjects were tested for one session per day for eight days. The first session was spent having subjects complete the first four of a series of six ability tests intended to profile the subject sample. The remaining two ability tests were administered at the beginning of the second session. These tests are further discussed under the subsection Ability Tests. Next, the experimental task was demonstrated, and the nature of the speed-accuracy tradeoff and how performance would be graded on both speed and accuracy of performance were explained. The subjects then performed 8 blocks of 20 practice trials. For these training sessions, subjects were told to make movements as quickly as possible and to try to eliminate any errors. Data on movement time and errors were collected. In the beginning of the third session subjects again performed 8 blocks of 20 practice trials without points. These data were used to establish a baseline level of performance for each subject, as described under Feedback Procedure. These baseline data were later used to establish mean movement times for each movement distance by target width condition for each subject. For the remainder of the third session and every following session subjects were given feedback on their performance in terms of points earned on a trial. The latter portion of the third session was devoted to introducing the point and penalty system by performing one block of 20 practice trials with points for each penalty level. This resulted in a total of 12 blocks and 240 trials throughout the third session.

The fourth session was again practice, with subjects performing 3 blocks of 20 trials for each penalty level with points for a total of 240 trials. The purpose of the practice in this session was to ensure that subjects understood how the cost for errors and the points for movement time were calculated. Also at the beginning of the session, the experimenter explained the nature of the changing cost associated with movement errors. Points were awarded for speed and accuracy.

The fifth through eighth sessions were the experimental sessions. Each session had 12 blocks of 20 trials, with a single penalty condition used in each session. The order of penalty condition across sessions was counterbalanced between subjects using a Latin square design. Also, at the end of the eighth session, all subjects performed the no-accuracy constraints task. These data were used to compare the two age groups on their noise-to-force ratios, independent of the other three factors and to obtain a measure of ability to produce force.

Ability Tests

The abilities tests were chosen to measure six primary abilities — semantic knowledge, induction, perceptual speed, working memory, simple reaction time, and choice reaction time. The tests intended to measure the first four abilities were administered during the first session, while the two reaction time tests were conducted at the beginning of the second session. Semantic knowledge was measured using the advanced vocabulary test developed by Ekstrom, French, Harman, and Dermen (1976). A number series completion test of Bleiszner, Willis, and Baltes (1981) was used to measure induction. Perceptual speed and working memory were gauged using the Digit Symbol Substitution Task and Backwards Digit Span tasks, respectively (Wechsler, 1981). Measures of simple reaction time and choice reaction time were acquired using computer tasks in the manner of Fisk and Rogers (1991; Hertzog, Fisk, & Cooper, 1994). Choice reaction time was measured at each of 2, 4, and 8 choice tasks. The results of the abilities tests are displayed in Table 1.

The purpose of these tests was to provide a basic description of the two samples. As expected, the older adults did better than the younger adults on the measure of vocabulary. The younger adults did significantly better on the other ability measures. These results and the means on the scores are approximately the same as those reported by other researchers (e.g., Fisk & Rogers, 1991).

Feedback Procedure

During the last four blocks in the third session during the cursor positioning practice (without points), the mean times for each subject at each of the 20 D by W conditions (5 D's × 4 W's) were calculated. These times were set as the baseline times against which each subject would compete for points. If a trial ended outside of the target box, subjects received a penalty according to the current penalty level (i.e., either −4, −8, −16, or −32 points), but if the trial ended within the target box, points were calculated based on the total positioning time, and the subject's baseline time for that D and W value target. Each point was based on a 5% deviation from the baseline time. For example, if one performed 52.5–57.4% faster than one's mean, one would earn 10 points; or, if one performed 52.5–57.4% slower than one's mean, one would lose 10 points.

Procedure

The first day, for the paper-and-pencil ability tests, the subjects were tested in groups of eight. The second day the subjects first performed the simple reaction time, then the choice reaction time tasks, and finally, after being instructed in the use of the apparatus, subjects began the cursor positioning task.

To begin, a box appeared informing the subject of the penalty value. At the beginning of each block a text box appeared in the middle of the screen saying, "Click here to begin next block." When the subject positioned the cursor within the box and pressed the mouse button, the block of trials began. At the beginning of each trial the home box appeared on the left edge of the screen, and the target box, of *W* height and width, appeared with its center horizontally displaced *D* pixels away from the center of the home box. This ensured that the participant knew the distance of the movement and the size of the target before beginning the trial.

Recording of the mouse position and time began when the subject initiated a trial. This was done by positioning the cursor within the home box and pressing and holding the mouse button. The trial ended when the subject released the mouse button, regardless of whether the cursor was located within the target box. The computer then displayed a message reporting the results of the subject's movement. This report consisted of two pieces of information. First, whether upon the release of the mouse button the cursor was positioned within the target box (e.g., "Right" or "Wrong"), and second, the number of points the subject gained or lost on that particular trial. On the early trials, where there were no points calculated, the feedback was simply time in ms. Anytime the cursor was not in the target box at the end of the trial, the trial was readministered in a random position among the remaining trials to be performed for that block. The home box and the target box for the next trial then replaced the current screen. The subject repeated these steps until all the trials for that block had been completed.

At the end of each block, the subjects were presented with a summary report of their results for that block of trials. This report included information on the number of correct trial points earned during that block, the number of incorrect trial points lost on that block, and the total number of points for the subject on that session. If all the blocks in the session had not been performed, a text box indicating the beginning of a new block appeared. Subjects were encouraged to rest, if needed, between blocks. When all blocks had been completed, the computer presented the subjects with the total number of points that they had earned for the session.

Movement Parsing

The movement data were categorized using a movement, filtering, and parsing program. In parsing the movement data, we first smoothed and differentiated the position data with the NER digital filter of Kaiser and Reed (1977). This filter had a passband that ranged from 0 to 29 Hz, a skirt that ranged from 29 to 31 Hz, and a stopband from 31 Hz upwards. This filter was used to reduce the effects of hand tremor and the jittery stops and starts due to friction with the mouse. Differentiating the smoothed position data was done twice with a 30 Hz low-pass filter to give us velocity and acceleration at each point in time.

The parsing algorithm was based on our previous work (Walker et al., 1993), which was based on the work of Jagacinski et al. (1980) and Meyer et al. (1988). As in Walker, Meyer, and Smelcer (1993), the parsing algorithm decomposed overall movements into submovements based on distance, velocity, and acceleration profiles. An initial movement of at least 75 pixels/sec lasting at least 20 ms was considered to begin the first submovement. The submovement was considered to end when either the velocity reached zero, or the acceleration changed signs after a relative minimum in velocity. The parser applied these rules and divided the data stream into a series of submovements.

After submovements had been located, the movements were broken up into three mutually exclusive and exhaustive categories. These categories were initiation time, execution time, and verification time. Initiation time was the time between the mouse button being depressed and the beginning of the first submovement. Execution time was time between the beginning of the first submovement and the termination of the final submovement. Verification time was defined as time between the end of the last submovement and the release of the mouse button.

Factor Isolation

Factor 1: Increased noise-to-force ratio. — We will isolate and describe age-related differences in the noise-to-force ratio by using an adapted version of the task introduced by Schmidt et al. (1979). This task, which we refer to as the no-accuracy constraints task, produces a measure of the noise-to-force ratio for both age groups. Subjects will be asked to aim their movement at a very small target, and then to make a single movement as rapidly as possible. The movement need only end *near* the target dot; no corrective submovements are required. Perceptual feedback and accuracy constraints are not important in the performance of this task. This allows us to describe differences in the noise-to-force ratio between the two groups in a task where perceptual feedback and strategy differences do not play a role in determining performance.

Factor 2: Less efficient processing of perceptual feedback. — Age-related differences in perceptual feedback on movement control can be isolated and described by analyzing movement according to stages. Some of our recent work (Walker et al., 1993, 1994) has investigated the factors that determine the duration of movement stages in a cursor positioning task. In that task, subjects had to press and hold a computer mouse button to begin a movement trial, then move the cursor to the target location, and finally release the mouse button to signal the end of the trial. This task allowed us to divide total cursor-positioning time into stages or phases of movement. These stages were: the initiation stage, defined as the time between pressing the mouse button to begin a trial and the start of movement; the execution stage, defined as the time between the beginning of the first submovement until the end of the last submovement; and the verification stage, defined as the time between the end of the last submovement and the release of the mouse button.

Age-related differences in perceptual feedback on movement control can be isolated and described by analyzing movement according to stages. Some of our recent work (Walker et al., 1993, 1994) has investigated the factors that determine the duration of movement stages in a cursor positioning task. In that task, subjects had to press and hold a computer mouse button to begin a movement trial, then move the cursor to the target location, and finally release the mouse button to signal the end of the trial. This task allowed us to divide total cursor-positioning time into stages or phases of movement. These stages were: the initiation stage, defined as the time between pressing the mouse button to begin a trial and the start of movement; the execution stage, defined as the time between the beginning of the first submovement until the end of the last submovement; and the verification stage, defined as the time between the end of the last submovement and the release of the mouse button. In our task, initiation time primarily reflects a simple reaction, and does not capture the time needed to plan or program the movement. Execution time is similar to movement time as used in many experimental movement control tasks (e.g., stylus tapping, wrist rotation) and consists of a series of submovements where the person makes a movement, visually checks for location of the cursor, and then moves again to reach the target location. Unlike the verification stage, age-related differences in the duration of the execution stage could be affected by all four factors. This stage of movement is what is often compared for different age groups.

The third stage of movement, verification, reflects the time required for the subject to determine that a correct movement has been made (the cursor is in the target location) and signal this by releasing the mouse button. The duration of this stage is dominated by perceptual feedback processes. Age-related differences in the duration of this stage of movement control provide a measure of the relative efficiency of the perceptual feedback mechanism in the two age groups. As a caveat, the perceptual processing involved in this stage may not be completely analagous to the processing that occurs during the execution stage, but it should provide a measure of perceptual processing unconfounded by motor noise.

Factor 3: Strategy differences. — Many movement control studies have attempted to reduce the importance of possible strategy differences by forcing both older and younger adults to maintain high accuracy levels. This does not solve the underlying problem, because equating accuracy, even at a high level, does not guarantee that the two groups are at the same point on the speed-accuracy tradeoff function (e.g., Hertzog, Vernon, & Rypma, 1993). Signal detection analyses can provide a useful tool for describing age-related strategy differences.

We will isolate and describe age-related strategy differences by using signal detection analyses. We will manipulate the rewards for accuracy and speed by awarding points for faster movements and subtracting points for movement errors. Over multiple task sessions, the points for the speed of movement will remain constant, but the points subtracted for movement error will vary dramatically (−4, −8, −16, −32). We can then use signal detection analyses to determine a value for strategy differences related to the speed-accuracy tradeoff function for the two groups.

Factor 4: Ability to produce force. — Age-related differences in the ability to produce force can be isolated and described by comparing the data between the no-accuracy constraints task (described in the section on noise-to-force ratio) and the accuracy-constrained task. This can be done by comparing the maximum velocity of the young group in the accuracy-constrained task with the older group in the no-accuracy constraints task with movements at similar distance. The key issue is whether the older adults are capable of producing forces in the no-accuracy constraints task that are equal to the forces younger adults produce when accuracy constraints are present. If older adults cannot produce this level of force with no-accuracy constraints, then the age-related differences in muscle strength are a source of age-related differences in movement performance in the accuracy-constrained task. If, however, older adults can produce the same amount of force with no-accuracy constraints as the younger adults produce in accuracy-constrained task, then the ability to produce force is not a factor in explaining age-related differences in movement performance during the execution stage of this task.

Results

The analyses are presented in six sections. In the first section we present results of the analyses of movement performance on the first three sessions to determine whether the subjects had reached a stable level of performance on the movement task. In the second section, we address the issue of age-related differences in the noise-to-force ratio. In this section we look at the ability of both age groups to produce rapid movements when there are no accuracy constraints, and, based on these data, calculate the force-to-noise function by age. In the third section we address age-related differences in the speed of perceptual feedback. In this section we perform a Distance by Target Width by Penalty Condition by Age analysis of variance (ANOVA) on the duration of the verification stage of movement. In the fourth section we look at possible age-related strategy differences. First we analyze percent correct trials in a Distance by Target Width by Penalty Condition by Age ANOVA. We then use signal detection analyses to produce the measures A′ and B″ which are analyzed by Age and Penalty Condition.

In the fifth section we address the issue of ability to produce force as an explanation of age-related differences in movement control. This is done by comparing maximum velocity of the two groups on the no-accuracy constraints task to the force used in the accuracy-constrained movement task. In the final section, we will investigate how these factors relate to performance during the execution stage of movement, where all the factors combine to determine performance. In this section we will first analyze the duration of the execution stage of movement by means of Distance (5) by Target Width (4) by Penalty Condition (4) by Age (2) ANOVAs. We will then use the same analyses to investigate the structure of the execution stage of movement. The dependent variables are mean number of submovements, duration of the first submovement, proportion of total distance moved during the first submovement, average velocity of the first submovement, and time to peak acceleration. For all statistical analyses, we used the Greenhouse-

Geiser adjustment in judging significant differences, with a p-value of .01 or less. This probability level was set to adjust for the analyses of multiple dependent measures. For significant main effects we used post-hoc contrasts to determine significant differences between means. Significant interactions were analyzed with tests for simple effects.

Initial Task Performance

Three ANOVAs were performed on mean number of correct trials, execution time, and total positioning time for the blocks of trials from sessions 3 and 4, where points were given as feedback. These analyses used Blocks (16), Age (2), Distance (5), and Width (4) as independent variables to determine if the two groups had reached a stable level of performance on the movement task. Of importance were two effects, the main effect of Block and the interaction of Block and Age. The analysis on mean number of correct trials revealed no significant main effects of Block, nor was the interaction of Block and Age significant. The analysis on execution time and total positioning time also revealed no significant effects of Block, nor were the interactions of Block and Age significant.

These results suggest that the participants in both age groups had reached a stable performance level by the end of the practice trials. These data were not used in any further analyses. All further analyses are based on data collected during sessions 5 through 8.

Analysis of Noise-to-Force Ratio

In the no-accuracy constraints task, participants were asked to move as quickly as possible to a point on the screen. They were told to aim for the target and make a single movement as quickly as they could. On each trial, time and distance from the target were recorded. These data were then used to calculate the noise-to-force ratios for each age group. This calculation was done in a four-step process. First, data were smoothed and parsed. Second, any trial in which the first submovement did not move at least 40% of the distance to the target, or on which more than 5 submovements occurred, was eliminated. We used these criteria to ensure that our measures of force and error would not be affected by the failure to follow the instructions to move as rapidly as possible to the target. These criteria eliminated 39% of the trials of the older adults and 33% of the young. Third, means and standard deviations of the distance from the target at the end of the first submovement were calculated for each of the eight target distances for each of the two age groups. The standard deviation of distance from the target was used as the measure of error or noise. Finally, mean peak (maximum) acceleration was calculated for each age group for each of the eight movement distances (used in this task) and used as the measure of force.

These steps resulted in a measure of noise (standard deviation of distance from the target at the end of the first submovement) and force (mean peak acceleration) for the eight movement distances for each of the two age groups. For each age group a regression analysis was performed with peak acceleration used as a predictor of the standard deviation of distance from the target. For younger adults, the best fitting equation had an intercept of 5.745 and a slope of .476, with an R^2 = .638. For older adults, the best-fitting linear equation had an intercept of −10.689, a slope of 1.461, with an R^2 = .629. The scatter plots with best-fitting regression line are presented in Figure 1.

As can be seen by the slope of the two regression lines, the older adults differ from the younger adults by approximately a factor of 3. This difference is much larger than expected, based on previous reports of age-related differences in movement performance. This finding clearly shows that differences in the noise-to-force ratio can play a role in age-related differences in movement control.

Effects of Perceptual Feedback

The effects of differences in perceptual feedback were isolated by comparing the duration of the verification stage of movement. The mean durations of the verification stage and the other stages of movement are presented in Table 2.

A Distance by Width by Penalty by Age ANOVA on verification time revealed four significant main effects and three significant two-way interactions. Older adults spent more time in the verification stage (M = 425 ms) than did younger adults (M = 173 ms), $F(1,30)$ = 110.46, MS_e = 372663.35. Participants also had longer verification stages with smaller target widths, $F(3,90)$ = 391.55, MS_e = 61761.89. However, both of these main effects must be interpreted in light of the significant Target Width by Age interaction, $F(3,90)$ = 52.12, MS_e = 61761.89. As shown in Figure 2, although older adults always took longer during the verification stage, the effect of age was greater for targets with smaller widths.

There were also significant main effects of penalty condition, $F(3,90)$ = 11.56, MS_e = 29818.42, and of distance, $F(4,120)$ = 10.80, MS_e = 7636.25. Verification time increased with increases in penalty and movement distance.

Overall, these analyses revealed that the perceptual feedback process can also be a major source of age-related differences in movement control. Mean duration of the

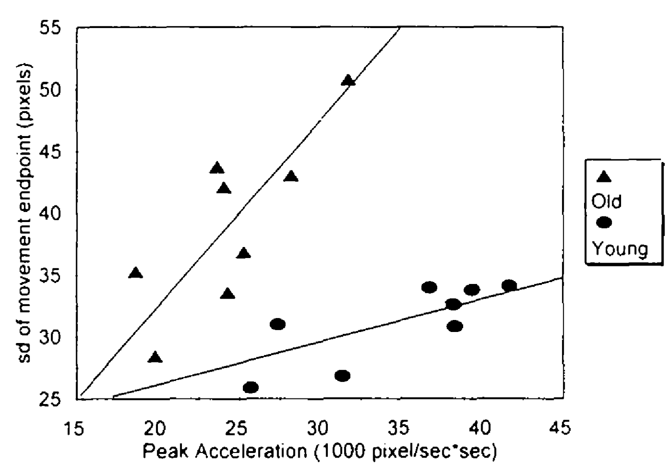

Figure 1. Scatter plots (and regression lines) for the standard deviation of the distance from the target at the end of the first submovement and peak acceleration for both old and young subjects.

Table 2. The Means and Standard Deviations (*SD*) of the Primary Dependent Measures for Age by Target Distance, Target Width, and Penalty Condition

	Initiation Time (ms)		Execution Time (ms)		Verification Time (ms)		Total Positioning Time (ms)	
	Mean	(*SD*)	Mean	(*SD*)	Mean	(*SD*)	Mean	(*SD*)
Young								
D = 100	32	(19)	359	(86)	165	(130)	556	(195)
D = 200	32	(20)	487	(94)	166	(130)	686	(200)
D = 300	34	(22)	565	(113)	175	(129)	770	(215)
D = 400	34	(22)	629	(119)	176	(138)	840	(228)
D = 500	35	(22)	702	(137)	184	(143)	920	(239)
W = 4	34	(22)	617	(162)	342	(129)	993	(230)
W = 8	34	(21)	592	(152)	187	(77)	813	(192)
W = 16	33	(22)	532	(146)	98	(44)	664	(166)
W = 32	32	(20)	454	(139)	62	(31)	548	(148)
P = -4	38	(22)	559	(162)	196	(154)	793	(270)
P = -8	33	(22)	546	(163)	184	(140)	763	(250)
P = -16	31	(20)	545	(158)	169	(129)	744	(244)
P = -32	31	(19)	545	(166)	141	(102)	717	(229)
Old								
D = 100	78	(47)	504	(134)	408	(258)	990	(352)
D = 200	72	(43)	656	(185)	410	(253)	1138	(387)
D = 300	73	(46)	754	(167)	334	(261)	1261	(375)
D = 400	72	(42)	841	(183)	304	(271)	1343	(392)
D = 500	75	(40)	961	(237)	443	(281)	1479	(428)
W = 4	76	(45)	794	(243)	763	(198)	1633	(366)
W = 8	74	(42)	775	(223)	497	(131)	1346	(309)
W = 16	74	(43)	744	(242)	275	(98)	1092	(310)
W = 32	72	(44)	660	(235)	165	(71)	897	(284)
P = -4	78	(47)	779	(306)	459	(289)	1316	(500)
P = -8	65	(35)	728	(219)	428	(275)	1222	(409)
P = -16	79	(50)	729	(215)	410	(250)	1217	(385)
P = -32	75	(39)	737	(210)	403	(241)	1214	(373)

Note: D = target distance; W = target width; P = penalty condition.

verification stage for the older adults was almost 2.5 times longer than that of the younger adults.

Strategy Differences

To investigate possible age-related differences in strategy we first analyzed mean proportion of correct trials, and then used signal detection analyses. The ANOVA on mean proportion of correct trials (trials on which an error did not occur) revealed two significant main effects and three significant two-way interactions. There was a significant effect of penalty, $F(3,90) = 18.97$, $MS_e = .00521$, and width, $F(3,90) = 102.80$, $MS_e = .00505$. As Table 3 shows, fewer errors were made at the highest penalty condition, and fewer errors were made for the widest targets. All of these effects must be interpreted in light of the significant interactions. Follow-up tests to the significant interaction of Distance and Age, $F(4,120) = 4.19$, $MS_e = .00376$, revealed that increasing distance increased accuracy for the younger subjects, but had no significant effect on the older subjects. Follow-up tests to the significant interaction of Penalty and Age, $F(3,90) = 10.37$, $MS_e = .00521$, revealed that accuracy increased as penalty increased for the younger adults, but not for the older adults. Follow-up tests to the significant interaction of Penalty and Width, $F(9,270) = 4.12$, $MS_e = .00282$, revealed that the differential effect of increasing penalty was more pronounced for movements to targets with the smallest width value than for movements to targets with any of the other three width values.

Signal Detection Analyses

For the signal detection analyses the component submovements of each movement trial were classified into one of the four response classes (hit, miss, false alarm, correct rejections), based on the accuracy of the movement, and the occurrence of a following submovement. Next, the "Hit" and "False Alarm" rate for each subject for each penalty condition was determined. These data were then used to calculate A′, the measure of sensitivity, and B″, the measure of decision criteria. We used Grier's (1971) formulas for the two measures:

$$A' = 1 - (1/4)[P(F)/P(H) - (1-P(H))/(1-P(F))]$$

$$B'' = [P(H)(1-P(H)) - P(F)(1-P(F))]/[P(H)(1-P(H)) + P(F)(1-P(F))] ,$$

where P(F) is the probability of a false alarm and P(H) is the probability of a hit. These measures were used instead of the traditional d′ and B because there was a very low number of false alarms and therefore a nonparametric version of signal detection was appropriate (e.g., Frey & Colliver, 1975). The means and standard deviations of A′ and B″ are presented in Table 3.

We next performed an Age by Penalty Condition ANOVA on both A′ and B″. The analysis on A′ yielded no significant main effects or interaction.

The analysis on B″ yielded a significant main effect of Age, $F(1,30) = 16.20$, $MS_e = .06887$, a significant main effect of Penalty Condition, $F(3,90) = 11.44$, $MS_e = .01256$, and a significant interaction of Age and Penalty Condition, $F(3,90) = 7.18$, $MS_e = .01256$. As is shown in Table 3, the older adults had a higher decision criteria, confirming the view that they are more error aversive. Follow-up analyses showed that younger adults change their decision criteria according to penalty, $F(3,45) = 11.89$, $p < .001$, while older adults did not show a significant adjustment.

These analyses clearly show that the two age groups do use different strategies concerning the speed-accuracy tradeoff function involved in movement control. While there was not a significant main effect of age on percent correct trials, the signal detection analyses reveal that the older adults were more conservative in their functioning. Specifically, the older adults made additional small, corrective submovements once the cursor was inside the target box. Interestingly, these data are consistent with analyses from more "cognitive" tasks (e.g., Brigham & Pressley, 1988; Hertzog et al., 1993; Kramer & Larish, 1996; Sharps & Gollin, 1987) in showing strategic differences between older and younger adults as a locus of performance differences.

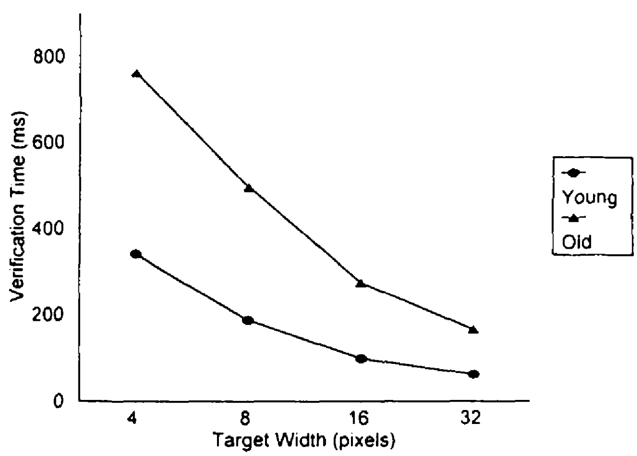

Figure 2. The effects of age and target width on the duration of the verification stage of movement with standard error bars.

Ability To Produce Force

With these analyses, we sought to determine if older adults' ability to produce force played a role in any age-related differences in the accuracy-constrained movement task. To do this we calculated mean peak velocity for each age group for the longest movement distance for both tasks. The distance of the movement was the same in both tasks.

As expected, the analysis on peak force produced in the accuracy-constrained task revealed that younger adults used more force ($M = 2.40$ pixels per ms) than did the older adults ($M = 1.69$ pixels per ms), $F(1,30) = 102.0$, $MS_e = 139.28$. However, the force produced by the older adults in the no-accuracy constraints task is equal to that produced by the younger adults in the accuracy-constrained task ($M = 2.53$ pixels per ms). This finding is important as it demonstrates that older adults *can* produce the same force as that used by the younger adults in the accuracy-constrained task. However, it appears that older adults do not choose to produce the same force as younger adults.

Structure of the Execution Stage of Movement

Having established that three of the four factors are different for older and younger adults, our next stage of analysis addressed how these factors combine to produce differences in the duration and submovement structure of the execution stage of movement. Initially we performed a four-factor ANOVA on the mean duration of the execution stage of movement. This analysis revealed three significant main effects and two significant interactions. The younger adults had shorter execution times ($M = 549$ ms) than the older adults ($M = 743$ ms), $F(1,20) = 24.10$, $MS_e = 997643.44$. Both distance, $F(4,120) = 503.08$, $MS_e = 24297.71$, and width, $F(3,90) = 264.18$, $MS_e = 10441.54$, had significant effects on execution time. Execution time increased as

Table 3. Means and Standard Deviations (*SD*) of Percent Correct, Hits, False Alarms, A′, and Beta″ for Each Age Group

	Percent Correct		Hits		False Alarms		A′		Beta″	
	Mean	(*SD*)	Mean	(*SD*)	Mean	(*SD*)	Mean	(*SD*)	Mean	(*SD*)
Younger										
Penalty −4	.92	(.09)	.764	(.072)	.059	(.034)	.919	(.018)	.526	(.250)
Penalty −8	.95	(.07)	.770	(.068)	.046	(.035)	.925	(.019)	.616	(.224)
Penalty −16	.96	(.06)	.775	(.058)	.035	(.023)	.931	(.015)	.677	(.189)
Penalty −32	.98	(.05)	.767	(.055)	.020	(.017)	.934	(.014)	.810	(.142)
Older										
Penalty −4	.97	(.09)	.654	(.078)	.022	(.019)	.904	(.018)	.827	(.142)
Penalty −8	.97	(.06)	.671	(.079)	.018	(.013)	.909	(.023)	.853	(.083)
Penalty −16	.97	(.06)	.660	(.075)	.021	(.012)	.905	(.021)	.830	(.094)
Penalty −32	.98	(.06)	.662	(.086)	.016	(.012)	.908	(.022)	.866	(.094)

movement distance increased, and execution time was longer for movements to smaller targets. There was also a significant Distance by Age interaction, $F(4,120) = 9.50$, $MS_e = 24297.71$. Simple effects tests revealed that the difference between older and younger adults in the execution stage increased when the movement distance was greater.

The finding of primary interest was the relatively modest age-related difference in the duration of the execution stage of movement. While the older adults took almost 40% longer in this stage, a larger age-related difference could have been expected if the large age-related differences in the noise-to-force ratio, the efficiency of the perceptual feedback loop, and in strategy combined in a simple linear fashion to produce performance. Instead, the older adults must be compensating for these differences to produce their level of performance in the execution stage of movement. To investigate this, we next analyzed the execution stage according to its submovement structure.

Submovement structure. — The means and standard deviations for mean number of submovements, duration of the first submovement, proportion of distance moved during the first submovement, average velocity of the first submovement, and percentage of execution time before peak velocity are presented in Table 4 by age and movement distance, target width, and penalty condition.

The ANOVA on mean number of submovements revealed three significant main effects. The main effect of distance, $F(4,120) = 112.60$, $MS_e = 1.19$, revealed that the number of submovements increased with distance to the target. The main effect of width, $F(3,90) = 200.54$, $MS_e = .34$, revealed that the number of submovements was greater for movements to smaller targets. In addition, there was a main effect of age, $F(1,30) = 11.55$, $MS_e = 33.79$. The older adults produced more submovements ($M = 3.60$) than did the younger adults ($M = 2.82$).

The ANOVA on the duration of the first submovement revealed two significant main effects and one significant two-way interaction. The significant main effect of distance, $F(4,120) = 124.45$, $MS_e = 25450.31$, $p < .001$, and significant main effect of width, $F(3,90) = 46.64$, $MS_e = 2087.43$, $p < .001$, must both be interpreted in light of the significant interaction of distance and width, $F(12,360) = 3.56$, $MS_e = 1179.59$, $p < .005$. While duration of the first submovement increased with distance and decreased as target width increased, the effect of distance had greater

Table 4. The Means and Standard Deviations (*SD*) of the Primary Dependent Measures for Age by Target Distance, Target Width, and Penalty Condition

	Number of Submovements		Duration of 1st Submovement		Proportion of Distance of 1st Submovement		Average Velocity of 1st Submovement		Proportion of Distance Before Peak Velocity	
	Mean	(*SD*)	Mean	(*SD*)	Mean	(*SD*)	Mean	(*SD*)	Mean	(*SD*)
Young										
D = 100	2.18	(0.59)	199	(49)	84	(8)	0.47	(0.12)	0.25	(0.06)
D = 200	2.57	(0.60)	280	(85)	88	(9)	0.70	(0.16)	0.25	(0.05)
D = 300	2.83	(0.74)	325	(111)	86	(14)	0.87	(0.19)	0.26	(0.05)
D = 400	3.06	(0.84)	351	(138)	82	(19)	0.99	(0.23)	0.25	(0.05)
D = 500	3.43	(0.93)	362	(164)	76	(23)	1.06	(0.27)	0.25	(0.05)
W = 4	3.17	(0.80)	316	(137)	83	(15)	0.80	(0.30)	0.23	(0.04)
W = 8	3.04	(0.80)	312	(133)	83	(16)	0.81	(0.30)	0.23	(0.04)
W = 16	2.72	(0.79)	303	(128)	84	(16)	0.83	(0.30)	0.26	(0.04)
W = 32	2.34	(0.81)	282	(121)	82	(19)	0.83	(0.27)	0.29	(0.05)
P = −4	2.86	(0.96)	311	(119)	84	(15)	0.81	(0.30)	0.26	(0.05)
P = −8	2.80	(0.80)	295	(124)	82	(18)	0.81	(0.30)	0.25	(0.05)
P = −16	2.74	(0.75)	310	(129)	85	(13)	0.83	(0.29)	0.25	(0.05)
P = −32	2.86	(0.92)	299	(147)	82	(19)	0.82	(0.28)	0.25	(0.05)
Old										
D = 100	2.91	(0.92)	217	(40)	73	(16)	0.36	(0.10)	0.24	(0.06)
D = 200	3.30	(1.01)	316	(70)	78	(14)	0.53	(0.13)	0.25	(0.05)
D = 300	3.57	(1.10)	375	(95)	79	(17)	0.67	(0.16)	0.26	(0.05)
D = 400	3.84	(1.16)	412	(115)	77	(19)	0.78	(0.17)	0.26	(0.05)
D = 500	4.38	(1.45)	442	(113)	74	(21)	0.87	(0.20)	0.26	(0.05)
W = 4	3.88	(1.24)	359	(131)	74	(18)	0.62	(0.24)	0.24	(0.05)
W = 8	3.72	(1.13)	360	(127)	76	(17)	0.63	(0.24)	0.24	(0.05)
W = 16	3.59	(1.21)	350	(122)	77	(17)	0.65	(0.24)	0.25	(0.05)
W = 32	3.20	(1.31)	340	(120)	77	(18)	0.66	(0.23)	0.28	(0.05)
P = −4	3.75	(1.49)	346	(122)	75	(20)	0.63	(0.23)	0.25	(0.05)
P = −8	3.75	(1.33)	327	(111)	72	(19)	0.65	(0.24)	0.25	(0.05)
P = −16	3.46	(1.05)	360	(130)	77	(16)	0.64	(0.23)	0.26	(0.05)
P = −32	3.44	(1.01)	375	(132)	80	(15)	0.65	(0.25)	0.26	(0.05)

Note: D = target distance; W = target width; P = penalty condition.

effects for movements to smaller targets than for movements to the widest target.

The ANOVA on proportion of distance to the target moved during the first submovement revealed a significant interaction between Distance and Width, $F(12,360) = 15.17$, $MS_e = .00550$. Follow-up analyses revealed that for smaller targets, the highest proportion of distance was moved at the second and third shortest movement distance.

The analysis of the average velocity of the first submovement revealed two significant main effects. Average velocity increased with the distance of the movement, $F(4,120) = 79.90$, $MS_e = .51291$, and increased as target width increased, $F(3,90) = 4.60$, $MS_e = .07554$.

The analysis on the percentage of execution time before peak velocity was reached revealed one significant main effect and one significant two-way interaction. The main effect of width, $F(3,90) = 180.87$, $MS_e = .00229$, revealed that proportion of time in acceleration increased with target width. Follow-up tests to the interaction of age and distance, $F(4,120) = 4.96$, $MS_e = .00624$, revealed that younger adults spent the highest proportion of time in acceleration phase during movements to the most distant targets. For older adults, the trend was the opposite, with the highest proportion of acceleration phase occurring when making movements to the closest targets.

Discussion

A major purpose of this experiment was to isolate and evaluate the importance of the four factors on the age-related differences in movement control. In general, there is evidence that supports the role of an increased noise-to-force ratio, less perceptual processing efficiency, and strategy differences in producing age-related differences in movement performance. More importantly, the present data argue that the factors do not combine in a simple linear fashion to predict age-related differences in movement control. These findings have important theoretical and methodological implications for understanding age-related differences in movement control. Below we will first review the evidence for the four factors, and then discuss a more integrative theoretical explanation for age-related differences in movement control performance. We will end by discussing the methodological considerations that come from this work.

Effects of Individual Factors

Differences in the noise-to-force ratio. — The major evidence concerning increased motor noise comes from the regression of peak acceleration on the standard deviation of distance from the target at the end of the first submovement. For both age groups there was a significant R^2 between noise and force. The differences in slope between the two groups are the key factor in judging the noise-to-force ratios. The slope was roughly three times larger for the older than for the younger adults.

Differences in perceptual feedback efficiency. — The evidence for age-related differences in the efficiency of perceptual feedback comes from the comparison of the duration of the verification stage of movement. In this stage, older adults took over twice as long as younger adults to verify the location of the cursor and release the mouse button. This finding strongly suggests that there are age-related differences in perceptual feedback efficiency and that this process plays a role in age-related differences in movement performance.

Differences in strategy. — There were several analyses that strongly suggested that older adults adopt a more conservative strategy than do younger adults. First, older adults did not adjust their movements for different penalty conditions. Younger adults made more errors and faster movements when penalty condition was low. Older adults showed no difference in error rate by penalty condition and showed a much smaller adjustment in execution and verification time by penalty condition than did younger adults. Strategy differences were also supported by the signal detection analyses. While there were no significant differences in sensitivity, as measured by A′, there was a significant difference in decision criteria, B″. Older adults had a significantly higher B″ than did younger adults, and again younger adults tended to adjust their criteria because of penalty condition, while older adults did not. Overall, there is strong evidence that older adults are more conservative or error averse.

Perhaps the most important aspect of this is the understanding of how the conservative strategy of the older adults was manifested. Older adults did not show lower overall error rates. Both age groups made errors on fewer than 5 percent of the trials. Instead, older adults made additional submovements when the cursor was already inside the target area ("misses" in the signal detection analyses). These unnecessary submovements resulted in a higher B″ score for the older adults.

Differences in ability to produce force. — Not surprisingly, we found evidence that the younger adults could produce more force than older adults, as measured by the maximum velocity in the no-accuracy constraints task and the accuracy-constrained task. However, the older adults did produce as much force in the no-accuracy task as the younger adults did in the accuracy-constrained task. This means that the slower performance of the older adults in the accuracy-constrained task was not caused by their inability to produce enough force, rather that the older adults chose to produce slower movements.

Overall Movement Performance and the Optimized Submovement Model

Given the large age-related differences in the measures of the noise-to-force ratio, perceptual feedback efficiency, and strategy, one could have expected much larger age-related differences in the execution stage of movement. During this stage of movement, where all three factors play roles in determining performance, older adults had only about 40% longer durations than the younger adults. This means that the differences in the noise-to-force ratio and perceptual feedback inefficiency cannot combine in a simple, linear fashion to determine performance during the execution stage of movement. Instead, the data suggest that older adults were compensating for their higher noise-to-signal ratio and lower perceptual efficiency. Our explanation for how this compensation occurs is based on the optimized submovement model of Meyer and colleagues (1988, 1990).

According to this model, when planning and programming movements, individuals must consider not only the physical aspects of the movement tasks (distance to be moved, size of the target location) and the speed and accuracy constraints on the task, but also their underlying noise-to-force ratio. Faced with a movement task, a person will seek to optimize performance by adjusting the force associated with the initial submovement. If the goal of the movement task is to make the movement in the minimum amount of time with the minimum number of errors, a person must choose an optimal initial force for the movement. Associated with the force will be a probability of ending in the target location at the end of the submovement (the higher the force, the lower the probability). If the submovement does not end in the target location, a secondary submovement must be made to reach the target. A secondary submovement obviously requires time to plan, program, and implement. For a person to achieve optimal performance, one must balance the possible advantage of a shorter movement time that can be produced with a high force movement with the disadvantage or cost of the need to produce a secondary, corrective submovement. The model also states that when movement difficulty is increased, the number of submovements required to produce optimum performance increases as a power function relationship between movement difficulty and movement time.

We believe that the smaller age-related difference in the duration of the execution stage of movement was found because the older adults were able to compensate for their higher noise-to-force ratios by producing more submovements and making these submovements perhaps more slowly (although the difference was not significant), thereby increasing the probability of ending in the target. This type of compensation for a higher noise-to-force ratio is consistent with the optimized submovement model. The age-related differences in the measure of the noise-to-force ratio and the duration of the execution time are also not too far from what is expected when one remembers that movement time increases as a power function of movement difficulty.

Another question that arises is how older adults compensate for the longer perceptual feedback time required (as revealed by the analysis of the verification stage). Given that we found a large difference in our measure of perceptual feedback efficiency, we would expect a larger difference in the duration of the execution stage because perceptual feedback information must be used to determine if an additional submovement is needed to reach the target. Our explanation for this is twofold. First, our measure of the proportion of distance moved on the first submovement was 83% for younger and 76% for the older adults. This suggests that under most movement conditions both groups were planning more than one submovement to reach the target. By planning for at least two submovements, the perceptual feedback time can be reduced by the expectation that an additional submovement will be required and that the direction of the submovement is known. This type of anticipation of the need for a response can allow a type of feedforward loop which would reduce the effects of less efficient perceptual feedback on the duration of the execution stage of movement.

Second, the verification stage may be slightly different from the perceptual feedback times that occur during submovements. As the perceptual feedback for the last submovement, it requires the additional action of releasing the mouse button to signal the end of the trial. This additional action may also reflect age differences and therefore make the duration of the verification stage an overestimation of age-related differences in perceptual feedback efficiency.

Overall, we believe our data show, unlike that of some researchers (e.g., Pratt, Chasteen, & Abrams, 1994), that older and younger adults have the same basic underlying mechanism for movement control. What is different between the two age groups seems to be the noise-to-signal ratio, speed of perceptual feedback, and a tendency for older adults to be more conservative or error aversive when producing movement. Older adults adjust to these limitations by adopting a strategy that produces very good performance given these limitations. The optimized submovement model seems to provide a good qualitative fit to performance for both age groups.

Methodological Considerations

Another contribution of this study is that it has shown how the many factors that combine to determine age-related differences in movement performance can be isolated and measured. The analysis of movement performance by submovement structure appears to be a critical next step in furthering our understanding of age-related differences, and an approach that has been used only recently in understanding these differences (e.g., Pratt et al., 1994; Haaland, Harrington, & Grice, 1993). Our use of signal detection analysis, made possible by varying the payoff function and by analyzing submovement structure, also seems to hold great promise as a method to equate for age-related strategy differences. Our findings suggest that previous work that has tried to control for these differences by simply equating overall accuracy level may have underestimated the conservative movement strategy of older adults. Finally, the use of stage analyses provided us with a measure of perceptual feedback efficiency. While these procedures are not the only way in which these factors can be isolated and measured, they do suggest that future work must use procedures which can isolate the contributions of the various factors in determining age-related differences in movement control. As it appears that movement control is not the result of a unitary mechanism, it is only when individual factors can be isolated and controlled that further advances beyond current understanding of age-related differences in movement control can be made.

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