

Aging and Movement: Variability of Force Pulses for Saccadic Eye Movements

Richard A. Abrams
Washington University

Jay Pratt
University of Toronto

Alison L. Chasteen
University of Michigan

Age-related differences in the trajectories of saccadic eye movements were examined. Younger and older adult subjects produced saccades to predictable target locations. Detailed features of the movements were examined such as the time of peak acceleration and the variability in the magnitude of the peak velocity. These and other measures reveal important details of the force pulses underlying the eye movements and the mental mechanisms that control them. Although minor differences were apparent between the eye movements of younger and older adults, the general patterns were the same across age groups. These results suggest that fundamental details of the brain mechanisms involved in the control of movement are the same for younger and older adults.

The most sensitive part of the human retina, the fovea, is limited in size. As a result, humans cannot completely process a visual scene in a single fixation. Instead, humans must move their eyes from one location to another. *Saccades* are the quick, abrupt, and jerky eye movements that accomplish this. The saccades allow different parts of a scene to stimulate the fovea, permitting the most detailed processing possible. Saccades play an important role in reading (e.g., Rayner & Pollatsek, 1988), scanning visual scenes and objects (e.g., Goldberg, Eggers, & Gouras, 1991), and while reaching or pointing (e.g., Abrams, Meyer, & Kornblum, 1990). Thus, age-related changes in the production of saccades could affect a variety of important behaviors.

As the population grows older, understanding changes in motor behavior in general has become increasingly important. This interest is evident in several recent studies that have examined differences in rapid aimed limb movements produced by younger and older adults (e.g., Amrhein, Goggin, & Stelmach, 1991; Haaland, Harrington, & Grice, 1993; Pratt, Chasteen, & Abrams, 1994). Much less work, however, has been done examining age-related differences in saccadic eye movements, perhaps because of the difficulty of accurately measuring them. Nevertheless, despite the relative difficulty of collecting eye

movements, the endeavor has the potential to be especially informative. This is because saccades have some virtues that permit their trajectories to more or less directly reflect details of the underlying force pulses and, in turn, details of the motor-control mechanisms that produce them. Thus eye movements can be informative of motor-control mechanisms in general. And the study of saccades in older adults may be informative with respect to age-related changes in motor-control mechanisms generally.

Previous Work on Saccadic Eye Movements of Older Adults

Only a few previous studies have specifically examined age-related changes in saccadic eye movements (e.g., Abel, Troost, & Dell'Osso, 1983; Sharpe & Zackon, 1987; Spooner, Sakala, & Baloh, 1980; Warabi, Kase, & Kato, 1984). This work has yielded a consistent pattern of results: When there is some spatial or temporal uncertainty or both about the target for an eye movement, older adults are slower to initiate saccades, and the saccades produced are slower in velocity relative to those of younger adults. Although these studies have succeeded in identifying a consistent pattern of age-related differences in eye movements, they also have some limitations. The limitations stem primarily from the fact that the goal of most of the previous work was to establish that eye movements do indeed reveal age-related differences. The goal was not to learn about more detailed, and somewhat less obvious, features of the oculomotor system of older adults.

For example, in each of the four previously mentioned studies, the dependent measures were limited to saccade latency, amplitude, and peak velocity. Thus, data on detailed kinematic features of the saccades were not collected. Also, in most of the studies there was uncertainty about when or where the target for the saccade would appear (one exception is Sharpe & Zackon, 1987), and many of the required saccades had relatively

Richard A. Abrams, Department of Psychology, Washington University; Jay Pratt, Department of Psychology, University of Toronto, Toronto, Ontario, Canada; Alison L. Chasteen, Department of Psychology, University of Michigan.

This research was supported by National Institutes of Health Grant MH45145 and by National Institute on Aging Grant AG0030.

We would like to thank Heidi Korthase, Alison Curtis, and Shawn Christ for assistance.

Correspondence concerning this article should be addressed to Richard A. Abrams, Department of Psychology, Campus Box 1125, Washington University, St. Louis, Missouri 63130. Electronic mail may be sent to rabrams@artsci.wustl.edu.

large amplitudes. These methodological features were reasonable given that the objective of the earlier research was to learn about how age might affect the ability to look to suddenly appearing targets. Such processes would include some uncertainty about when and where the target for the eye movement would appear; they would include relatively large eye movements; and they could reasonably be measured by changes in gross features of the eye movements, such as their latency, amplitude, and peak velocity. However, these features also render the data from these experiments less useful for making inferences about more detailed aspects of the underlying force pulses used to control and produce the movements. Such an undertaking is the goal of this study.

Our Investigation

Our concern is somewhat different from that of earlier researchers who studied eye movements in younger and older adults. Our goal is not to understand the oculomotor system *per se*, but instead to use eye movements to allow us to make inferences about properties of the mental mechanisms that control movements more generally in older adults. In particular, by examining detailed dynamic and kinematic features of saccadic eye movements, it may be possible to learn about the mechanisms involved in planning the durations and amplitudes of the force pulses that produce the eye movements. To the extent that such mechanisms are also involved in the production of other types of movements, our conclusions have implications beyond the oculomotor system.

Abrams, Meyer, and Kornblum (1989) took the same approach in their study on dynamic features of saccades in younger adults (see also Abrams, 1994). They found that features of the eye movements revealed underlying principles of motor control that were consistent with a model formulated to describe the control of limb movements. Saccades provided a nearly ideal movement with which to study some of the predictions of the model. This is because the eye is biomechanically relatively simple, and its movements are more likely to reflect features of the underlying neurological control signals. Using the same reasoning, we have assumed that features of eye movements of older adults might be more likely than limb movements to reveal age-related changes in the underlying motor-control mechanisms, and that has been the purpose of our investigation.

Symmetric Impulse-Variability Model

Abrams et al. (1989) were specifically concerned with examining some of the assumptions and predictions of one model of a class of models known as impulse-variability models. These models regard movements as arising from the application of a pulse of force (an impulse) to the member to be moved (e.g., limb or eye) with a specific magnitude and a specific duration. By adjusting the magnitude and duration of the impulse, movements of different amplitudes and speeds can be produced. The models make assumptions about features of the impulses, and the assumptions in turn permit predictions about certain aspects of the movements. The model that Abrams et al. (1989) examined is one proposed by Meyer, Smith, and Wright (1982) and is known as the *symmetric impulse-variability model*.

The symmetric impulse-variability model contains several important assumptions about how rapid aimed movements are produced. Our goal, however, has not been specifically to test that model. Nevertheless, the model includes a number of assumptions about qualitative features of saccades that are relatively easy to confirm, and we have attempted to do so for the older adults studied in our investigation. Furthermore, taken together, the model's assumptions permit predictions about certain important features of the movements produced. To the extent that these features reflect fundamental aspects of the human motor-control system, examination of such features for age-related changes may be informative regarding the nature of age-related differences in movements.

Speed–Accuracy Trade-off

Perhaps the most important prediction that comes from the symmetric impulse-variability model is the one regarding the form of the movement speed–accuracy trade-off. *Speed–accuracy trade-off* refers to the fact that for most (if not all) human endeavors, increased output in general can be obtained only at the cost of some sacrifice in the quality of the output. For movements, the trade-off is that faster, higher velocity movements usually have more spatial variability in their endpoints. It is important to note that the speed–accuracy trade-off under consideration here is the movement speed–accuracy trade-off: the trade-off between the speed of a movement and its spatial precision. This is distinct from the more commonly mentioned trade-off involving the speed of response onset and response accuracy. For our purposes, what is important is that the symmetric impulse-variability model predicts that the speed–accuracy trade-off for movements should have a particular mathematical form and, in particular, the trade-off should be a linear one. Fundamental differences in the production of movements by younger and older adults might be expected to alter the form of the movement speed–accuracy trade-off, and our study has provided an opportunity to determine if that occurs. It is worth noting that considerable effort has been expended by motor-control researchers in an effort to understand why movements exhibit particular speed–accuracy trade-offs (for a review, see Meyer, Abrams, Kornblum, Wright, & Smith, 1988).

Overview of the Experiment

In our experiment, we had younger and older adults look to fixed targets a small distance away with complete temporal and spatial certainty about the required response. We informed the subjects about the precise target location in advance, and we did not impose time pressure because we were specifically interested in the force pulses that underlie the movements. We wanted to avoid any additional variability that might be due to spatial or temporal uncertainty. We also studied fairly small saccades. This is in part because most naturally occurring saccades are fairly small (Bahill, Adler, & Stark, 1975). For example, at a typical reading distance of 36 cm (Trautman, Trautman, & Moskal, 1995), the average saccade size during reading is 3.81° of visual angle (Morrison & Rayner, 1981). We also concentrated on small saccades because the manner in which force impulses are produced for larger saccades may be different from

that for smaller saccades. In particular, small saccades are produced by adjusting both the magnitude and the duration of the pulse of force that moves the eye, as assumed by the model. However, once saccade amplitude exceeds about 10° or 15° , increases in amplitude may be accomplished by changing only the duration of the force pulse, not its magnitude (Abrams et al., 1989). Furthermore, there is already evidence that small saccades appear to be well-described by the symmetric impulse-variability model for younger adults (Abrams et al., 1989).

Method

Subjects. Two groups of 24 subjects each participated in the experiment. The younger adult group (8 men and 16 women), which consisted of normal Washington University students, ranged in age from 20 to 30 years ($M = 21.4$ years). These subjects were drawn from the same pool that serves researchers throughout the department. The older adult group (10 men and 14 women), obtained through the Washington University Aging and Development Volunteer Pool, ranged in age from 60 to 84 years ($M = 71.7$ years). The older subjects had an average of 14.2 years of education. These subjects were healthy, active, community-dwelling, and independent older adults who could transport themselves to the university campus. All of the subjects could read text presented on a computer monitor at a distance of 44 cm without any corrective lenses. Each subject participated in a single hour-long session and was paid \$10 for his or her participation.

Apparatus and procedure. The experiment was conducted in a dimly illuminated, sound-attenuated room. Subjects were seated directly in front of a computer monitor, with their heads held steady by a chin-head rest. The position of the right eye was monitored with a scleral-reflectance eye movement monitor mounted on a spectacle frame (Applied Science Laboratories, Model 210).

At the beginning of each trial, the subject saw a display that included a fixation point (a plus sign) directly in front of him or her (0°) and a saccade target (a dot) to the right of the fixation point. The subject had 2 s in which to examine the display and fixate upon the fixation point. Once fixated, the plus sign changed into a dot, and then 1 s later the subject heard a countdown sequence of three 400-Hz warning tones and a final 1000-Hz response tone. (Each tone was 50 ms in duration, and tones were separated by 400 ms.)

During the countdown sequence, subjects remained fixated on the central fixation point; departures greater than 1.5° invoked a calibration routine (described later), and the trial was restarted. Upon hearing the response tone, subjects were required to look at the dot to the right of the fixation point. Subjects were not asked to minimize their latencies or the durations of their movements; they were simply told to look at the target dot. (It is important to note that the speed of a saccade depends strongly on its amplitude, but is not subject to conscious modification. Thus, there was no need to provide subjects with instructions regarding the speed with which they should complete the movements.) Both the fixation dot and the target dot remained illuminated throughout the trial.

After each trial, subjects received feedback regarding their responses. If the saccade was initiated before the response tone or did not begin within 400 ms after the response tone or if the saccade ended more than 1.5° from the target, an error message was displayed for 1 s. Error trials were not repeated. If no error occurred on a trial, the next trial began after a 1,500-ms intertrial interval.

Eye-movement recording and analysis. The analog output from the eye-movement monitor was digitized and recorded at a rate of 1000 Hz. The eye-movement monitor was calibrated at the beginning of each session, and the calibration was checked at the beginning of each trial. Calibration was accomplished by sampling from the eye-movement monitor while a subject fixated at each of five points spaced evenly across the cathode-ray tube.

The eye-movement trajectories were digitally filtered and differentiated, using a low-pass filter with an 80-Hz cutoff. The resulting velocity profiles were analyzed to identify and measure the saccades. A saccade was defined to start at the first moment in time after the response tone such that (a) the velocity of the eye exceeded $10^\circ/\text{s}$, and then (b) remained above that value while subsequently reaching $35^\circ/\text{s}$ or more for at least 10 ms. Similarly, a saccade was defined to end when the velocity of the eye fell below $10^\circ/\text{s}$. The $35^\circ/\text{s}$ criterion was selected because it is well below the velocities of the saccades that we have previously studied (Abrams et al., 1989), yet well above the noise level of our eye movement monitor. The resolution of the system was approximately $.05^\circ$ when properly calibrated. Measurements of movement acceleration were obtained by differentiating the velocity profiles.

Design. Three different saccade target locations were used: 3.5° , 5.5° , and 7.5° to the right of fixation. The target distances were blocked, and each subject completed two blocks of 35 trials for each target distance (for a total of 210 trials per subject). After every two blocks, subjects were given a short break. The order of the blocked target distances was counterbalanced across subjects.

Results and Discussion

The dependent measures that were examined are those that pertain to the shape of the force pulses that underlie the movements and the amount of variability in various aspects of those force pulses. To aid in understanding these measures, consider Figure 1. There we have plotted a hypothetical saccade trajectory (position as a function of time), as well as the velocity (first derivative of the trajectory) and acceleration (second derivative of the trajectory) as a function of time. Labels on the figure indicate some of the important dependent measures that we examined. For most of the measures, we compared both means and standard deviations across saccade target distances and age groups. One feature that is worth noting involves the *acceleration-time curve*. Because the mass of the eye remains constant, the acceleration-time curve reflects the net amount of force being applied to the eye over time. Thus, peak acceleration corresponds to the peak force, and we often refer to the acceleration-time curves as *force-time curves* for this reason. In what follows, we have first reported overall features of the saccades such as amplitude and duration. Then we have provided data that bear on the form of the speed-accuracy trade-off. Finally, we examine the shape of the force-time curves.

Saccade amplitude and duration. Overall features of the saccades such as the mean amplitude and duration are shown in Table 1 separately for the two age groups. Also shown in the table is a measure of the spatial variability of the saccades, S_D , which is the standard deviation of the saccade distances. These data were analyzed using a 2×3 (age \times target distance) analysis of variance (ANOVA).

Overall, longer target distances resulted in longer saccade distances, $F(2, 92) = 493.0$, $MSE = 0.30$, $p < .0001$, and longer saccade durations, $F(2, 92) = 57.0$, $MSE = 35.9$, $p < .0001$. It is important to note that there was no main effect of age on either the amplitudes or durations, $F_s(1, 46) < 1$, nor were there any Age \times Target Distance interactions, $F_s(2, 92) < 1$.

Also included in the table are the latencies with which subjects initiated the saccades in each condition. Although these data do not bear directly on the form of the movement speed-accuracy trade-off, they are interesting nonetheless because they show that older and younger adults initiated saccades at the

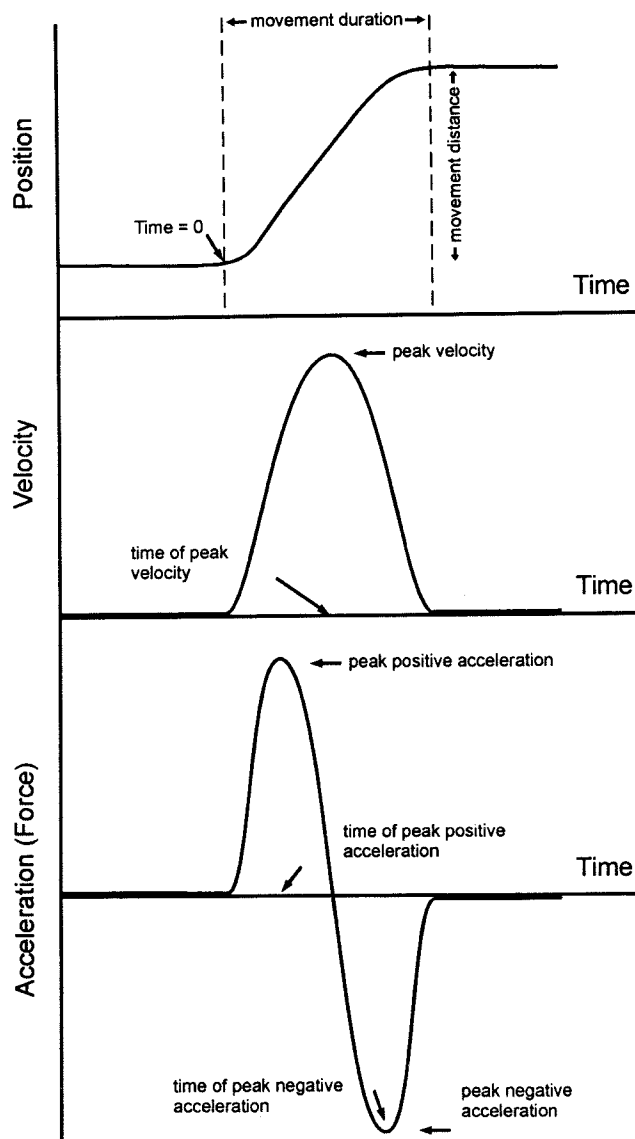


Figure 1. Hypothetical saccade trajectory (top panel), saccade velocity as a function of time (middle panel), and acceleration as a function of time (bottom panel). Labels on the figure indicate some of the major dependent variables observed in the experiment. Note that because the mass of the eye remains constant, the acceleration–time function reflects the net force applied to the eye over time and is often referred to as a force–time curve.

same time, $F(1, 46) = 2.2$, $p > .10$. Recall that the task was unspeeded, with an auditory countdown signal, so this result is not too surprising.

Although the task was not speeded, subjects had a limited time interval within which they could begin their eye movements. If the saccade began outside of this window, or if blinks or other artifacts contaminated the recordings, the trial was not usable. Older adults had more such trials than younger adults; mean for younger = 7%, for older = 12%; $F(1, 46) = 7.4$, $p < .01$. However, target distance was unrelated to the probability

of a non usable trial, $F(2, 92) < 1.8$, $p > .15$, nor was there an interaction between target distance and age, $F(2, 92) < 1$.

The relationship between saccade amplitude and duration is shown plotted in the top panel of Figure 2. The figure shows that saccade duration increased linearly with saccade amplitude for both age groups (younger: slope = 3.53 ms/deg, intercept = 26.4 ms, $r = .998$, mean r across subjects = .90; older: slope = 4.0 ms/deg, intercept = 23.4 ms, $r = .999$, mean r across subjects = .91), consistent with the findings of other investigators who studied younger adults (e.g., Abrams et al., 1989; Baloh, Sills, Kumley, & Honrubia, 1975).

As seen in Table 1, the longer target distances also resulted in saccades with greater average velocities, $F(2, 92) = 128.0$, $MSE = 217$, $p < .0001$, and larger S_D s, $F(2, 92) = 23.6$, $MSE = .12$, $p < .0001$. But there were no age-related differences in these measures, $F(1, 46) < 1$ for velocity, $F(1, 46) = 3.8$, $p > .05$, for S_D s (the trend is such that older adults had slightly larger S_D s), nor were there age by target interactions, $F_s(2, 92) < 1$.

Form of the speed–accuracy trade-off. According to the symmetric impulse-variability model of Meyer et al. (1982), a movement speed–accuracy trade-off will occur as a result of neuromotor noise in the motor system. This noise adds variability to the spatial endpoints of the movements as a person attempts to repeatedly produce a given movement to a fixed target (the noise prevents the movements from being identical). According to the model, the amount of variability in the production of the force pulses for movements increases in proportion to the mean amplitude of the force pulse. If that is true, then it can be shown that the model predicts that the standard deviation of the movement spatial endpoints should increase linearly with increases in the average velocity of the movements (see Meyer et al., 1982 and Abrams et al., 1989, for more details about this prediction).

Data relevant to the form of the speed–accuracy trade-off are shown plotted in the lower panel of Figure 2, where we have plotted from Table 1 the standard deviation of the movement endpoints (S_D) as a function of the saccade average velocity. Note that the linear trends account for over 97% (younger) and 99% (older) of the variance in S_D (younger: slope = .0086, intercept = .034, $r = .988$, mean r across subjects = .30; older: slope = .012, intercept = -.09, $r = .999$, mean r across subjects

Table 1
Overall Features of the Saccades

Age group/target distance (deg)	Feature				
	Mean distance (deg)	Duration (ms)	S_D (deg)	Average velocity (deg/s)	Latency (ms)
Younger adults					
3.5	3.55	38.7	0.81	92.8	275.3
5.5	5.28	45.5	1.09	118.0	289.2
7.5	7.08	51.2	1.25	143.6	284.8
Older adults					
3.5	3.55	37.7	1.02	93.5	313.1
5.5	5.34	44.4	1.36	121.8	295.8
7.5	6.97	51.4	1.56	139.2	310.4

Note. S_D = standard deviation of the movement endpoints.

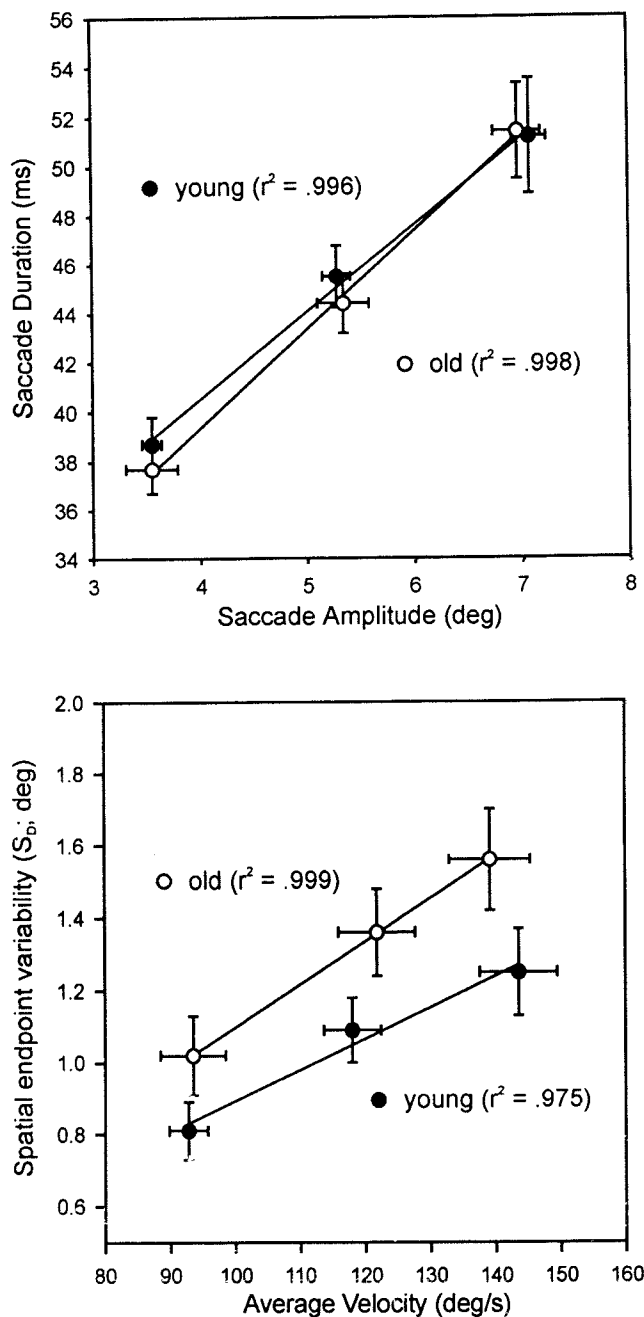


Figure 2. Top panel: Mean saccade duration as a function of observed saccade amplitude. Bottom panel: Standard deviation of saccade spatial endpoints (S_D) as a function of average saccade velocity. In both panels, data are plotted separately for the two age groups, and the lines are the best fitting regression functions. Error bars show the standard error of the mean.

= .62). Thus, the eye movements of both older and younger adults obey the form of the speed-accuracy trade-off predicted by the symmetric impulse-variability model. Perhaps most importantly for present purposes, the linear relation is as strong for the older adults as for the younger adults showing that the form of the speed-accuracy trade-off does not change with age.

Variability of force pulses. The preceding analysis has shown that eye movements of both older and younger adults obey the form of speed-accuracy trade-off predicted by the symmetric impulse variability model. It has already been known for some time that limb movements also exhibit a linear speed-accuracy trade-off (e.g., Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). Unlike limb movements, eye movements also permit one to examine detailed features of the movement trajectories that bear on various assumptions made by the model that lead to the predicted speed-accuracy trade-off. In particular, the symmetric impulse-variability model assumes that a person selects two parameters in order to produce a movement: a *force parameter*, which determines the amount of force applied to the eye or limb, and a *time parameter*, which determines the duration of force application. A critical assumption of the model is that the neuromotor noise discussed earlier affects the values of these parameters. Thus, while a person may attempt to produce a movement on one trial that is identical to the movement on a previous trial, noise in the motor system prevents that person from selecting (or applying) precisely the same force and time parameters as those used previously. According to the model, the standard deviation of the force parameter and the standard deviation of the time parameter are assumed to increase in proportion to their respective mean values (Meyer et al., 1982). It is this assumed linearity of the noise in the force and time parameters that accounts in part for the model's ability to predict a linear speed-accuracy trade-off. As Abrams et al. (1989) have shown, it is possible to obtain estimates of the force and time parameters by directly observing key aspects of the eye movement trajectories, and we turn to this next.

Table 2 shows the mean and standard deviation of the magnitude of peak positive acceleration, which serves as a good estimate of the value of the force parameter, and the mean and standard deviation of the moment of peak velocity (measured from the beginning of the saccade) which is a good estimate of the value of the time parameter (see Abrams et al., 1989, for a discussion of the use of these measures as estimates of the force and time parameters). Both mean peak acceleration, $F(2, 92) = 94.7$, $MSE = 32,852.0$, $p < .0001$, and mean time of peak velocity, $F(2, 92) = 37.7$, $MSE = 2.5$, $p < .0001$, increased with target distance. No main effect for age, $F_s(1, 46) < 1$, or interaction effects, $F(2, 92) < 1$ for time of peak velocity, $F(2, 92) < 2.1$, $p > .13$ for peak acceleration, were found. Similarly, the standard deviation of peak acceleration, $F(2, 92) = 5.3$, $MSE = 54,8710$, $p < .01$, and the standard deviation of time to peak velocity also increased with target distance, $F(2, 92) = 7.7$, $MSE = 6.9$, $p < .002$. Once again, no main effects for age, $F_s(1, 46) < 1.3$, $p_s > .25$, or interaction effects, $F_s(2, 92) < 1$, were found.

The top panel in Figure 3 shows the relation between the standard deviation of peak acceleration and the mean of peak acceleration. For both groups of subjects the variability increased nearly linearly with the mean force (younger: slope = .28, intercept = -55, $r = .999$, mean r across subjects = .37; older: slope = .34, intercept = -60.5, $r = .978$, mean r across subjects = .28). The relation between the standard deviation of the time of peak velocity and the mean time of peak velocity are shown in the bottom panel of Figure 3. For both subject groups the variability increased nearly linearly with increases

Table 2
Kinematic Features of the Saccades

Age group/target distance (deg)	Feature			
	Peak positive acceleration (deg/s/s)	Std. dev. of peak acceleration (deg/s/s)	Time of peak velocity (ms)	Std. dev. of time of peak velocity (ms)
Younger adults				
3.5	12,751	3,000	17.5	3.59
5.5	15,849	3,932	20.3	4.89
7.5	18,549	4,620	23.0	5.48
Older adults				
3.5	12,748	3,799	17.6	3.57
5.5	15,247	4,388	21.0	4.69
7.5	17,077	5,297	23.3	5.89

Note. Std. dev. = standard deviation.

in the mean (younger: slope = .34, intercept = -2.3, $r = .981$, mean r across subjects = .31; older: slope = .40, intercept = -3.58, $r = .993$, mean r across subjects = .61). Thus, the variability of the force and time parameters appears to be proportional to their means for both younger and older adults, as predicted by the symmetric impulse-variability model.

Form of the force-time functions. In addition to assumptions about variability in force and time parameters, the symmetric impulse-variability model makes a number of other assumptions. Perhaps most importantly, the model assumes that the force-time curves that underlie movements all have a particular shape, and that force-time curves for different movements are rescaled versions of a standard, prototypical force time curve. In particular, the force-time curves are assumed to consist of two mirror-image sections: one in which the force is positive, and one in which it is negative. The transition from positive to negative is assumed to occur at the temporal midpoint of the movement. Furthermore, each component is assumed to be symmetric and have a peak (either positive or negative) at its own temporal midpoint.

To evaluate these assumptions, we have plotted representations of the force-time curves for each target distance and each age group in Figure 4. These figures were made by plotting the mean accelerations (i.e., forces) and times of occurrence associated with five successive events in the saccades: movement onset, peak positive acceleration, peak velocity, peak negative acceleration (i.e., the maximum deceleration), and movement end (acceleration is nonzero only at the peak positive and negative acceleration). The acceleration plots for both age groups closely resemble the general shape of the force-time curves proposed by the symmetric impulse-variability model.

Rescalability of force-time functions. As mentioned earlier, the symmetric impulse-variability model assumes that force-time curves for movements of various sizes should be rescaled versions of one another—rescaled in the force and time domains. In order to examine that assumption, the bottom panel of Figure 4 shows the force-time curves from the top panel rescaled in both force and time. In the figure, the acceleration was normalized with respect to the peak positive acceleration, and all times were normalized with respect to the overall movement duration. If the assumptions of the symmetric impulse-

variability model are correct, and there are no differences between groups, then all of the plots should fall roughly on top of each other. Furthermore, the peak positive acceleration, peak velocity, and peak negative acceleration should occur at times of .25, .50, and .75, respectively, and the magnitude of peak negative acceleration should be equal to -1.0. As seen in the figure, these assumptions appear to be qualitatively correct, for both age groups.

We also analyzed quantitatively the force-time curves in the bottom panel of Figure 4, first to determine the extent to which the symmetric-impulse variability model applies to both younger and older adults, and second to determine the extent to which the age groups differ from one another. Indeed, while the model describes the rescaled force-time curves quite well qualitatively, there were some minor differences between the actual and predicted values. For example, the peak velocity occurred close to but slightly before the temporal midpoint of the movement for both younger and older subjects, $t(23) > 4.0$, $p < .001$. Similarly, the peak acceleration also occurred somewhat earlier than 25% of the movement duration, $t(23) > 2.9$, $p < .01$. Nevertheless, the time of peak negative acceleration was not different from the 75% point predicted by the model for both younger and older subjects, $t(23) < 1$ for younger, $t(23) = 2.0$, $p > .05$ for older, although the older adult mean of 77% was almost reliably different from 75%. Finally, the model assumes that the peak negative acceleration should be equal in value (but opposite in sign) to the peak positive acceleration. Although the observed values were reasonably close, peak negative accelerations were somewhat smaller than peak positive acceleration in both the younger, $t(23) = 5.9$, $p < .001$, and the older adults, $t(23) = 2.5$, $p < .05$.

Thus, although the model does a reasonably good job of characterizing the actual force-time curves from saccades of both younger and older adults, there are some aspects of the data that are not consistent with the model's predictions. Some of these same observations have been made previously (Abrams et al., 1989), suggesting that some aspects of saccade production are not being adequately accounted for by the model. Nevertheless, for present purposes we are also interested in differences between older and younger adults. To examine these we compared the relative (i.e. rescaled) times for the peak positive

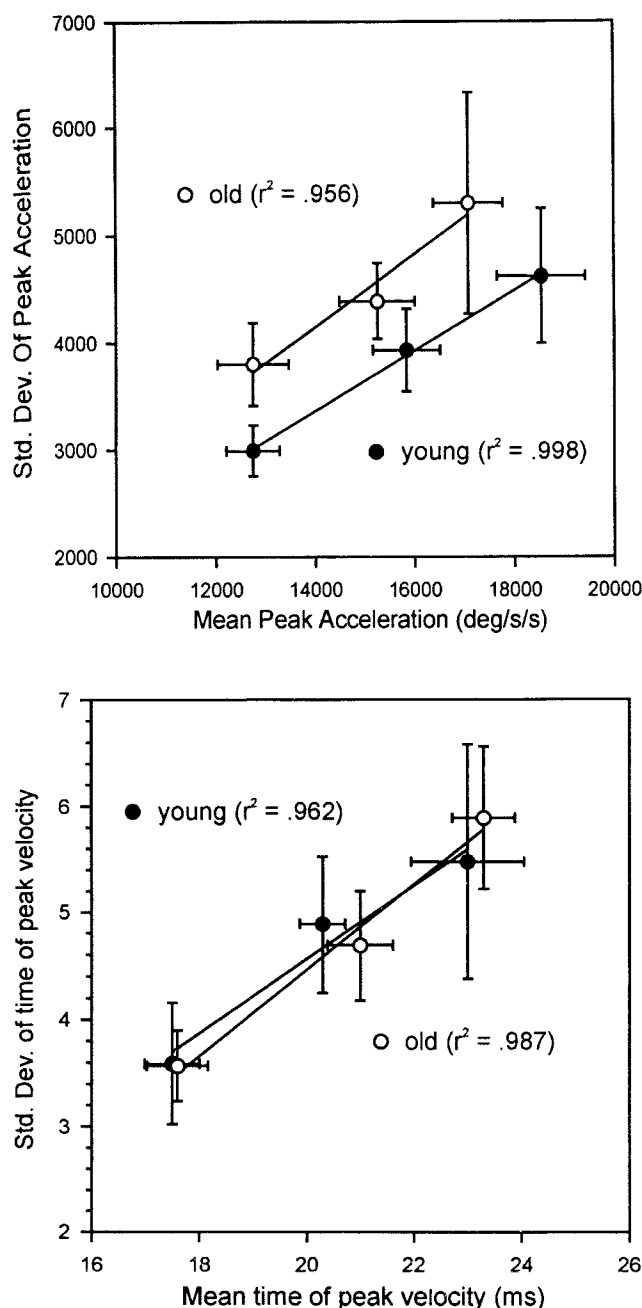


Figure 3. Top panel: Standard deviation (Std. Dev.) of peak acceleration as a function of the mean peak acceleration for saccades. Bottom panel: Standard deviation of the time to peak velocity as a function of the mean time to peak velocity. In both panels, data are plotted separately for the two age groups, and the lines are the best fitting regression functions. Error bars show the standard error of the mean.

acceleration, peak velocity and peak negative acceleration between younger and older subjects, separately for each target distance. We also compared the normalized magnitude of the peak negative acceleration. In all, twelve comparisons were performed (all t tests with $df = 46$). The only differences observed between older and younger subjects were in the relative time of

peak negative acceleration, and then only for the two shortest target distances, $t_s(46) > 2.0$, $p_s < .05$. Thus, the saccades of younger and older adults do not appear to be very different from one another.

Phase planes. If saccades of various sizes are derived by rescaling a prototypical force time curve then plots of eye movement velocity as a function of position should yield curves that are of similar shape for saccades of different sizes. Such plots, known as phase planes, are shown in the top panel of Figure 5

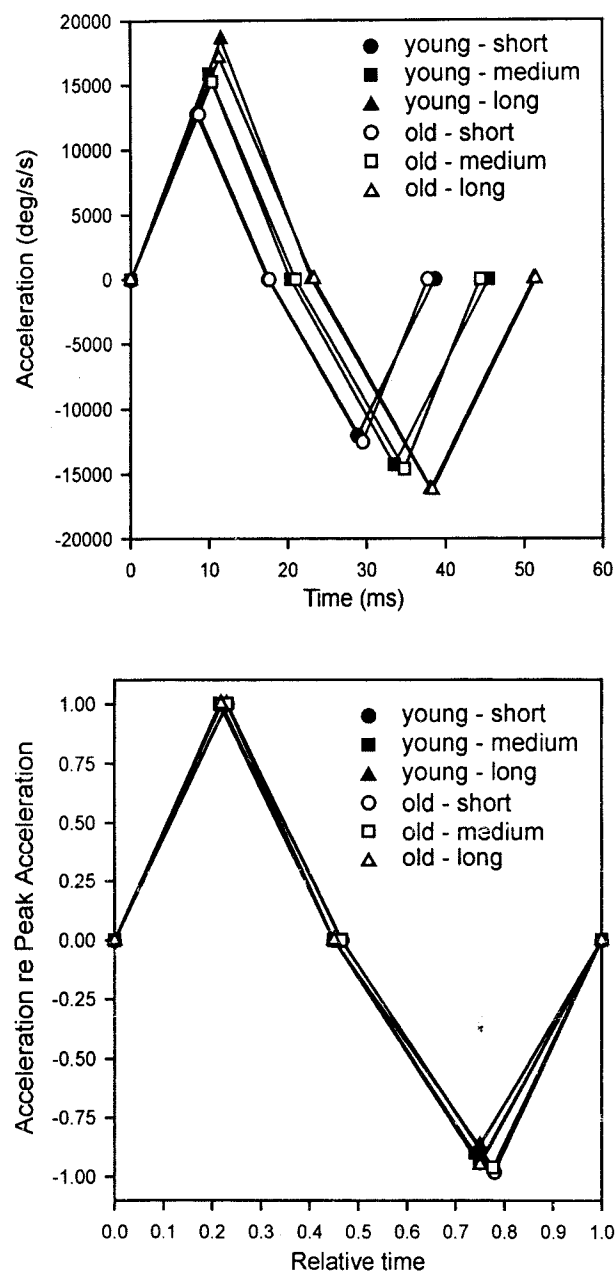


Figure 4. Top panel: Mean acceleration-time functions for saccades to each of the target amplitudes studied, measured at five moments in time, separately for the two age groups. Bottom panel: Acceleration-time functions from the top panel rescaled in force and time.

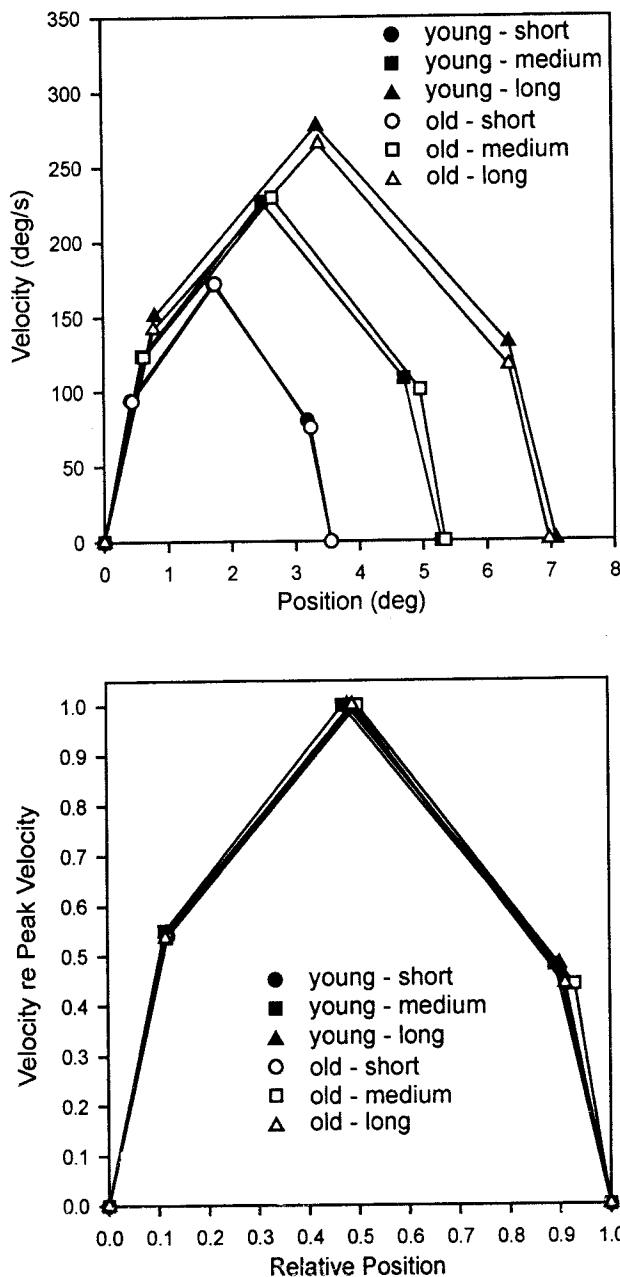


Figure 5. Top panel: Mean phase planes (velocity vs. position) of saccades directed to each of the target amplitudes, separately for the two age groups. Bottom panel: Phase planes from the top panel rescaled in velocity and position.

in actual units, and in the bottom panel with both velocity and position rescaled. As was true for the force–time curves, the phase planes from saccades of different sizes all have the same general shape. This was true for both younger and older adults. Thus, to the extent that these data reflect details of the processes underlying the production of saccadic eye movements, it appears that the saccades of older and younger adults are very similar.

Power analysis. We found age-related differences in one kinematic feature of the eye movements. To determine whether

we had sufficient power to detect such effects more generally, we conducted two power analyses. First, we set α to .05 and power to .80. On the basis of our earlier work on age related difference in eye movements (Pratt, Abrams, & Chasteen, 1997), we assumed a large effect size. With those assumptions, a total n of 41 would be needed (Cohen & Cohen, 1983). Thus, the 24 participants per group used in the present study should have provided sufficient power to detect kinematic differences between the younger and older adults. Next, we computed the effect size that would have been detectable with 48 subjects and power = .80. That computation revealed that an F ratio of 8.76 would have been needed to attain significance at α = .05. Note that most of our F s were near or below 1.

General Discussion

In our investigation we examined detailed aspects of the saccadic eye movements of older adults. The purpose of this was to learn more about fundamental aspects of the motor-control system involved in the production of eye movements. The eye movement data were evaluated both with respect to similar data obtained from younger adults, and also with respect to the prediction of a model of movement production that has been shown in the past to apply to both limb and eye movements of younger adults. The results of these comparisons revealed that older adults appear to produce eye movements in fundamentally the same way as younger adults. Furthermore, the model of movement production under consideration applies equally well to older and younger adults.

According to the symmetric impulse-variability model, movements of different sizes are produced by rescaling a prototypical force–time function in force and time. An examination of the eye movements from the present study revealed that movements of different sizes do indeed appear to arise from force–time curves that all have the same general shape. This was true for both younger and older adults. Furthermore, according to the model neuromotor noise in the motor system (either in the selection of the force and time parameter values, or in their implementation) introduces some variability as a person attempts to repeatedly produce the same movement. Estimates of this variability confirmed that it is related to the mean values of the force and time parameters in the manner predicted by the model, for both younger and older adults. Taken together, the principles of force–time rescalability and proportional noise in force and time parameters lead to the prediction that the speed–accuracy trade-off for eye movements should be linear. More specifically, the standard deviation of the spatial endpoints of the eye movements should increase linearly with the average velocity of the movements. The predicted relation was observed in the eye movements of both younger and older adults.

We have concluded that the present data suggest that younger and older adults produce movements in essentially the same fundamental ways. That conclusion, however, appears to be at odds with other research by us and others that has revealed age-related differences in movements. For example, consider our earlier study (Pratt et al., 1994) in which we examined detailed features of the corrective submovements within rapid aimed limb movements. There we concluded that “the mechanisms underlying movements of older adults are qualitatively different

from those in younger adults'' (Pratt et al., 1994, p. 325). One potential explanation of this apparent discrepancy is that different movement systems were being examined in the two studies. Perhaps one of the virtues of the eye movement system is that it is relatively immune to the effects of aging. However, the real key to the discrepant results involves the different levels of analysis adopted by us in the two studies. In the Pratt et al. (1994) study, we examined only relatively gross features of the movements such as the amplitude and duration of the ballistic primary submovements, and of the corrective secondary submovements, while subjects pointed to visible targets. And we interpreted the differences observed as indicative, at least in part, of different processes governing the acquisition and use of visual feedback information between younger and older adults. In that study we did not examine detailed features of the individual submovements themselves like we did with the eye movements here. Thus, the present results might be regarded as indicative of the basic processes underlying the selection of force and time parameters and the production of force pulses for movements. Our earlier results, on the other hand, are more reflective of the manner in which people decide which force pulses are necessary—or of the processes that determine what submovement is needed—and not so much with how the forces for the submovement are produced.

Likewise, the same comments can be made regarding the differences between the present results and those of others who have found age-related differences in eye movements. As noted previously, most of the prior research on eye movements has focused on relatively gross features of the movement behavior such as saccade latency and amplitude. The tasks used typically included relatively large eye movements and there was uncertainty about when and where the target for the movement would appear. Under those conditions, the responses would undoubtedly reflect many processes other than those involved in producing force pulses for movements per se. For example, target detection, target localization and other decision processes related to the planning of the movement might all be expected to affect the latency of the movements. And age related differences in these processes would also be reflected in the movements. Such differences however, would not necessarily bear on the nature of the force pulses that underlie the movements and the variability in them, as we have shown.

In conclusion, our results show that a model of human movement production, which makes predictions about the form of the movement speed-accuracy trade-off, applies to the eye movements of older adults. Thus, older and younger adults produce force pulses for eye movements in essentially the same fundamental ways. Differences in richer movement situations such as those used by others in the past may reflect age-related differences in perception, use of visual feedback, peripheral effector system dexterity, motor programming, or other decision and planning processes related to the selection of the desired movement. However, the actual implementation of the movement appears to be accomplished in similar ways.

References

- Abel, L. A., Troost, B. T., & Dell'Osso, L. F. (1983). The effects of age on normal saccadic characteristics and their variability. *Vision Research*, 23, 33–37.
- Abrams, R. A. (1994). The forces that move the eye. *Current Directions in Psychological Science*, 3, 65–67.
- Abrams, R. A., Meyer, D. E., & Kornblum, S. (1989). Speed and accuracy of saccadic eye movements: Characteristics of impulse variability in the oculomotor system. *Journal of Experimental Psychology: Human Perception and Performance*, 15, 529–543.
- Abrams, R. A., Meyer, D. E., & Kornblum, S. (1990). Eye-hand coordination: Oculomotor control in rapid aimed limb movements. *Journal of Experimental Psychology: Human Perception and Performance*, 16, 248–267.
- Amrhein, P. C., Goggin, N. E., & Stelmach, G. E. (1991). Age differences in the maintenance and restructuring of movement preparation. *Psychology and Aging*, 6, 451–466.
- Bahill, A. T., Adler, D., & Stark, L. (1975). Most naturally occurring human saccades have magnitudes 15 degrees or less. *Investigative Ophthalmology*, 14, 468–469.
- Baloh, R. W., Sills, A. W., Kumley, W. E., & Honrubia, V. (1975). Quantitative measurement of saccade amplitude, duration, and velocity. *Neurology*, 25, 1065–1070.
- Cohen, J., & Cohen, P. (1983). *Applied multiple regression/correlation analysis for the behavioral sciences*. Hillsdale, NJ: Erlbaum.
- Goldberg, M. E., Eggers, H. M., & Gouras, P. (1991). The ocular motor system. In E. R. Kandel, J. H. Schwartz, & T. M. Jessel (Eds.), *Principles of neural science* (3rd ed., pp. 660–679). New York: Elsevier.
- Haaland, K. Y., Harrington, D. L., & Grice, J. W. (1993). Effects of aging on planning and implementing arm movements. *Psychology and Aging*, 8, 617–632.
- Meyer, D. E., Abrams, R. A., Kornblum, S., Wright, C. E., & Smith, J. E. K. (1988). Optimality in human motor performance: Ideal control of rapid aimed movements. *Psychological Review*, 95, 340–370.
- Meyer, D. E., Smith, J. E. K., & Wright, C. E. (1982). Models for the speed and accuracy of rapid aimed movements. *Psychological Review*, 89, 449–482.
- Morrison, R., & Rayner, K. (1981). Saccade size in reading depends upon character spaces and not visual angle. *Perception & Psychophysics*, 30, 395–396.
- Pratt, J., Abrams, R. A., & Chasteen, A. L. (1997). The initiation and inhibition of saccadic eye movements in younger and older adults: An analysis of the gap effect. *Journals of Gerontology: Psychological Sciences*, 52B, P103–P107.
- Pratt, J., Chasteen, A. L., & Abrams, R. A. (1994). Rapid aimed limb movements: Age differences and practice effects in component submovements. *Psychology and Aging*, 9, 325–334.
- Rayner, K., & Pollatsek, A. (1988). *Psychology of reading*. Englewood Cliffs, NJ: Prentice Hall.
- Schmidt, R. A., Zelaznik, H., Hawkins, B., Frank, J. S., & Quinn, J., (1979). Motor-output variability: A theory for the accuracy of rapid motor acts. *Psychological Review*, 86, 415–451.
- Sharpe, J. A., & Zackon, D. H. (1987). Senescent saccades. *Acta Otolaryngol*, 104, 422–428.
- Spooner, J. W., Sakala, S. M., & Baloh, R. W. (1980). Effect of aging on eye tracking. *Archives of Neurology*, 37, 575–576.
- Trautman, E., Trautman, M., & Moskal, P. (1995). Preferred viewing distances for handheld and structurally fixed displays. *Ergonomics*, 38, 1385–1394.
- Warabi, T., Kase, M., & Kato, T. (1984). Effect of aging on the accuracy of visually guided saccadic eye movement. *Annals of Neurology*, 16, 449–454.

Received July 31, 1997

Revision received January 23, 1998

Accepted January 23, 1998 ■