

Horizontal Saccade Dynamics across the Human Life Span

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PURPOSE. To investigate saccade dynamics as a function of age to determine whether they follow the pattern of development and decline predicted by Weale's model of aging.

METHODS. One hundred ninety-five participants between the ages of 3 and 86 years made visually guided horizontal prosaccades ranging in size from 1° to 60° in response to dot stimuli. Eye movements were recorded binocularly with a video-based eye tracker, sampling at 120 Hz. Saccadic latency, accuracy, and velocity were measured and analyzed as a function of age.

RESULTS. Mean saccadic latency decreased from 439 ms at 3 years to 172 ms at 14 years, followed by a period of relative stability to age 50 and finally, gradually increased to 264 ms at ≥80 years. For saccadic accuracy (amplitude gain), there was a statistically significant ($P < 0.05$) interaction between saccade size and age. Participants made increasingly hypometric saccades as age and saccade size increased. Average age group saccadic asymptotic peak velocity (V_{max}) increased during childhood from 446 deg/s at age 3, to a peak of 610 deg/s at 14 years and then gradually declined with age to approximately 345 deg/s for participants ≥80 years.

CONCLUSIONS. Age affected saccadic latency, accuracy, and velocity. For each parameter there was a different pattern of development and decline probably related to the way in which the portion of the brain that controls each function develops and ages. (*Invest Ophthalmol Vis Sci.* 2006;47:2478-2484) DOI:10.1167/iovs.05-1311

Weale,¹ in discussing the theories of aging, developed a model based on the principle of minimizing energy expenditure within a biological system. The result was a trapezoidal age-related function wherein energy consumption develops, goes through a period of relative stability, and then declines. Assuming that puberty is the goal of evolution, he goes on to postulate that development will continue until puberty (12-18 years in humans), and the plateau will extend until the next generation reaches puberty (conservatively, 2×18), after which, the organism begins to decline. He gives

many examples of physiological functions that more or less follow this general trend. It seems that visual functions are no exception. Most visual functions (e.g., visual acuity, contrast sensitivity, color vision) are known to develop with age.² The age at which they become adultlike varies somewhat with the particular function but, according to Regan,³ is usually at 9 to 10 years. At the other end of the lifespan, there is a tendency for visual function to decline.⁴

Saccades, the rapid eye movements used for obtaining fixation of a given target, have been described in terms of their latency, accuracy, and peak velocity. It seems plausible that saccade dynamics would also follow a pattern of development, relative stability, and decline. Saccadic latency has been well studied in the literature with consistent results. Virtually all studies have found that saccadic latencies are shorter in young adults (18-35 years) than in infants (<6 months),^{5,6} children 4 to 18 years of age,⁷⁻¹⁴ and older people (>60 years).^{8,11,12,15-26} In addition, the variability of saccadic latencies follows a similar pattern wherein it is relatively high in infants compared with adults,⁵ decreases with age through childhood and adolescence,^{9,19} and then increases in later years.^{17-20,23,24}

Numerous studies have shown that saccadic accuracy is relatively unaffected by age.^{7,9,12,13,17,20,26} However, in infants, hypometria is consistently reported,^{5,6,27,28} and hypermetria is rare.²⁷ Munoz et al.¹¹ studying 5- to 79-year-olds reported that accuracy varies as a function of age and found the youngest age group that they tested (5-8-year-olds) to be the most hypometric. Fioravanti et al.²⁹ find hypometria of approximately 10% for all target displacements in young adults but in children find that accuracy depends on the step size. Children (5-15 years) overshoot small target displacements and undershoot large ones. This effect is larger in younger children than in older ones. Olincy et al.²¹ found progressively reduced accuracy across the age range tested (19-79 years). Tedeschi et al.²⁵ noted a decrease in saccadic accuracy for persons over 45 years of age, whereas Sharpe and Zackon²³ found decreased accuracy of horizontal saccades in the elderly (66-87 years) compared with those of middle age (35-63 years). Huaman and Sharpe¹⁸ reported similar decreases in the saccadic accuracy of vertical saccades in the elderly.

There is still considerable debate as to whether age is a factor in saccadic velocity. Saccadic velocity data in preschool children are limited (a total of three children between the ages of 7 months and <5 years), and much of what exists was collected by using electroculography (EOG), which is known to have artifacts and baseline drift.³⁰ Conflicting results prevent conclusions from being reached as to whether saccadic velocity decreases in the elderly.

Hainline et al.³¹ found peak velocity in infants between 2 weeks and 5 months of age to be slower than that in adults in response to "form" stimuli and similar to adults in response to "texture" stimuli. In children, all possible outcomes have been reported, attesting to the difficulty in accurately measuring this parameter in children. Rosenhall et al.¹² noted saccadic peak velocities to be slower in children (7-13 years) than in adults (20-50 years). Munoz et al.¹¹ showed no difference in saccadic

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peak velocity as a function of age for 20° saccades, nor did Salman et al.¹³ Fukushima et al.,⁹ comparing the saccadic peak velocities of children (age 4–13), reported no difference from those of young adults (age 20–38). In contrast, Fioravanti et al.²⁹ found the saccadic peak velocities of the youngest children they tested (age 5–10 years) to be greater than those of older children (11–13 years) and adults (25–39 years). Likewise, Funk and Anderson,³² based on the slope of the amplitude-duration relationship, conclude that children (6–10 years) make faster saccades than do adults. At the other end of the lifespan, several studies^{12,20,22–26} have shown a significant decrease in peak velocities in the elderly (>60 years) compared with young adults, whereas others have reported a small decrease,^{15,17} and some,^{11,18,33,34} no difference.

It is especially important to resolve the controversies around the relationship between age and eye movement dynamics, as ocular motor abnormalities are frequently used to diagnose neurologic disease.³⁵ In addition, abnormalities in eye movement control have been reported in disorders such as dyslexia and learning disabilities.^{36–38} It is difficult to claim abnormality of any sort, if normal values for the ages in question are not yet established. The purpose of this article is to investigate, using a video-based eye tracking system, whether saccade dynamics vary as a function of age and, if so, whether they follow the pattern of development and decline predicted by Weale's¹ model.

METHODS

Participants

Data were obtained from 195 people, approximately equally distributed with regard to gender (102 female, 93 male). Participants ranged in age from 3 to 86 years. Participants less than 50 years of age had no known ocular, ocular motor, neurologic, or systemic problems and were taking no medications as determined by self or parental report. For participants 50 years of age and over, clinical records were available including a complete list of medications. In this case, participants with multiple illnesses, with ocular motor or neurologic disease, with systemic diseases known to have a direct effect on eye movements, or those taking medications known to affect eye movements were excluded from the study. Persons with hypertension and/or cataract were not excluded, because the prevalence of these conditions in this population is extremely high and they are not known to affect eye movement dynamics directly.

Informed consent was obtained from participants over the age of 18 years and from the parents or guardians of participants under 18 years of age. As well, verbal assent was obtained in those cases in which someone other than the participant provided consent. The research adhered to the tenets of the Declaration of Helsinki.

Eye Movement Recording

Simultaneous binocular horizontal eye position records were collected from participants. Eye movements were recorded with a video-based eye-tracker (Series 2020 binocular CCD; El-Mar, Downsview, Ontario, Canada). The El-Mar eye-tracker is a high-resolution, noninvasive, user- and participant-friendly instrument that, for horizontal and vertical movements, compares favorably to the magnetic search coil technique for oculomotor testing in humans.³⁹ The system is free of drift, has a maximum resolution of 6 minutes of arc, a 120-Hz sampling rate, and a linear range of at least $\pm 30^\circ$ and $\pm 25^\circ$ in the horizontal and vertical meridians, respectively.

Before data collection, the instrument was calibrated for each participant, by recording fixations at seven vertical and seven horizontal points across a range of $\pm 10^\circ$, at a distance of 2 m from a calibration array projected onto a tangent screen. Participants were seated with their heads steadied by a chinrest, which was adjusted so that the eyes were in approximately the primary position when looking at the center of the array. Although refractive errors were not corrected

during data collection, it was verified at the time of calibration that all participants were able to see the targets well enough to localize them without any difficulty. After calibration, subjects made visually guided horizontal prosaccades in response to dot stimuli. A white dot on a black background was randomly presented, without gaps or overlaps between stimuli, generating a variety of saccade sizes. Two different test distances (1 and 2 m) were used, allowing us to generate saccades ranging in size from 1° to 60° in the horizontal direction.

Analysis

Eye-position data were differentiated with respect to time, generating velocity data. Saccades were marked automatically with a velocity threshold technique and verified manually for artifact and accuracy. A saccade was considered to have been made in response to a specific stimulus if the following criteria were met: (1) the saccade was the first saccade after the stimulus, (2) it was in the correct direction, and (3) it occurred between 100 and 1000 ms after stimulus onset. Once a saccade was determined to have been in response to the stimulus, the time of stimulus onset was subtracted from the saccade-onset time to give the latency of the saccade. Latencies were calculated for all saccades meeting the inclusion criteria. For each individual, the mean latency and standard deviation of the mean latency were then calculated. Similar criteria and methodology were used to determine saccadic accuracy except, in this case, the amplitude of the first saccade after the stimulus was divided by the magnitude of the stimulus giving the saccadic amplitude gain.

Saccades with latencies or gains that fell outside of two standard deviations from the mean were considered not to have been in response to the stimulus, despite meeting the previous criteria, and therefore were removed. The means and standard deviations were recalculated for both parameters. The mean values were then averaged across subjects, and standard errors were calculated for each age group. For subjects who had sufficient data in all saccade sizes ($n = 90$), saccadic latency and gain were further examined as a function of stimulus size, grouped into four ranges: $\leq 5^\circ$, $> 5^\circ$ to $\leq 10^\circ$, $> 10^\circ$ to $\leq 20^\circ$, and $> 20^\circ$.

Peak velocities were determined for between 50 and 200 saccades (depending on the quality of eye tracking) of a variety of amplitudes and plotted as a function of saccadic amplitude. The results were then fit with an exponential function for each participant, and the parameters of the function (V_{\max} – asymptotic peak velocity and K – slope at the origin) were determined. Considerable care was taken to ensure that a sufficient number of large saccades were obtained for accurate determination of the asymptote. If the number is not sufficient, asymptotic peak velocity can be significantly underestimated. Data that did not meet this criterion were excluded from further analysis. The parameters of the function were then averaged across subjects for each age group.

An equal number of subjects for every age was not available. In an attempt to determine any impact of the unbalanced number of participant, univariate analyses of variance (ANOVAs) were run on each of latency, gain, and V_{\max} with the data organized in several ways. In all cases, statistically significant main effects were further examined between age groups using Bonferroni corrected post hoc tests and the corrected probabilities are given throughout. Age groupings and the number of participants in each group for each of the methods are shown in Table 1.

In the first instance (Table 1, All Subjects: A), the data were grouped as follows: < 5 years, yearly age groups between 5 and 14 years, 15 to 20 years, and each decade after 20 years up to 90 years. All the 176 participants who had suitable data for both velocity and latency were included, and the number of participants was left unbalanced within the groups. The second method (Table 1, All Subjects: B) also included all 176 participants, and the number of participants was unbalanced within groups. However, the data were organized into hemidecades for ages < 20 years and in decades thereafter.

In the third grouping (Table 1, Developmental), data were organized into six groups based on approximate age of the various life

TABLE 1. Age Groupings for Various Analysis Methods

All Subjects: A		All Subjects: B		Developmental		Children		Latency and Gain <i>f</i> x Amplitude		
Age Range	<i>n</i>	Age Range	<i>n</i>	Age Range	<i>n</i>	Age Range	<i>n</i>	Age Range	<i>n</i>	<i>n</i> *
<5	13	<5	25	<5	15	3	6	<10	37	10
5	12	5 to <10	56	5 to <10	15	4	7	10 to <20	25	11
6	16	10 to <15	49	10 to <15	15	5	12	20 to <30	3	3
7	13	15 to <20	3	15 to <35	13	6	16	30 to <40	4	4
8	14	20 to <30	7	35 to <60	15	7	13	40 to <50	3	3
9	13	30 to <40	15	60 to <90	13	8	14	50 to <60	4	4
10	14	40 to <50	5			9	13	60 to <70	7	7
11	12	50 to <60	3			10	14	70 to <80	4	4
12	9	60 to <70	8			11	12	80+	3	3
13	5	70+	5			12	9			
14	5					13	5			
15 to <20	7					14	5			
20 to <30	6									
30 to <40	14									
40 to <50	6									
50 to <60	4									
60 to <70	7									
70 to <80	3									
80+	3									
Total	176		176		86		126		90	49

* More balanced *n*.

stages in normal individuals (i.e., preschool children, school age children, adolescents, young adults, middle age adults, and elderly adults). Consecutive subjects were taken from each year to balance the number of participants in the groups. Balancing of the numbers was an effort to determine whether the number of participants affected the outcome of the ANOVA. A fourth method (Table 1, Children) analyzed only the data for participants between the ages of 3 and 14 years, grouped by year, to examine more closely the developmental phase.

Finally, saccadic latency and gain were examined as a function of age and saccade size using a mixed design with age as the between-subjects variable and saccade size as the repeated measure. In this case, a subset of the data (Subset *n* = 90) for subjects who had sufficient data for all saccades sizes ($\leq 5^\circ$, $>5^\circ$ to $\leq 10^\circ$, $>10^\circ$ to $\leq 20^\circ$, $>20^\circ$) was analyzed. These data were grouped by decade. A further subset

(Subset Balanced *n* = 49), consisting of consecutive subjects from each year grouped by decade was also analyzed. Again, this method was used to determine the effect of a balanced number of participants on the statistical outcomes.

RESULTS

Useable latency data were obtained from 183 participants and useable velocity data from 188. In 176 participants, useable data were available for both latency and velocity. In these 176 participants, average age group values for saccadic reaction time (latency) decreased from 439 ms at 3 years to 172 ms at 14 years, followed by a period of relative stability to age 50, and

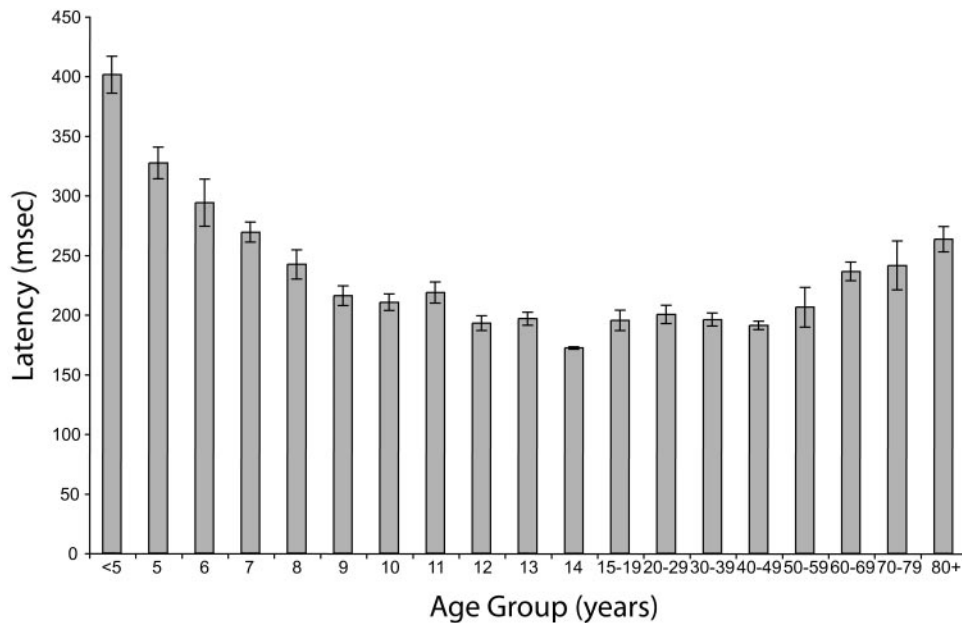


FIGURE 1. Mean ± (SE) latency of saccades for all subjects: group A.

TABLE 2. Statistical Outcomes for Velocity, Latency, and Accuracy (Gain) for the Various Subject Groups

Age Group	V_{max}		Latency*		Gain*	
	F	P	F	P	F	P
All Subjects: A	3.994	0.000	22.450	0.000	0.655	0.851
All Subjects: B	7.990	0.000	29.173	0.000	0.904	0.523
Developmental	10.464	0.000	50.924	0.000	0.557	0.733
Children	1.880	0.048	26.824	0.000	0.641	0.790

* Overall latency and gain (i.e., all sizes of saccades grouped together).

finally a gradual increase to 264 ms at ≥ 80 years (Fig. 1). The univariate ANOVAs indicate that there is a significant effect ($P < 0.000$) of age on latency for all the grouping methods (Table 2). Therefore, the unbalanced data and different grouping methods had little effect on the outcome. Post hoc tests for the Developmental group indicate that subjects < 5 years of age had latencies that were significantly longer than those in all other age groups ($P < 0.000$), 5- to < 10 -year-olds' latencies were longer than all other age groups except < 5 years and 60 to < 90 years ($P < 0.000$), and 35 to < 60 years were shorter than 60 to < 90 years ($P = 0.023$). Post hoc tests on the Children group indicated that all ages up to 7 years were different ($P < 0.05$) from all others except those on either side. For example, 4 years was not significantly different from 3 or 5 years, but was different from every other age group. Between 7 and 14 years of age, there were no significant differences between any of the age groups. Saccadic latency considered as a function of stimulus size shows a significant interaction ($n = 90$, $P = 0.001$; $n = 49$, $P = 0.031$) between age and stimulus size (Table 3) such that latencies are longer for larger saccades in younger participants (Fig. 2).

When one examines the average gain of all the tested saccades, accuracy appears to be unchanged with approximately 10% hypometria through out the lifespan (probabilities vary from $P = 0.523$ to $P = 0.851$ depending on the grouping method; Table 2). When accuracy is considered in relation to stimulus amplitude, it can be seen that balancing the participant numbers affected the outcome (Table 3). For the Balanced n Subset (Table 3), there was a significant effect of age on saccadic accuracy ($P < 0.000$) and on saccade size ($P = 0.001$), as in the unbalanced data. However, the effect of size increased with age, and the interaction term is statistically significant ($P = 0.013$) in the balanced n subset. After the age of 50, saccades greater than 20° had hypometria exceeding 20% and the mean hypometria was nearly 40% by the ninth decade. Small saccades ($< 5^\circ$) were not nearly as significantly affected. Under the age of 20 there was a tendency to overshoot target steps less than 10° and to undershoot target steps greater than 10° (Fig. 3).

TABLE 3. Statistical Outcomes for Subsets Used to Determine Effect of Step Size and Age on Saccadic Latency and Accuracy (Gain)

	Subset $n = 90$		Balanced n Subset	
	F	P	F	P
Latency				
Age	5.253	0.000	3.153	0.007
Size	0.848	0.472	1.634	0.198
Age \times size	2.311	0.001	1.720	0.031
Gain				
Age	1.677	0.117	9.576	0.000
Size	7.923	0.000	6.535	0.001
Age \times size	1.202	0.242	1.916	0.013

Average age group saccadic asymptotic peak velocity (V_{max}) increases during childhood from 446 deg/s at age 3 to a peak of 610 deg/s at 14 years and then gradually declines with age to approximately 345 deg/s for participants ≥ 80 years (Fig. 4). Similarly, the slope at the origin (K) initially increased from 8.0 at 3 years to 11.1 at 14 years and then declined to 6.1 for participants ≥ 80 years. Given that both V_{max} and K change and yet the data continue to be described by an exponential function, the indication is that the velocity changes are applicable to saccades of all sizes, not just the large ones.

The univariate ANOVAs indicate that there is a significant effect ($P < 0.05$) of age on asymptotic peak velocity with all the grouping methods (Table 2), and the unbalanced data has minimal effect on the outcome. Post hoc pair-wise comparisons for the Developmental group (which has balanced subject numbers) indicate that the 10- to < 15 -year age group made faster saccades than all other age groups ($P < 0.05$), suggesting a peak in asymptotic peak velocity between 10 and 15 years of age. Examining the Children grouping, we found a gradual increase in V_{max} with increasing age (Fig. 5) between the ages of 3 and 14 years. The data can be fit with the linear function $y = 10.6x + 448$ ($F = 18.05$, $P < 0.000$).

DISCUSSION

Our results indicate an effect of age for all the saccade parameters studied. Latency and peak velocity developed through childhood and early adolescence, stabilized through the middle

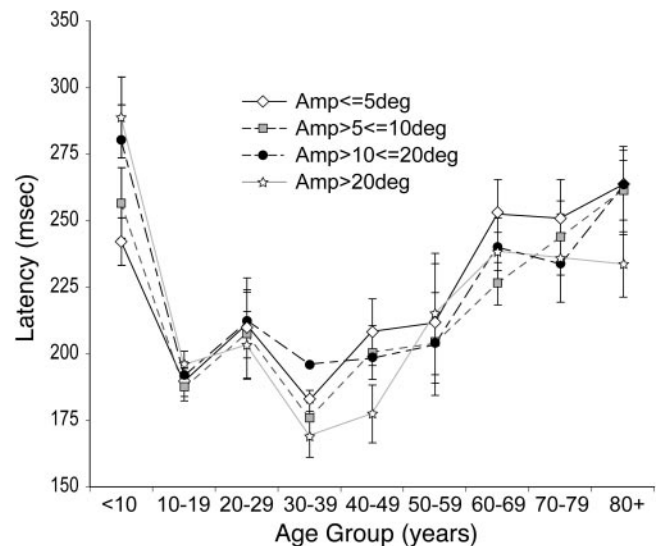


FIGURE 2. Mean \pm (SE) latency across age, grouped by decade, for a subset of the data ($n = 90$), for subjects who had sufficient data for all saccades sizes, and broken down into the four groups according to amplitude.

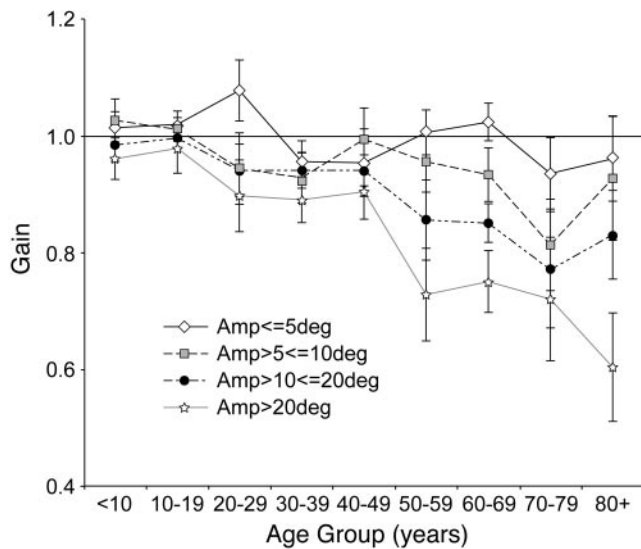


FIGURE 3. Mean ± (SE) amplitude gain across age, grouped by decade, for a subset of the data ($n = 90$), for subjects who had sufficient data for all saccades sizes, grouped by decade, and broken down into four groups according to amplitude.

decades, and then declined in later decades. Most saccades were hypometric for all ages studied. However, for saccades $<10^\circ$, participants under the age of 30 were much more likely to make hypermetric saccades than those over the age of 30. Large saccades ($>10^\circ$) were hypometric for all ages but became increasingly so as age increased.

The results for latency are consistent with the plethora of previous research.⁵⁻²⁶ However, we noted a significant interaction between saccade size and age. The effect is statistically significant, and warrants further investigation. Our results are in agreement with the studies that find a decrease in saccadic accuracy with age.^{18,21,23,25} These studies tend to have in common the evaluation of accuracy as a function of saccade size as well as age and/or the use of large saccades. Of the studies that do not show an effect of age, two^{7,17} used only

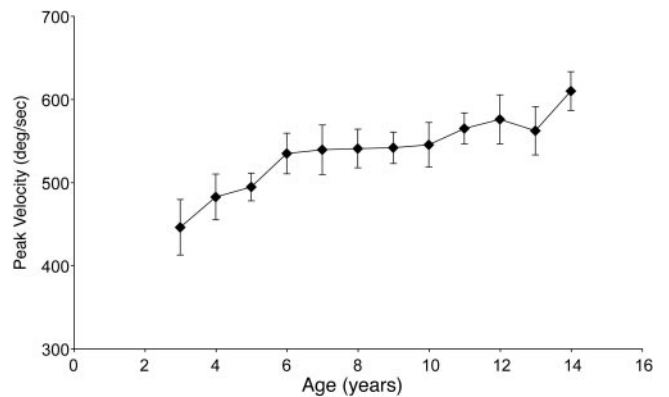


FIGURE 5. Mean ± (SE) saccadic asymptotic peak velocity for children between 3 and 14 years of age.

small saccade sizes, and two others^{9,13} tested over subject age ranges (4-38 years) for which one would not expect to see any effect of age, based on the data from our study. Of the remaining studies, all using EOG, one study showed no effect of size and no effect of age,¹² and the other two^{20,26} reported no overall effect of age but that a subset of their elderly subjects showed hypometria. Our findings are consistent with those of Fioravanti et al.,²⁹ who found that children overshoot small targets and undershoot large ones.

Contrary to Fioravanti et al.,²⁹ who reported saccades to be fastest in the youngest group they tested, we found that saccades were slower in very young children than in older children and adults. Despite reporting increased peak saccadic velocities in their youngest age group, they found durations to be longest in this group and skewness ratios to be higher. One would expect that if saccades of a given size were faster, they would also be shorter and have lower skewness ratios. In fact, Funk and Anderson³² concluded that children's saccades are faster than adults, because there were shorter durations in children compared with the adult data in the literature. Fioravanti et al.²⁹ used an infrared limbal tracker and needed to apply linearization curves to their data, introducing the possibility of systematic errors. It is unclear whether the curves

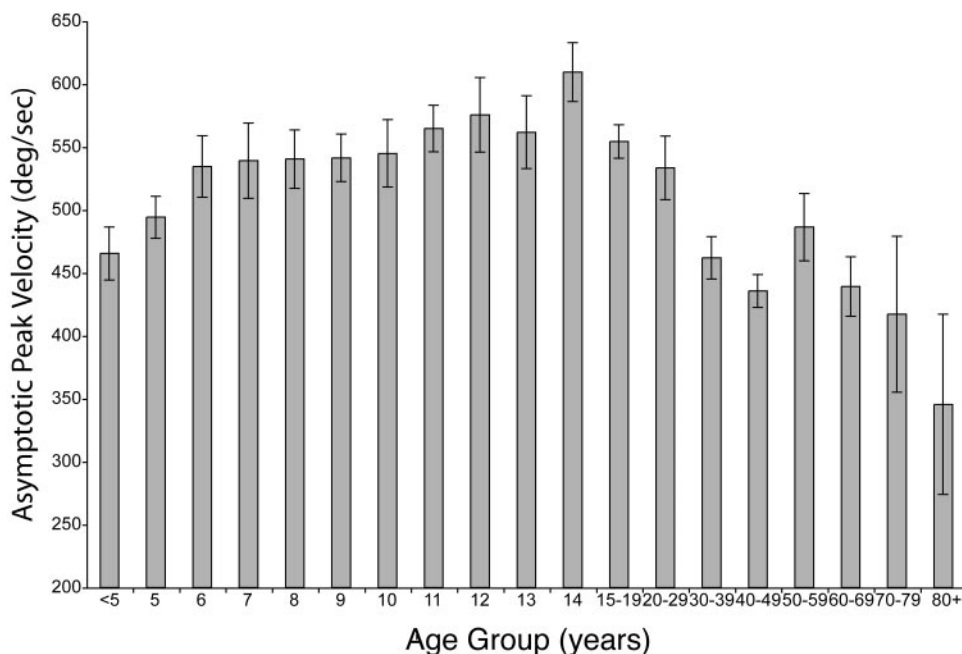


FIGURE 4. Mean ± (SE) saccadic asymptotic peak velocity for all subjects: group A.

were generated for each individual or for each of their age groups, or whether the same curves were used for everyone.

Our results also differ from those of Munoz et al.¹¹ and Fukushima et al.,⁹ who found no difference in saccadic velocity throughout the lifespan. Ceiling effects in their EOG-based results could be the explanation. Fukushima et al.⁹ used a 100-Hz sampling rate and low-pass filtered to 30 Hz, whereas Munoz et al.¹¹ had a differentiator cutoff frequency of 45.9 Hz. Another notable difference was the use of gap and overlap paradigms in their studies, but not in ours. It is unlikely, however, that this would affect peak velocity. The most likely explanation for the differences in outcome is the number of very young children included in the sample. In our study, the biggest differences in velocity were seen in 3 ($n = 6$), 4 ($n = 7$), and 5-year-olds ($n = 12$). We were the only ones to study 3 year olds. Fukushima et al.⁹ included three 4-year-olds and four 5-year-olds, whereas the data from the youngest age group of Munoz et al.¹¹ were an average of results in 5- to 8-year-olds. It appears that the development of velocity occurs at very young ages, and collection of further data from a larger sample of preschool children is warranted. In addition, a longitudinal study, although difficult, would be beneficial.

At the other end of the lifespan, most studies,^{12,15,17,20,22-26} including ours, show a decrease in saccadic peak velocities in the elderly. Of the four studies^{11,18,33,34} that do not, two^{18,34} were measuring vertical saccades, and one¹¹ reported inconsistent results, in that they found no difference in peak velocity with age but did note an increase in duration.

Between 3 and 14 years of age, the decrease in latency during development represents an improvement of >100%, whereas the increase in peak velocity is less than 50% for the same time period. As well, the period of most rapid change ends earlier for velocity than for latency. These differences are consistent with the literature indicating that the two processes are controlled by different parts of the brain. If we consider velocity to be controlled at the level of the brain stem and latency at the cortical level,³⁵ it should not be too surprising that velocity is relatively well developed at an earlier age than is latency, especially, because the white matter of the frontal lobe continues to mature until approximately age 20 years.^{40,41} After peaking at 14 years of age, the decline in function of saccadic velocity appears to be greater than that for latency (~43% vs. ~35%). The implication is that aging is not simply the reversal of development. One might speculate that development of saccadic velocity is the result of synaptic development, resulting in increased efficiency, whereas aging is the loss of contractibility⁴² or mechanical efficiency⁴³ of the muscle. By the same token, latency development could be attributed to cortical maturation,^{44,45} either in the form of synaptic pruning⁴⁶ or increased myelination,^{40,41} and aging to decreased neuronal density⁴⁶ and cortical gray matter.⁴¹

Although some of our results, such as latency, are in reasonable accord with Weale's model,¹ others clearly are not (e.g., accuracy). Latency and velocity go through periods of development, stability, and decline, but the time courses for each are different. For example, the period of stability for latency extends from 10 to 50 years, whereas that for velocity begins earlier (~7 years) and ends at approximately 30 years. Our study does not preclude that saccadic accuracy goes through a period of development, but if it does, it is likely to have occurred before 3 years, the youngest age in our study. There is clearly a period of decline in saccadic accuracy. Puberty may still be the evolutionary goal of the organism, but it is not necessarily the goal of specific functions that make up the organism. Development and decline may well represent evolutionary efficiency, but the organism requires that some functions mature earlier than others for the overall goal to be achieved.

In conclusion, our study indicates that the magnitude of normative values for saccadic parameters varies across the human lifespan. It is, therefore, important for clinicians to consider normal age-related effects when investigating ocular motor disease. It is also important for scientists comparing study groups, to control for the effects of development and aging. Finally, models of the ocular motor system should be capable of explaining age-related changes.

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