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Generation of braking saccades in congenital nystagmus

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Abstract *Objectives:* We examined eye movement records of two congenital nystagmus (CN) subjects, whose waveforms contained braking saccades, to test the hypothesis that eye velocity, rather than eye position, is the more important criterion for braking saccade generation. Specifically, we wished to determine the criteria and timing used by their ocular motor systems in triggering these unique saccades. *Materials and methods:* For the records analyzed, eye movements were measured by either scleral search coil or IR limbic reflection and data were sampled at rates of 200-488 Hz with a resolution of 12 bits for analysis by custom software. Both position and velocity were used to determine critical timing points in CN cycles, including saccadic onset, duration, offset, and magnitude. Phase planes at various times (between 40 and 70 ms) prior to saccade onset helped determine (using foveation window criteria for best acuity) the conditions to generate a braking saccade. *Results:* Braking saccades do brake CN slow phases, with average slowing (unrelated to braking-saccade size) of 62 and 119% for the two waveforms studied. At 70 ms prior to braking saccades, both eye position and velocity usually still satisfied the criteria for good acuity established in the previous foveation period; by 40 ms, velocity no longer did. Thus, high eye velocity was the only criterion that could be used for saccade generation. Braking saccades result in longer foveation times per second for CN waveforms. *Conclusions:* Eye velocity is the main criterion used to trigger braking saccades and the determination to trigger them occurs closer to 40 than 70 ms prior to their execution. Braking saccades can increase the nystagmus acuity function and allow better acuity.

Key words Congenital nystagmus; braking saccades; foveation; saccadic system

Introduction The ability to see clearly depends on more than just the refractive properties of the lens and cornea. The object of interest

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using transitional cycles. When selecting PC cycles, care was taken to properly differentiate them from J_{cf} , a similar appearing waveform; if the distance from the apparent end of the saccade and the point of foveation was under 0.5° , the saccade was considered foveating, rather than braking, and the cycle was discarded. By using both PP_{fs} and PC waveforms from the two subjects, we were able to perform an internal cross-check, comparing our results both across subjects as well as across the waveforms for each subject.

RECORDING Some horizontal eye movement recordings were made using infrared reflection (Applied Scientific Laboratories, Waltham, MA, USA). In the horizontal plane, the system was linear to $\pm 20^\circ$ and monotonic to $\pm 25\text{-}30^\circ$ with a sensitivity of 0.25° . The IR signal from each eye was calibrated with the other eye behind cover to obtain accurate position information and to document small tropias and phorias hidden by the nystagmus. Eye positions and velocities (obtained by analog differentiation of the position channels) were displayed on a strip-chart recording system (Beckman Type R612 Dynograph). The total system bandwidth (position and velocity) was 0-100 Hz. The data were digitized at 400 Hz with 12-bit resolution. The remaining data from S1 were taken from recordings made in the laboratory of Dr. R.M. Steinman using a phase-detecting revolving magnetic field technique. The sensor coils consisted of nine turns of fine copper wire imbedded in an annulus of silicone rubber molded to adhere to the eye by suction. The signals were digitized at 488 Hz with a resolution of 16 bits. The system's sensitivity was less than one minute of arc, with linearity of one part in 14,014 and drift of 0.2-0.3 minarc/hour. Noise was less than two minarc and eye position was stored to the nearest minarc. Further details of this system can be found elsewhere.⁵

PROTOCOL Subjects were seated in a chair with headrest and either a bite board or a chin stabilizer, far enough from an arc of red LEDs to prevent convergence effects (>5 feet). At this distance, the LED subtended less than 0.1° of visual angle. The room was dimly illuminated to minimize extraneous visual stimuli. Written consent was obtained from subjects before the testing. All test procedures were carefully explained to the subject before the experiment began, and were reinforced with verbal commands during the trials. An experiment consisted of from one to ten trials, each lasting under a minute with time allowed between trials for the subject to rest. Trials were kept this short to guard against boredom because CN intensity is known to decrease with inattention. All trials were fixation trials with the subject kept stationary; no pursuit or vestibulo-ocular reflex (VOR) was involved. This research, involving human subjects, followed the Declaration of Helsinki and informed consent was obtained after the nature and possible consequences of the study were explained. The research was approved by an institutional human experimentation committee.

ANALYSIS Data were sampled at 200 or 488 Hz and were digitized with a resolution of 12 or 16 bits, respectively. Only eye position was measured directly, with velocity derived from the position data by means

of a variable degree central-point differentiator. For a sampling frequency of 488 Hz, the -3 dB cutoff frequency of 55 Hz is slightly lower than the recommendation of 70 Hz by Juhola and Pyykkö.⁶ However, careful comparisons of the differentiated signals to unfiltered signals, in both the time and frequency domains, confirmed that the filtering did not change the timing of the saccades, though it could lead to a slight decrease (~10%) in saccadic amplitudes. All analyses were carried out in the MATLAB environment using software written for this study.

Peak velocity When measuring the peak velocity of the saccade, the velocity of the slow phase must be accounted for. Simply using the peak of the velocity record is not sufficient; the slow-phase velocity at the beginning of the saccade must be added. Measuring only the velocity from zero to the peak ignores a major portion of the saccade (the segments that occur before the first zero crossing and after the second zero crossing), leading to a false, low value for the velocity. Winters et al.⁷ recognized this when they studied normal saccades in the presence of large-velocity VOR.

Magnitude There are several ways to calculate the magnitude of the saccade. The first, and easiest, is simply to use position-derived onset and offset points, and calculate the difference in position at these times. The problem with this approach is that it leads to artificially small saccades, for it does not take into account that the eye was moving with great velocity in the other direction and, therefore, took some amount of time to slow and reverse. This is clearly illustrated in Figure 1; the position record shows no change in eye position, yet the velocity record clearly indicates that a braking saccade has occurred. This saccade has *zero magnitude*, which would not be possible if the slow-phase velocity had not reduced the saccade's magnitude.

An approximation that may be used to determine 'true' saccadic size is to simply calculate the distance the eye traveled between the time the velocity-derived saccade onset occurred and the time the position-derived onset occurred and add this distance to the magnitude obtained by using only the position-derived onset and offset. It must be stressed that this is a first approximation, and that we plan to examine other approximations.

Period of CN and critical times in the CN cycle To study CN, a cyclic phenomenon, we must first define when a cycle of CN starts and when it ends. Dell'Osso et al.⁸ chose the center of the foveation period as the beginning of each cycle (and therefore the end of the preceding cycle). It is often a difficult task to know where the center of the foveation period is, and no accuracy is lost by choosing the end of the foveating saccade, just prior to the start of the foveation period, as the beginning of a cycle (Fig. 2a).

Time of generation We examined the eye's behavior, looking backwards in time from the beginning of each saccade, starting at -40 ms

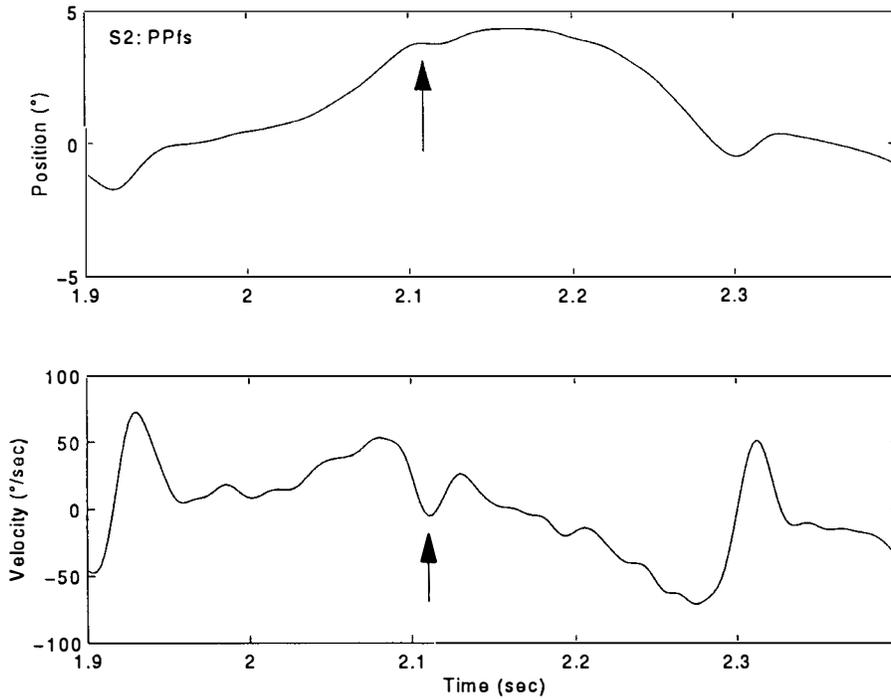
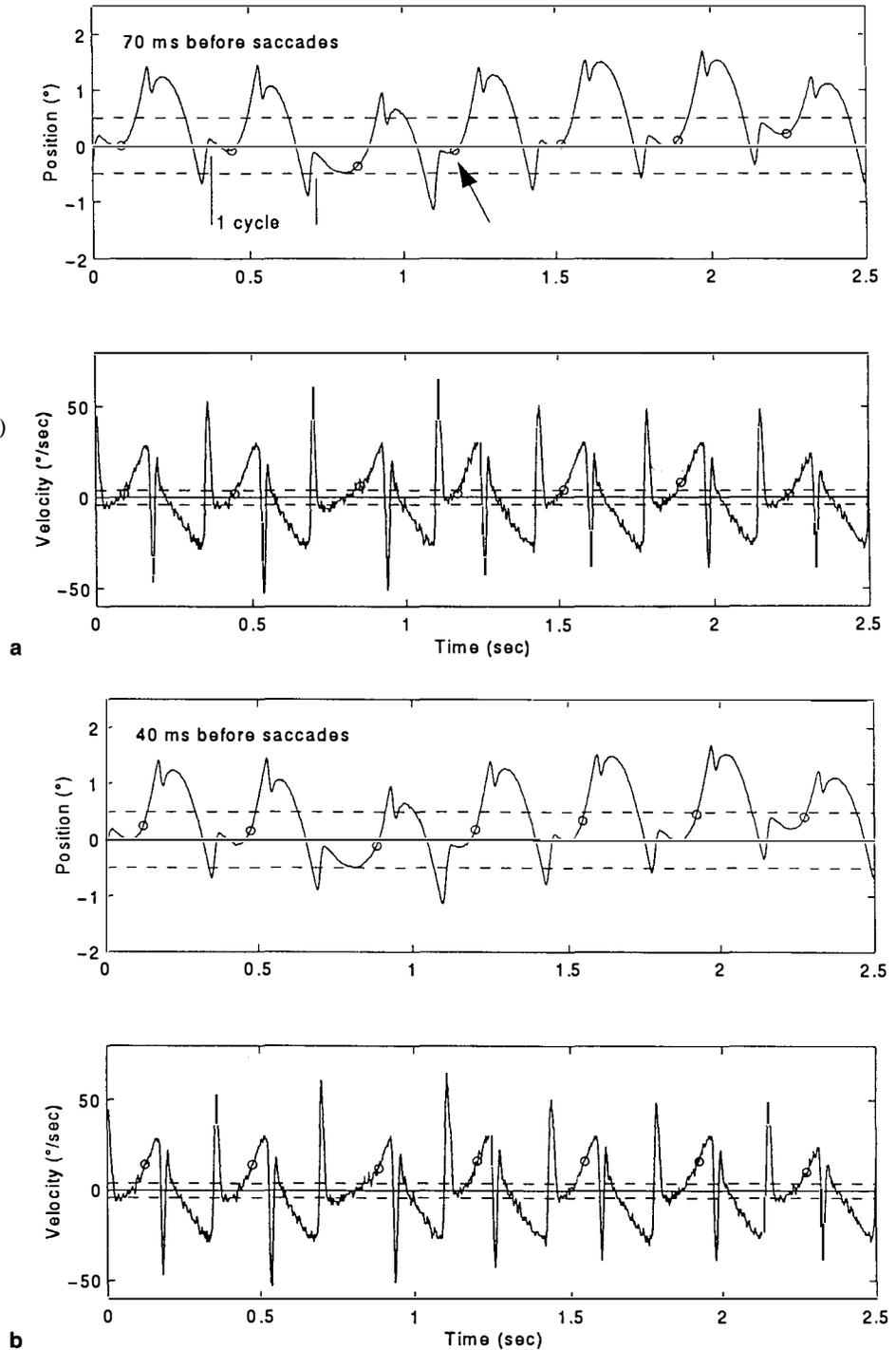


Fig. 1. A braking saccade of 'zero magnitude'. The position trace shows no change in eye position (arrow), yet the velocity trace shows that there is clearly a saccade (arrow).

and working back to -70 ms. We chose -40 ms as the closest time, for this is about the shortest interval Bruce and Goldberg found between when a command could be issued to move the eye and the eye's subsequent movement.⁹ The bulk of this delay is distributed in the brainstem, the neuromuscular junction, and the contraction time of the extraocular muscle. We stopped at -70 ms because, as can be seen by the arrow in Figure 2a, to go much beyond this point would involve moving out of the cycle being examined and into the previous one. Such results would be meaningless, for the braking saccade is affected only by the events of the cycle in which it occurs. At each time under consideration, we first measured the eye's position. If the target was seen to be within the fovea, then the need to make a saccade should not exist. Likewise, if at that time, the velocity was within slip limits, there would be no impetus to generate a saccade to slow the eye. The position and velocity behavior can be summarized in a single plot, known as a phase plane.

Phase plane analysis Control systems engineers have used the phase plane to analyze complex periodic and pseudoperiodic behavior for decades. In a phase plane, one variable is plotted against its derivative, resulting in a trajectory of the system's behavior. Dell'Osso et al.⁸ introduced this approach to the study of CN cycles. It is also possible to use the phase plane to look only at a particular aspect of eye movement, such as we did in this study, examining the eye's behavior at discrete times prior to the onset of a saccade. In the center of the phase plane is a box whose limits are the foveal extent and the slip velocity, referred to as the 'foveation window'. Points which appear in this region represent times when the target appears with best acuity, for the

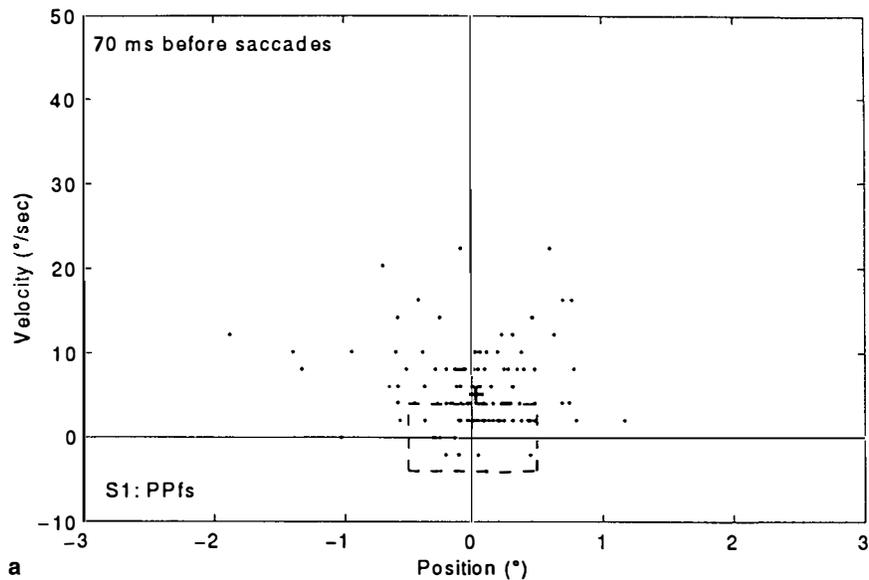
Fig. 2. Five-second excerpt from S1's PP_{fs} waveform. The beginning of the cycle has been defined to occur at the end of the foveating saccade which precedes it. (a) One cycle is indicated by the vertical lines in the position trace. Note the reliability and repeatability of the foveation periods. Circles indicate the sample that occurred closest to 70 ms before saccade onset. The majority of these samples fall within the foveal extent. The velocity yields analogous results. The majority of samples at -70 ms falls within the slip velocity limits. (b) As above, but for 40 ms before saccades. Note that position samples are still within the foveal extent, but that velocity samples are well outside slip limits. The point indicated by the arrow is discussed in the text.



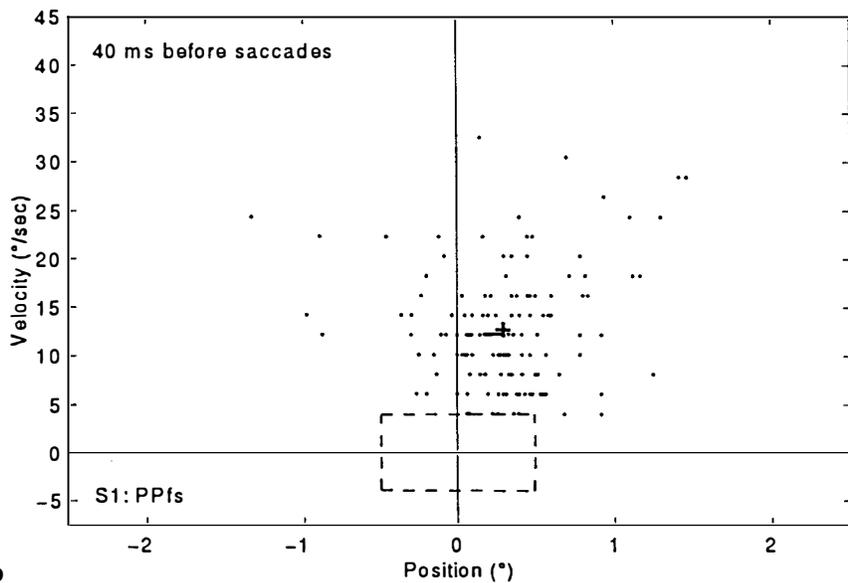
target is relatively stable with respect to the fovea, and is imaged on its most sensitive region.

Results

PHASE PLANE TIMING To estimate time of braking saccade generation required examination of both the eye's position and velocity at selected instants in time prior to the actual onset of the saccade. By



a

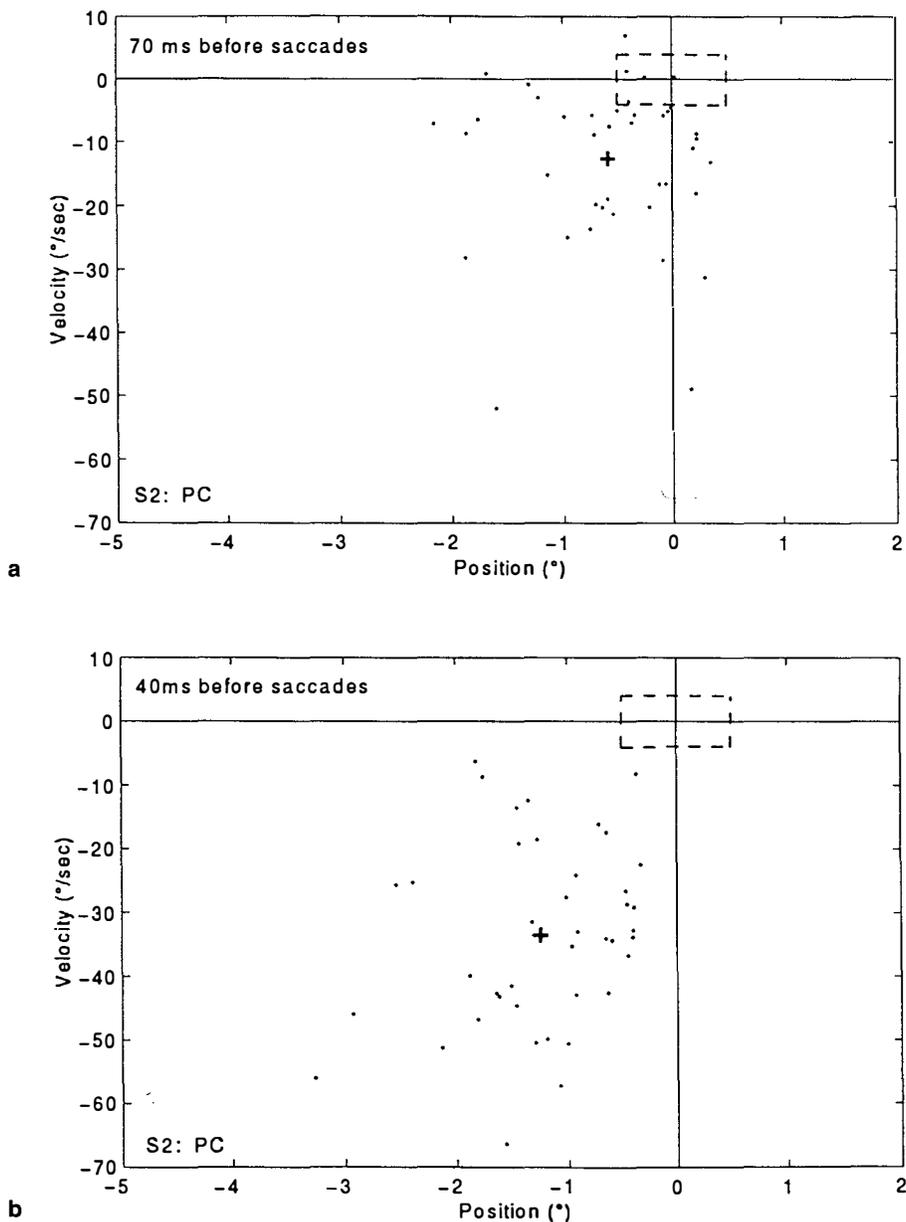


b

plotting these points in a phase plane, it was possible to determine when either, both, or neither the crucial position and velocity criteria were being met. Figure 2 shows a five-second excerpt from the position and velocity records of S1, for times when his waveform was PP_{fs}. This is a very well-behaved, stable CN where the subject was consistently able to keep his eyes within $\pm 1^\circ$ of the target throughout the oscillation, and had repeatable foveation periods with durations ranging from 50 to 70 ms. The circles indicate the sample that occurred closest to 70 ms before the onset of the braking saccade, as determined from the velocity-derived criterion. It should be noted that at -70 ms, the vast majority of circles occurred well within the foveal extent of $\pm 0.5^\circ$. Similar results can be seen for the velocity record (Fig. 2b); with few exceptions the velocity fell within the slip-velocity limits. Figure 3a shows the phase plane for all saccades recorded from this subject. We

Fig. 3. Phase-plane representation of S1's PP_{fs} waveform. In this and subsequent figures, the rectangular box centered around the origin is the foveation window ($\pm 0.5^\circ$ by $\pm 4^\circ/\text{s}$) and the crosses represent the position and velocity averages. (a) At 70 ms before saccades, the average position lies within the fovea and the average velocity is just on the slip velocity border. (b) At 40 ms before saccades, the average position remains on the fovea, but now average velocity is well beyond the slip velocity border.

Fig. 4. Phase-plane representation of S2's pseudocycloid (PC in this and subsequent figures) waveforms. (a) At 70 ms before saccades, the average position is just on the edge of the fovea, while average velocity is $12^{\circ}/s$. (b) At 40 ms before saccades, both the average position and average velocity have moved far beyond the limits for good visual acuity.



calculated the average position and velocity of all the points and plotted it along with the individual points. The average position fell well within the foveal limits, and the average velocity fell at $5^{\circ}/s$, just outside the strict $\pm 4^{\circ}/s$ limit we imposed for minimal decrease in acuity, but still low enough to insure very little blurring.

Figure 3b shows the phase plane analysis for points 40 ms before the saccades. As was the case for -70 ms, the average position of the target was still within the fovea, but now the average velocity was well beyond even the most liberal limits for velocity, at about $15^{\circ}/s$.

Figure 4, analogous to the previous two figures, is for S2 during the intervals that he exhibited PC waveforms. As above, in (a), the average position and velocity were more likely to fall within their respective limits at 70 ms, with the image position just beyond the fovea. In

	PP _{fs}		PC	
	Mean%	Max%	Mean%	Max%
S1	61.99*	128.6	125.5	151.6
S2	74.4	100	119.4*	146.9

*Subject's preferred waveform.

Figure 4b, 40 ms prior to saccade onset, both the average position and average velocity were well outside the foveation window, making it less likely to satisfy its slip criterion.

TABLE 1. Braking effect of the waveforms.

BRAKING EFFECT Because braking saccades are purported to slow the eye, we calculated how effective they were by taking the absolute difference (the velocity of the slow phase just prior to beginning of the saccade minus the velocity of the slow phase just after completion of the saccade) and also expressing braking as a percentage reduction (difference/presaccadic velocity). S1's PC and S2's PP_{fs} results were similar. In both subjects, for *both* their waveforms, the saccades acted to slow the eye. However, the range of the effect differed for each waveform. For S1's PP_{fs}, the braking ranged from about a 20% reduction for the less effective saccades, to 100% for saccades that completely stopped the eye, to >100% for saccades that caused the eye to reverse its direction. The average amount of braking was 61.99%. For the PC waveform, the saccade *always* acted to change the direction of the eye, regardless of subject, so the amount of braking seen was always greater than 100%. For S2, this range was as high as 146.9%, with an average slowdown of 119.4%. Table 1 details the average and maximum braking effect for both waveforms in each subject.

SACCADE DURATION EFFECT We next determined if the magnitude of the braking saccade influenced the duration of the CN cycle. Figure 5a shows a plot of intercycle interval vs. the magnitude of the braking saccade. As the magnitude of the braking saccade increased, there was a general decrease in the time between successive cycles. For a more qualitative illustration of this phenomenon, Figure 5b shows a several-second record of a switch between pendular with foveating saccades (P_{fs}) and PP_{fs} waveforms for S1. As can easily be seen, when there was no braking saccade (P_{fs}), the eye traveled further from the target before reversing and returning to primary position. This extra distance led to an increase in the time between successive cycles. Compare this to the case when a braking saccade was present (PP_{fs}): the maximum excursion was reduced, leading to a shorter time between cycles. We calculated the nystagmus acuity function (NAF)¹⁰ for each waveform in both subjects. For S1, the NAF was 0.603 for the PP_{fs} waveform and decreased by approximately 50-66% (0.301-0.218) for the PC waveform. For S2, the NAF was 0.271 for the PC waveform, while the PP_{fs} waveform was too transient to calculate an NAF (i.e., no runs greater than 1.5 s were found).

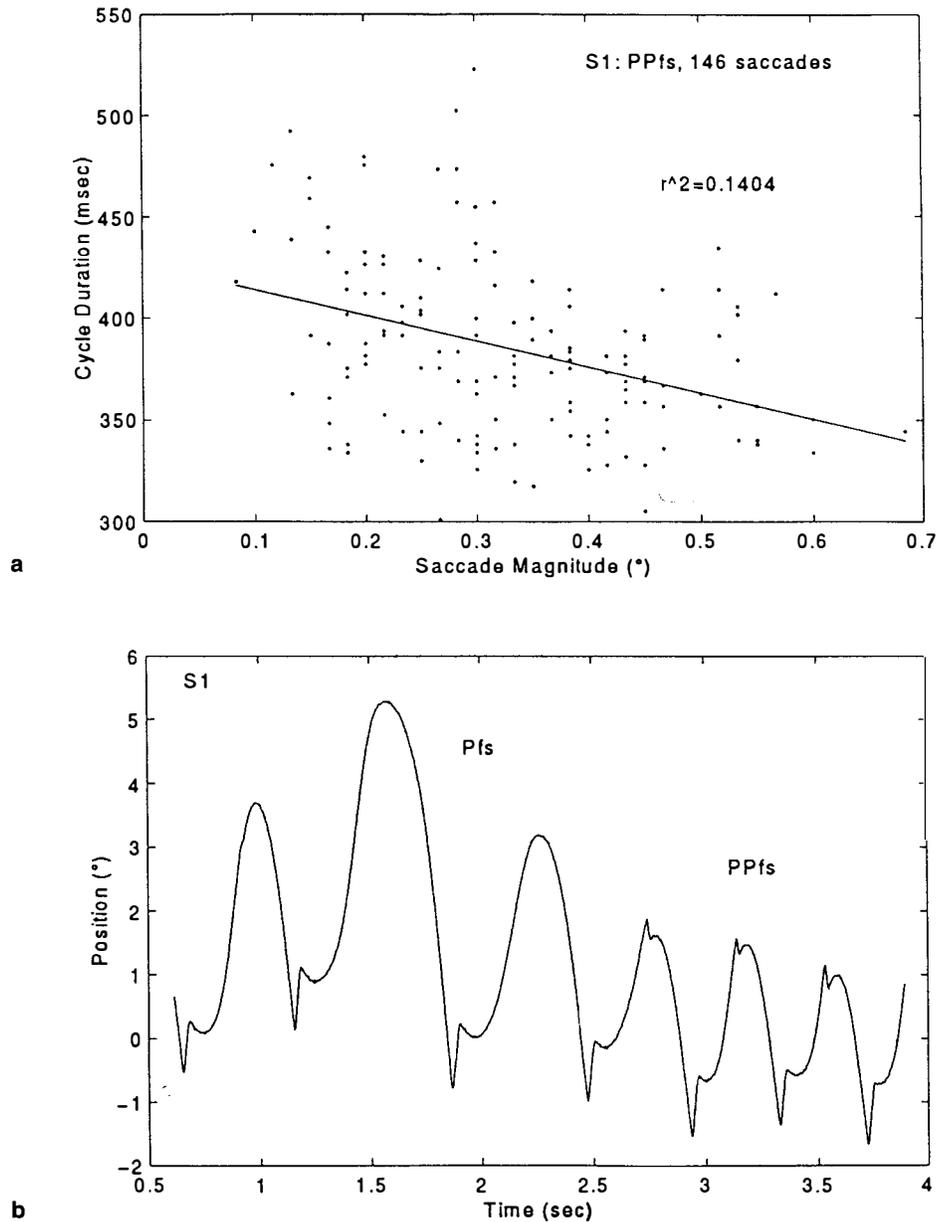


Fig. 5. (a) Cycle duration vs. braking saccade magnitude for S1. (b) Transition between pendular with foveating saccades (P_{fs}) and PP_{fs} . Note the increased magnitude and duration of the slow phase when there is no braking saccade to oppose the runaway.

SACCADE MAGNITUDE EFFECT We next investigated whether the amount of braking effect was dependent on the magnitude of the braking saccade. For S1's PP_{fs} waveform, there did not appear to be a discernibly strong relationship between the size of the saccade and the amount of braking that it provided. For S2's PC waveform, again, no strong relationship between saccade magnitude and braking slowdown was observed.

INITIAL POSITION AND VELOCITY EFFECTS To answer the question of whether the magnitude of the braking saccade depends on the behavior of the eye at the time of generation, we considered the position, velocity, and acceleration of the eye at various times from 40 ms to 70

ms before saccade onset. For neither S1's PP_{fs} nor S2's PC waveforms, was there any dependence on the size of braking saccades on either eye position, velocity, or acceleration at any time between 40 ms and 70 ms prior to the saccade. Thus, any size braking saccade may occur no matter what the initial conditions of the eye's motion.

Discussion The goals of this study were to investigate the conditions for the generation of braking saccades and their effect on CN waveforms and to test the hypothesis that braking saccades are primarily determined by eye velocity. This included determining which criteria (the position and velocity signals that the ocular motor system may monitor) are used to decide when there is a need to slow the eye, as well as the time at which the braking saccade is programmed. We chose position and velocity because they are the most important variables in determining visual acuity; the target image must be within the central one degree of vision (on the fovea) and must not be moving too rapidly across the retina (slip-velocity limit).

Our results suggest that the velocity criterion is the stronger of the two, based on the results of Figures 4 and 5. The eye's behavior 70 ms before the onset of the braking saccade indicates that its mean velocity still remains within the slip-velocity limit established during the previous foveation period. Therefore, given the velocity requirements necessary for good visual acuity, there is no compelling need to slow the eye further and there should be no impetus to generate a braking saccade. When, on the other hand, we consider the eye at 40 ms before onset, the mean eye *velocity* increases to a value well beyond even the most generous upper value for the slip-velocity limits, prompting a need to slow the eye's runaway and leading to the generation of a braking saccade. These data suggest that the time at which the saccade is programmed is more likely to be nearer -40 ms than -70 ms.

Using this same reasoning, it appears that the position criterion is not important for the triggering of a braking saccade because, at all times between 40 ms and 70 ms before saccade onset, the mean eye position remains within the foveal extent, and thus, there is no reason to change the eye's *position*.

These results are also intuitively pleasing, for the braking saccade does not appear to be affected by visual input. We state this based on several observations. First, the braking saccade leads to no significant change in the position of the eye, as would be expected if the ocular motor system were reacting to a target (such as the change caused by a foveating saccade). Second, the duration of the low-velocity period following the completion of a braking saccade (which can be seen as analogous to the foveation period that follows a foveating saccade), is considerably shorter, ranging from 10 ms to 40 ms (mean=20.3±6.02 ms), than that of the foveation period. Foveation periods ranged from 50 ms to well over 100 ms in both these subjects; in other subjects, they have been measured to be up to 450 ms. Additionally, the magnitudes of braking saccades were fairly constant, not appearing to have any strong dependence on where the eye was pointing at the suspected time of generation. Finally, this conclusion is strengthened by noting

that waveforms with braking saccades still appear when the subject is in the dark with no target.

We found that the size of the saccade that is programmed does not depend on the position, velocity, or acceleration of the eye at the time the decision to generate a braking saccade was made. This suggests that the braking saccade is an automatic response to the monitored velocity signal rising above threshold, requiring a minimum of processing time. This is consistent with our selection of 40 ms before saccade onset as the time at which the saccade is most likely generated. The qualitatively similar, though quantitatively different, results seen for the different waveforms in each subject may be due to the fact that each subject appears to have a 'favored' waveform, and tends to use that waveform to achieve his best visual acuity. When S1's CN shifted to the secondary waveform, the NAF, and hence acuity, tended to decrease. For S2, the secondary waveform was merely a transient occurrence of several cycles at a time and could not be used to calculate visual acuity over a 2-5 s interval. As a consequence of the shift from primary to secondary waveform, the position and velocity criteria for generating a braking saccade may have been relaxed to reflect this lessened demand on the visual and ocular motor systems. This is mostly in agreement with the conclusion reached by Abadi and Dickinson,¹¹ although we stress that their 'waveform shape' should not be read to simply mean 'waveform'. For example, in their prior work,¹² they suggested that PC waveforms yielded better sensitivity than did pendular (P) or P_{fs} waveforms, owing to longer foveation periods in the PC case. We, however, have shown that it is possible for at least one subject (S1) to consistently display PP_{fs} cycles with longer low-velocity intervals than seen in his PC cycles; the crucial factor is foveation time in the waveform, not the waveform itself.

The main benefit of the braking saccade appears to be an increase in NAF and visual acuity. As shown in Figure 5b, when the braking saccades are made, the time between corresponding points of successive CN cycles has been decreased, which means that the frequency of the nystagmus has been *increased*. At first, this might appear to be a paradox: an increase in nystagmus frequency leading to an increase in visual acuity. In reality, there is no contradiction, for when considering visual acuity, frequency is *not* the important feature of the waveform. Instead, one must consider the *foveation periods*, which are the times when the target is within the fovea and moving slower than the slip velocity limit with respect to it. Visual acuity in CN is highest when these foveation periods are repeated reliably from cycle to cycle.⁸ Note that when the CN is of low amplitude, the braking saccade can actually bring the eye near the target, giving a 'double shot' of foveation for that particular cycle. In these cases we expect, and have demonstrated,⁸ that acuity would increase even more, for there are now two separate foveation periods in one CN cycle, although (as mentioned above) the one following the braking saccade is of shorter duration.

The braking saccade appears to serve just as its name suggests, applying the brakes to a runaway ocular motor system. In all CN cycles we examined, the braking saccade slowed the eye, and in some cases

stopped it, or even caused it to reverse direction. As shown above, the PC waveform *always* experienced a reversal in velocity, while the PP_{fs} was only rarely completely halted or reversed. Braking saccades appear to function in the same way as vestibular or optokinetic fast phases.

Note that the braking saccade seen in the PC waveform looks, at first glance, to be a foveating saccade. This is not the case, however, for the saccade does *not* serve to bring the fovea to the target, but instead stops short, requiring the slow eye movement system to complete the motion. It is also worth mentioning that the duration of slow-velocity periods following PC braking saccades was longer than those that follow PP_{fs} braking saccades in our subjects. This re-emphasizes that the periods following braking saccades can either serve a visual purpose (foveation), as for PC waveforms, or not, as for PP_{fs} waveforms.

The velocity criterion that we have found appears to be necessary, but not always sufficient to generate a braking saccade. As noted above, there are very similar CN waveforms which appear to differ only when a braking saccade is present (e.g., P_{fs} and PP_{fs}). The decision to include a braking saccade may also depend on the specific and varied demands the subject makes on their visual system at the time: i.e., if their visual acuity is not sufficient for the task at hand, then the interjection of braking saccades may act to increase acuity as needed.

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