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Overlapping Saccades and Glissades are Produced by Fatigue in the Saccadic Eye Movement System

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Saccadic eye movements and their neurological control signals change significantly as the human fatigues. Electronic instrumentation with a bandwidth extending from DC to 1 kHz enabled the recording of anomalous looking saccadic eye movements that occurred as the subject's physiological state changed. Fatigue can produce: overlapping saccades in which the high-frequency saccadic bursts should show large pauses; glissades in which the high-frequency bursts should be much shorter than appropriate for the size of the intended saccades; and low-velocity, long-duration, non-Main Sequence saccades in which the motoneuronal bursts should be of lower frequency and longer duration than normal. As few as 30 saccades of 50 deg magnitude or a longer sequence of saccades as small as 10 deg can produce these aberrant eye movements and their concomitant neuronal firing pattern variations. The effects of fatigue could explain some of the variations between and spread within published data for velocity vs amplitude of human saccadic eye movements. Measuring the resistance to eye movement fatigue could become either a common clinical tool for diagnosing specific or general disease states, or a research tool for studying dyslexia or fatigue.

INTRODUCTION

When the saccadic eye movement system fatigues, saccades become slower, and the neurological control signal stratagem changes. The term fatigue is used here in a broad sense, as it was by McFarland (22) at the International Congress on Fatigue Assessment: "a group of phenomena associated with impairment, or loss, of efficiency and skill." Dodge and Cline (17) noted that the last four saccades of every set of ten saccades were slower than the first four. Subsequently, the slowing of saccades by fatigue has been reported for 60-deg saccades (14), 40-deg saccades (8,

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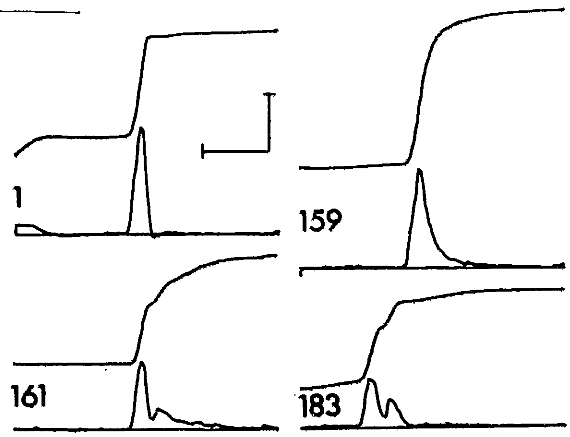

FIG. 1. Eye position (top) and eye velocity (bottom) as functions of time for four different saccades of a temporal sequence. The first recorded saccade of the day, record no. 1, is normal; the subsequent saccades show symptoms of fatigue. The calibrations represent 5 deg, 250 deg/sec, and 100 msec.

15, 26, 27), 30-deg saccades (13, 23), and 17-deg saccades (29); but fatigue studies have failed to show any effects of fatigue for 10-deg saccades (13), 15-deg saccades (23), and 90-deg saccades (21). Cook (12) showed that shapes of the velocity records changed during some experimental runs, but the velocity records of Lion and Brockhurst (21) for 90-deg saccades showed no variation in shape.

The purposes of this paper are: to show that glissades, overlapping saccades, and low-velocity, non-Main Sequence saccades are produced by fatigue of the saccadic eye movement system; to demonstrate that small saccades can produce fatigue; to show that as few as 30 saccades of 50-deg magnitude may produce significant effects of fatigue; to suggest the variations in neurological control signals concomitant with fatigue; and to suggest future clinical and research applications of recording these anomalous eye movements.

METHODS

Saccades were made at a rate of 40 saccades/min (0.33 Hz). The target for saccades 25-deg and smaller was a small spot of white light 1 mm in diameter emitted from a slide projector and reflected off of a mirror galvanometer. For larger eye movements the targets were pieces of white tape. All targets were presented on a semicircular screen 46 cm in front of the subject. The subject's head was supported with a head rest and a bite bar covered with dental impression compound.

The bandwidth of the measuring system which included photodiodes, d-c amplifiers, a computer velocity program, a computer slow-down plotting routine, and a X-Y plotter extended from dc to 1 kHz. This large bandwidth was essential for observing many of these anomalous saccades.

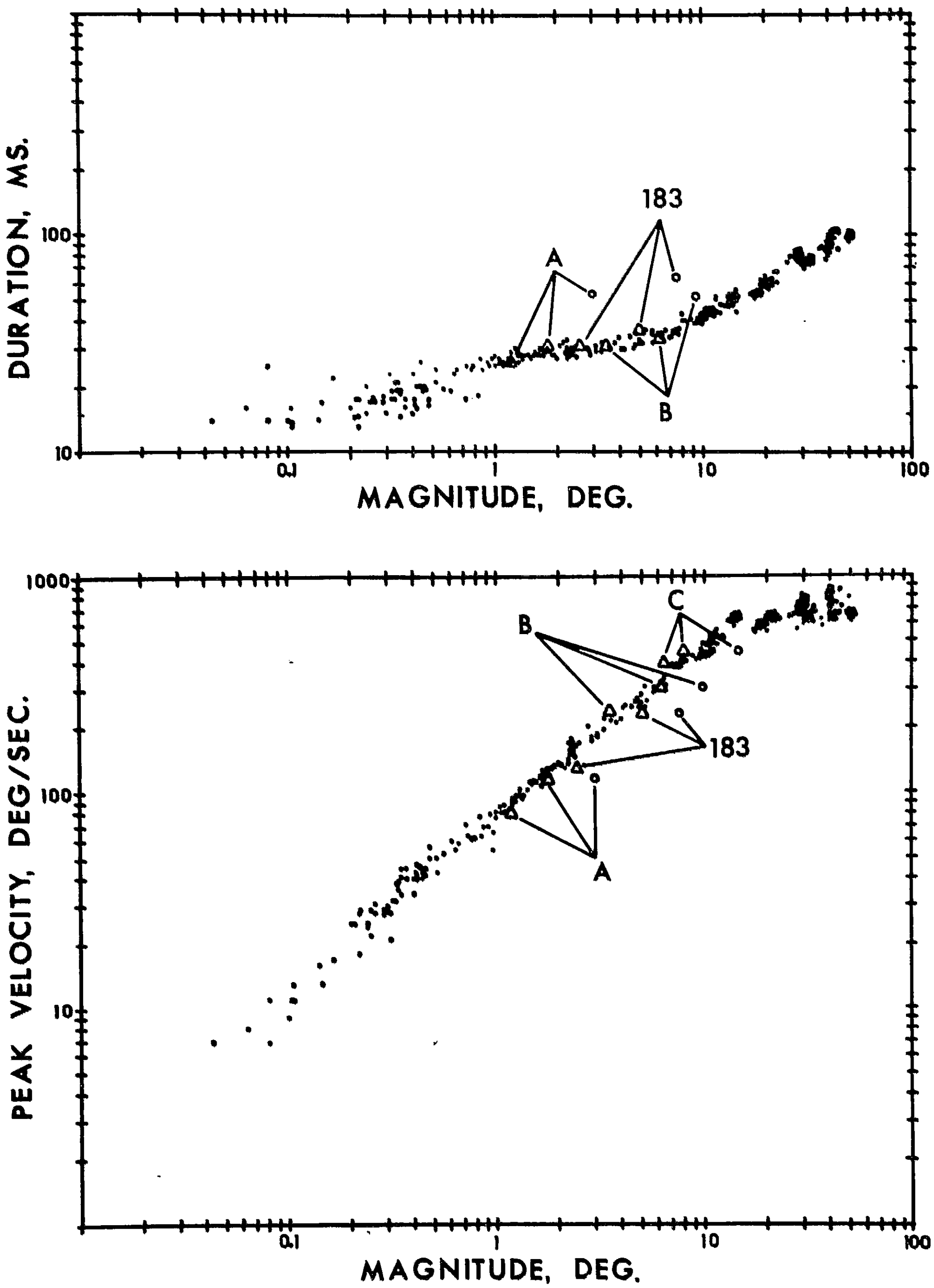

FIG. 2. Main Sequence diagrams with some of the saccades of Figs. 1 and 3 indicated.

Other details of the instrumentation were discussed by Bahill, Clark, and Stark (3).

RESULTS

A variety of anomalous looking saccadic eye movements can be produced by fatigued subjects. Figure 1 is a temporal series of saccadic eye

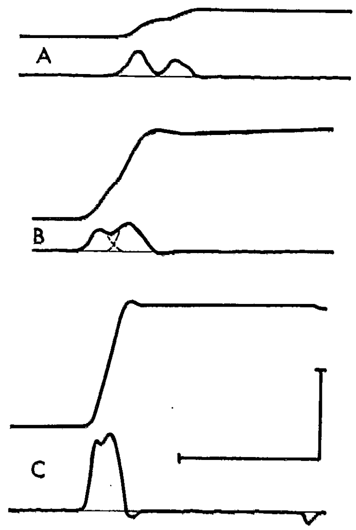

FIG. 3. Eye position and eye velocity for overlapping saccades executed by three different subjects. The calibration marks represent: 10 deg for all records; 465 deg/sec and 90 msec for A, 975 deg/sec and 100 msec for B, and 515 deg/sec and 160 msec for C.

movements which illustrate some of these. The saccade of record no. 1 was the first measured saccade of the day; it was normal, for it fits on the Main Sequence (5) diagrams (Fig. 2). Later in the run, glissades began to appear. In the 159th movement the fast saccadic phase fell short of the final position and a glissade completed the eye movement. Glissades are the slow drifting eye movements that are sometimes appended to the end of the fast saccadic portion of the eye movement (4, 31, 32). They are monocular phenomena. That is, one eye will make a fast saccadic eye movement (Figs. 1, no. 1 and 4A) to the final position, and the other eye will glissade into the final position (Figs. 1, no. 159 and 4C). Glissades also occur in unfatigued subjects, but the frequency of occurrence is increased by fatigue.

The 161st record shows a saccadic portion that took the eye only halfway to its final position. This saccade was inappropriately small, but normal for its size, because it was a 5.4 deg, 325 deg/sec, 34 msec, Main Sequence saccade. As this subject continued repetitive tracking of the target, overlapping saccades became common. The 183rd movement of this sequence shows two overlapping saccades that were spaced so close together that their velocity profiles overlapped. Each of these saccades was normal, for they fit on the Main Sequence diagrams, as shown by the triangles with the numbers 183 in Fig. 2. If this movement was treated as one large strange saccade, then the peak velocity and duration would be off the Main Sequence as shown with the circles in Fig. 2.

All of our subjects would break down into overalpping saccades when fatigued. Overlapping saccades from three different subjects and with vary-

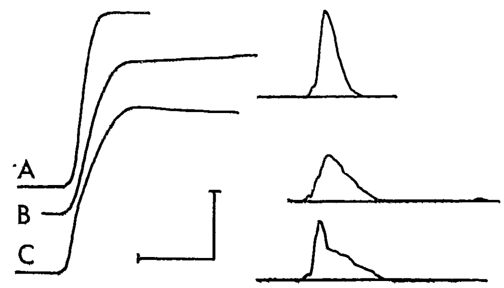

FIG. 4. Eye position and eye velocity for 50 deg saccadic eye movements. A is normal, C has a glissade, and B is a low-velocity, long-duration non-Main Sequence saccadic eye movement. The calibrations represent 20 deg, 540 deg/sec, and 140 msec.

ing amounts of overlap are shown in Fig. 3A, B and C. This central nervous system (CNS) decomposition of one large saccade into two smaller saccades is not related to primary position, for we have recorded overlapping saccades while the subject was making saccades between two points 30 and 40 deg temporal of primary position. Overlapping saccades are monocular phenomena. For example one eye may utilize a pair of overlapping saccades to get to the new eye position, while at the same time the other eye may use one large smooth saccade.

Low-velocity, long-duration, non-Main Sequence saccades may also be produced by fatigue (Fig. 4B). This saccade (Fig. 4B) had about a 50% reduction in velocity. This type of low-velocity saccade often resulted when the subject attempted to make a smaller saccade after being fatigued by larger saccades. Occasionally the second saccade of an overlapping saccadic pair was such a low-velocity saccade. About 70% of the saccades of unfatigued subjects have dynamic overshoot (3). Fatigue reduces this percentage and also increases the frequency of occurrence of saccades with abnormally large amounts of dynamic overshoot.

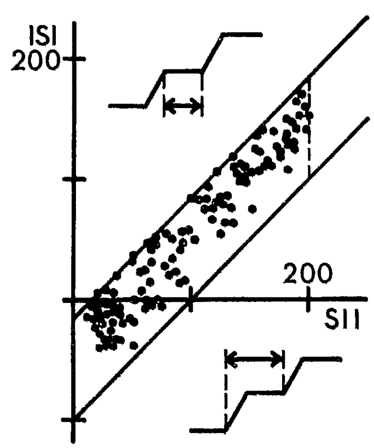

FIG. 5. Intersaccadic interval (ISI) vs saccadic initiation interval (SII) for double saccades. Definitions of these terms are illustrated by the eye position vs time schematics next to each axis and are given in the text. Time intervals are in msec.

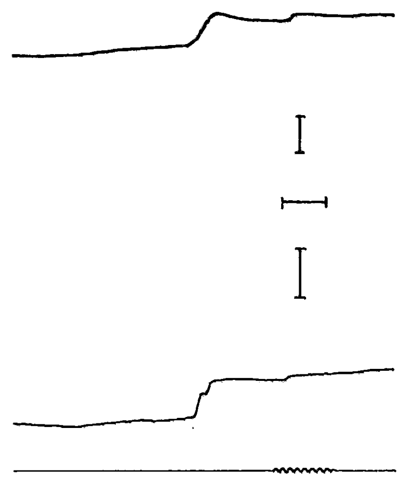

FIG. 6. Monocular double saccades executed by a fatigued subject. This figure shows: the position of the right eye as a function of time (middle trace) exhibiting a double saccadic pair followed by a small corrective saccade, the position of the left eye (top) displaying a large saccade followed by a glissade and the corrective saccade, and the timing record (bottom). The calibrations represent (top) 10 deg for the left eye, (middle) 100 msec, and (bottom) 10 deg for the right eye. Leftward eye movements are represented by upward deflections in these recordings.

Two parameters of particular interest for double saccades are plotted in Fig. 5. The ordinate is the intersaccadic interval, or the time between the *end* of the first saccade and the beginning of the second saccade. The abscissa is the saccadic initiation interval, the time between the *start* of the first saccade and the beginning of the second saccade. The sampled data range (33), where the saccadic initiation interval is greater than 200 msec, contains most normally observed human saccades. The closely spaced saccade range (2) contains saccades that have intersaccadic intervals less than 200 msec, but not overlapping saccades. Saccades in this range may be produced for a variety of reasons other than fatigue (2). All saccadic pairs with saccadic initiation intervals less than 200 msec are called double saccades. This term includes all closely spaced and overlapping saccades, but excludes saccadic pairs that fit the sampled-data model. Double saccades are monocular phenomena (Fig. 6). The intersaccadic interval is negative in the overlapping saccade range; meaning, that the second saccade begins before the velocity has returned to zero under the influence of the first saccade. This is illustrated by the dashed lines of Figs. 3 and 7. The overlapping saccades of Figs. 1 and 3, as well as many other saccadic pairs, are represented in Fig. 5. Points on the upper line of the region were occupied by microsaccades (15 msec duration) preceding second saccades by varying intervals; points on the lower line of the region are derived from 50-deg (100 msec duration) primary saccades preceding secondary saccades at varying intervals. It would be possible to have points below this line, but none are indicated because we have not studied saccades larger than 50 deg.

Most of our subjects did not fatigue as rapidly as the subject of Fig. 1. In a typical subject, after 500 saccades of 10-deg magnitude, the fixations became inaccurate, more corrective saccades were seen, and double saccades began to appear. However, when requested to make "more accurate" saccades, the subject responded with normally shaped saccades. After 1200 ten-deg saccades, the subject could still usually make normally-shaped saccades upon request; however, the maximum velocities were 10% smaller than for the first saccades of the day, and some overlapping saccades appeared. Large saccades are much more fatiguing than 10-deg saccades. After making only 30 50-deg or 80 30-deg saccades, the subject could not produce normally-shaped saccades. All further saccades would have symptoms of fatigue (Figs. 1, 3, and 4).

After the subjects were fatigued, attempts to produce dishabituation by admonishing or encouraging the subject, or by changing the size of the target steps would reduce the number of multiple saccades (staircase tracking), but would not eliminate the glissades, overlapping saccades, and non-Main Sequence saccades. When a subject became fatigued on 20-deg saccades, subsequent switches to 50-deg target jumps would still elicit fatigued saccades. However, the converse was not necessarily true. When the subject was fatigued on 50-deg saccades, subsequent changes to 20-deg target jumps might elicit some normal 20-deg saccades, before fatigue sets in again.

DISCUSSION

Overlapping saccades seem to be two saccades spaced close together, so that the eye does not have time to decelerate to zero velocity before the second saccade begins to accelerate the eye. This does not mean that the pulse portion of the saccadic controller signals need overlap, because the duration of the pulse portion of the controller signal is about one-half the duration of the saccade. Figure 7 shows the proposed neuronal controller signals for the saccades of Fig. 1 record, no. 183. This decomposition of one large movement into two smaller ones is an amplitude decomposition and not just a temporal decomposition of the saccadic duration. For example, this saccadic pair has amplitudes of 5.0 and 2.5 deg for a total of 7.5 deg; whereas, the duration of each, 36 msec plus 32 msec, totals 68 msec, which is larger than the 40 msec duration of a 7.5-deg saccade. Brooks (10) has noted similar amplitude decompositions for the movements of monkey forearms.

Overlapping saccades have been portrayed by other investigators. Miles (26) photographed the corneal reflection of the eye and showed both over-

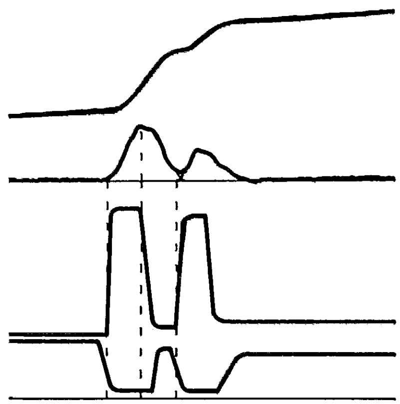

FIG. 7. Overlapping saccades showing (from top to bottom), as functions of time, the eye position, eye velocity, proposed neuronal activity of the agonist and proposed neuronal activity of the antagonist motoneuronal pools for the saccades of Fig. 1, record no. 183.

lapping and closely spaced double saccades for sleepy subjects. Täumer and Kommerell (30), using Electro-oculography (EOG) have shown records of saccadic eye movements with double saccades. We have found (6) that double saccades occur frequently in the horizontal and vertical components of oblique saccades. Palmieri, Oliva, and Scotto (28), using photomultiplier tubes and a corneal reflection technique, have also shown records which we interpret as overlapping saccades in oblique eye movements. Barmack (7) elicited overlapping saccades by having a monkey attempt to track a target that decelerated abruptly immediately before the saccade was initiated. He showed that the acceleration/deceleration ratio of the second saccade was smaller than for a normal saccade. This would be expected because the eye is decelerating at the end of the first and the beginning of the second saccade, and the muscle forces must overcome the apparent inertia (5) of the decelerating eyeball. However, at this same time, the eye has a non-zero velocity; it is already moving in the intended direction. Thus, the initial conditions on velocity and acceleration for the second saccade are unusual, but self-compensating, resulting in a normal, or Main Sequence, saccade.

Glissades were recorded and named by Weber and Daroff (31, 32). A glissade is due to an amplitude mismatch between the phasic and tonic components of the motoneuronal control signal (4). For the saccadic eye movement with the appended glissade (Fig. 4C) the pulse portion of the motoneuronal controller signal should have been smaller than for a similar sized normal saccadic eye movement (Fig. 4A). This amplitude decrement could be due to lower motoneuronal firing frequencies or lessened recruitment of the motoneurons.

It is important to exercise great care to eliminate abrupt nonlinearities from the measurement devices and electronics, because abrupt nonlinearities in the instrumentation may produce artifacts which look somewhat like overlapping saccades. We are confident that the saccades of this paper were *not* so contaminated, because when there is a nonlinearity in the instrumentation, all records will have an inflection point at the same point in space (for example, 5 deg left of primary position). In all of the experiments reported here, we have recorded normal saccades with no inflection point which precede and succeed the overlapping saccades. The junctions of the two overlapping saccades occurred at different points in space for each of the pairs of overlapping saccades used for this report. Furthermore, instrumental artifacts will not increase the duration of the recorded eye movements. For example, a 7.5-deg saccade contaminated with instrumental artifact will have a duration of 40 msec—the duration of a normal 7.5-deg saccade. Instrumental artifact will not increase the duration to 68 msec as the CNS amplitude decomposition did (Fig. 7).

As mentioned earlier, Lion and Brockhurst (21), using limited bandwidth EOG, did not note any effetcs of fatigue on 90-deg saccades. Their bandwidth was on the order of 3 Hz which, unfortunately, distorted their records and filtered out all symptoms of fatigue noted in this report. In fact, the apparent peak velocity of their records occurred almost at the end of the saccades, where the actual velocity is near zero. Most of the authors who did record signs of fatigue (8, 13–15, 17, 23, 26, 27, 29) used a photographic corneal reflection technique which had the requisite large bandwidth. The other two studies which recorded these signs used photodiodes (12) and EOG filtered at 700 Hz (8).

The slowing of saccades by fatigue and the rapidity of fatigue's onset explain a large part of the variations in saccadic velocity seen by various experimenters. For instance, Bahill, Clark and Stark (5) took great care to prevent fatiguing their subjects. They found that the maximum saccadic velocity of their fastest 20-deg saccade was 640 deg/sec, and the average value of the maximum saccadic velocities for all of their 20-deg saccades was 605 deg/sec. Ninety-five percent of all saccades were within ± 35 deg/sec of this mean. Boghen et al. (9) were not concerned with the effects of fatigue. They reported that their fastest 20-deg saccades had maximum velocities (by the photodiode method) of 625 deg/sec, which is about the same as Bahill, Clark, and Stark; but, their mean maximum velocity of 440 deg/sec was lower, and their 95% range was ± 190 deg/sec. A large part of this variation was probably due to fatigue.

The term fatigue has been used here in a general sense, encompassing physiological factors, as well as psychological ones. Fatigue is a time correlated decrement of efficiency and timing (11) caused by anxiety, frustration, or boredom (22) or by monotony, boredom and stress (18), or by a high level of arousal while performing a monotonous task (11). This usage of the term fatigue is more general than that used by Harris and

Stark (19), who differentiated between decrements in performance caused by sensory adaptation, CNS habituation, and muscular fatigue; or by Kuroda, Klissouras, and Milsum (20), who studied muscular fatigue. The fatigue noted here is probably manifested at several levels. In the typical fatigue sequence shown in Fig. 1, glissades were the first signs of fatigue to appear. In these eye movements the controller signal pulse duration did not carry the eye as far as normal. This could have been due to fatigue of the extraocular muscles or motoneurons. Later, in order to compensate, the CNS may have changed its stratagem to produce double saccades or low-velocity, long-duration, non-Main Sequence saccades. Injections of diazepam (Valium) which increases presynaptic inhibition in the spinal cord, and affects the limbic system and cerebellar structures, also produced double saccades and low velocity saccades (1). Alcohol produced similar decrements in the speed of saccades (16, 25).

After the experiments two of our subjects described their subjective sensations and indicated that they had almost fallen asleep on several occasions. For the sake of completeness, we will add the following presumably irrelevant comment that our two subjects who showed fatigue most quickly lacked thymus glands.

The primary purposes of this report were to show the unusual looking saccades that are produced by fatigued subjects and to provide insight into the concomitant neuronal firing pattern variations. However, the ease with which fatigue can be induced may make the measurement of these anomalous eye movements an important clinical and research tool. For instance, resistance to fatigue could be a quantitative test for certain diseases. It has been reported (24) that patients with myasthenia gravis have slower saccades. Perhaps they will also exhibit these signs of fatigue quicker than normal subjects. Measurement of eye movements could be used as an indicator of the general physiological state of people who must perform critical tasks under unusual conditions, such as airline pilots. Although our two subjects who fatigued most rapidly did not have reading difficulties, it might be possible that dyslexic children may be discriminated by their level of resistance to fatigue for various sized eye movements, particularly for those that fall into the range of normal sized reading saccades. It seems that the eye movement system would be ideal for physiologists and human factors engineers specifically studying fatigue, because the task is simple with little subject discomfort, the measurements are easy to make, and the eye movement system seems to be a sensitive indicator of fatigue.

Large saccades wil produce fatigue in the eye movement system quickly, although small saccades can also fatigue the system. As few as 30 sequential saccades of 50-deg magnitude can produce fatigue. Signs of fatigue include: failure of the saccade to carry the eye to its final position, allowing the completion of the movement to be accomplished by a glissade; decomposition of the movement into overlapping saccades; and low-velocity, long-duration, non-Main Sequence saccades.

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