TECHNICAL REPORT

EMMA – an eye movement measurement and analysis system

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Abstract

A system has been developed for stimulation, recording and analysis of a wide range of eye movements. Eye movements are stimulated with an LED bar or a video projector under the control of a PC. The eye movements are measured using a scleral reflection technique (IRIS instrument), and sampled and stored on a PC. A range of tests have been developed to measure saccadic and smooth pursuit eye movements. A variety of tools have been developed to assist in the analysis of the data. Several research studies have ably demonstrated the utility and versatility of the system.

Key words eye movements, smooth pursuit, saccades, saccadic suppression, neurological disorders.

Introduction

This paper describes an eye movement measurement and analysis (EMMA) system which has been developed for the stimulation, measurement, recording and analysis of a wide variety of horizontal and vertical eye movements. Development began in 1993 using a single PC and LED bar to do simple saccadic tests, and has expanded to include a second PC and video generator capable of smooth pursuit and more complex saccadic tests.

System hardware

EMMA consists of an IRIS instrument, two PCs, an LED bar, colour video projector, and multi-tone audio generator (Figure 1). The IRIS instrument (Skalar Medical, The Netherlands) uses arrays of infra-red LEDs and detectors to determine the horizontal or vertical position of each eye by comparing the amount of IR light reflected from the sclera on each side of the iris [1]. Accuracy is ±0.5° and range is linear up to ±20°. The two outputs of the IRIS (i.e., one channel per eye) are sampled at 200 Hz by the main PC. The sampling rate may be increased if required. The data is saved to hard disk for later analysis, but can also be used during a test in order to generate display changes synchronised with the subject's saccades. The main PC also controls stimuli generated on an LED bar – a curved bar containing 8-mm red LEDs at 5° intervals up to ±35°. A second PC, connected to the main PC via a parallel port link, is used to display a target on a large screen (1160 by 1540 mm, 640 by 480 pixels) using a colour video projector. This allows the display of targets ±25° horizontally and ±15° vertically. A multi-tone audio generator can generate tones up to 10 kHz through either an external speaker or headphones, in which case there is a facility to control which ear the tone is received by (with variable-volume white noise received by the other). A 'bite bar', consisting of a wooden tongue depressor wrapped in dental wax, is used to hold the subject's head still during testing, at a distance of 1.5 m from the LED bar or 1.7 m from the video screen. The subject is seated in a chair, which can be raised or lowered so that the subject's eyes are at the same height as the stimulus.

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Software

The EMMA software is written in Modula-2 and runs under a DOS operating system. The software provides for file handling, calibration, eye movement tests and data analysis.

Calibration

Calibration of the IRIS instrument for saccadic tests is achieved by asking the subject to fixate at 0°, then to fixate alternately between ±15°. The sensors are adjusted so the recorded eye movements match the actual eye movements.

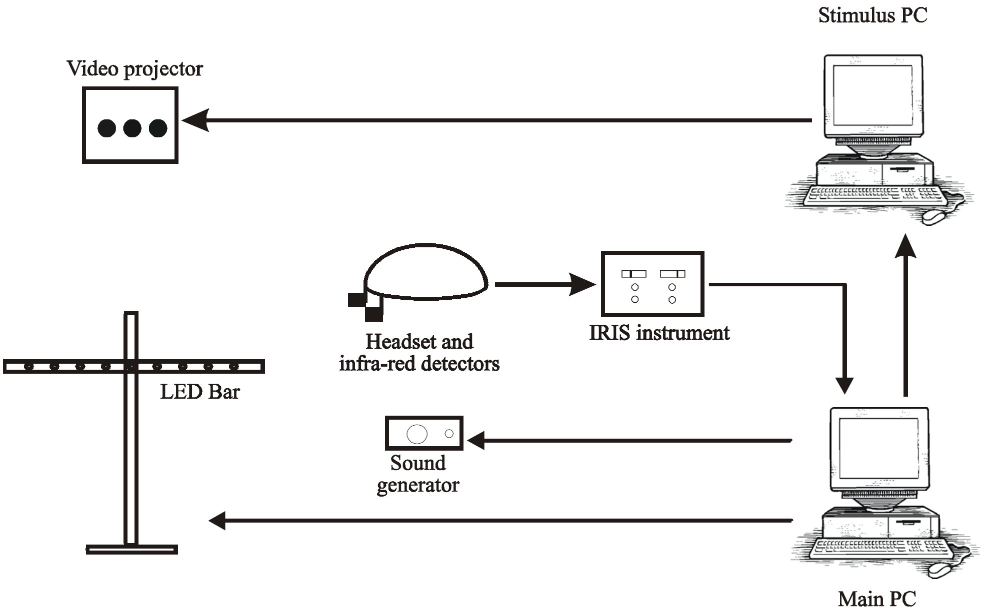

Figure 1. *EMMA system block diagram.*

Calibration for a smooth pursuit test is achieved by asking the subject to follow a target moving sinusoidally between ±20°. A display of the eye position versus stimulus position allows the operator to adjust the sensors until a straight diagonal line is viewed on the monitor; that is, the eye and stimulus positions correspond throughout the stimulus range.

The IRIS instrument is very sensitive to small changes in sensor position due to movement of the headset. The result is a zero drift or change in gain during a test. The software can correct for this based on known eye positions during the test and the use of linear regression to calculate the offset and gain factor prior to analysis of the test data.

Eye movement tests

Text files are used to define the operation of a test. Tests with irregular positions and timing use pre-generated data so the test can be precisely replicated with different subjects. A real-time display of eye position is provided on the main PC monitor during tests.

LED bar based tests

Self-paced – Subject moves eyes between two continuously illuminated LEDs positioned at equal angles left and right of centre as fast as they can within a set time period.

Predictive – Subject moves eyes between two alternately illuminated LEDs positioned at equal angles left and right of centre. A tone is given when the LED position changes.

Reflexive – Subject moves eyes to follow LEDs illuminated at irregular positions and time intervals. A tone is given when the LED position changes.

Memory-guided – While subject maintains fixation on an illuminated LED, a second LED is flashed at another irregular angle for 400 ms. After a variable time a tone is given, the subject must move their eyes to where they remember the flash to have occurred. After a set time, the LED at the position where they should have been fixating is illuminated. After another set time the process is repeated.

Sequences – Subject is asked to follow a sequence of LED positions (typically 3–5 positions) at varying intervals which can be repeated *n* times for practice. The auditory stimulus of the first position in the sequence is lower (1200 Hz) than that of subsequent positions (1700 Hz) so the subject can become synchronised more easily. On the *n*th +1 time the subject must repeat the sequence without the visual and auditory cues, attempting to replicate the position and timing of the practice sequence.

Visual reaction time – Subject fixates on the right-most of two illuminated LEDs which are positioned at equal angles left and right of centre. After an irregular interval this LED is extinguished for 50 ms and the subject moves their eyes as quickly as possible to the left LED. The process is repeated in the opposite direction.

Auditory reaction time – Subject moves eyes between two continuously illuminated LEDs positioned at equal angles left and right of centre when an auditory tone is given at irregular intervals.

Video based tests

Saccadic displacement – This generalised test allows the generation of stimuli with a new target being presented either immediately after the previous target, or after a gap period, or with a period when both targets are present. This allows the generation of standard reflexive saccades, express saccades, or overlap saccades respectively. Anti-saccades can also be generated. Additionally, in all paradigms, the saccade can trigger gaze-contingent changes

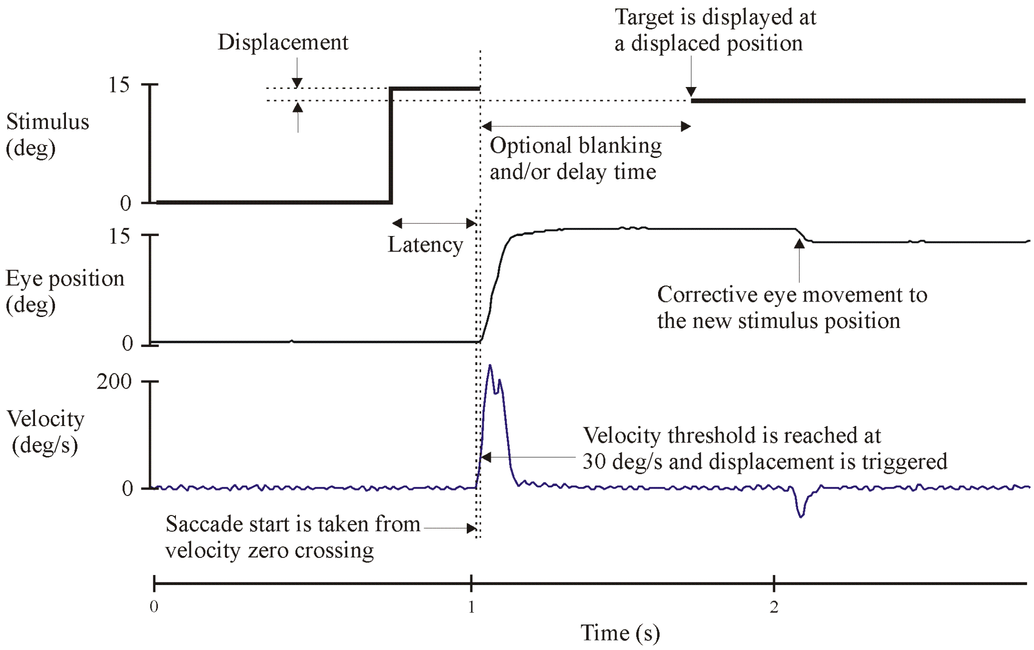

Figure 2. *Stimulus, eye position and eye velocity recordings during a saccadic adaptation test.*

in the stimulus. The target can be displaced (either during the saccade or after a set delay) or extinguished for a set period and then redisplayed at a given location (Figure 2). The target is a small square (20 mm, 0.67°) of variable colour which is superimposed onto a background image. Gaze-contingent position changes can be applied to either the target, or to the entire background image and target together.

Stimulus displacements may be horizontal, vertical or oblique, and in the same or opposite direction to eye movement. Due to intrasaccadic visual suppression, the subject will not usually see the image move if the displacement is <12.5% of the primary step[2]. The subject can provide feedback of any detected displacement by pressing a key on a keyboard. Execution of saccades to a target which is displaced intrasaccadically by a consistent direction and distance eventually leads the saccadic system to adapt the size of saccades made to a given stimulus movement[3].

Adaptation can also be induced in memory-guided saccades in a video-based test that is similar to the LED-based remembered test except that when the target reappears after the execution of a memory-guided saccade, it is at a position displaced from its original appearance.

Smooth pursuit tests – Subject aims to follow a stimulus, typically a yellow hollow circle with cross hairs (90 mm, 3° total diameter) which moves horizontally on the screen with a sinusoidal velocity. The maximum velocity of the sinusoid can be varied and is typically between 10 and 80 deg/s. Other target shapes available are a small circle (20 mm, 0.67°) and a vertical bar (10 mm by 90 mm, 0.3° by 3°).

The target can also move in a random fashion, with the random waveform generated via the sum-of-sinusoids method, which in this case was the addition of 21 harmonically related sinusoids of random phase and a fundamental frequency of 0.007 Hz. The resulting target (for a maximum target angle of ±20°) has a maximum velocity of 88 deg/s and average velocity of 27 deg/s.

Eye movement analysis

Saccades

Analysis of saccadic tests is achieved by placing three cursors at different positions on each saccade. The first cursor indicates the beginning of the saccade and can be placed automatically using a velocity threshold criterion which searches forward from the previous trial. The second cursor is placed at the end of the primary saccade, and the third at the final eye position for that trial. The software makes a 'best guess' at the positions for each cursor which the operator can check and move if necessary before measuring the data for that trial. The gain, latency and maximum velocity are measured (Figure 3) along with many additional parameters specific to each test.

Sequences

The sequence test has further measures calculated for each sequence of saccades (Figure 4) including:

- Absolute Time Index (ATI) = Rt/Tt where Rt is the response time (total time the subject takes to complete the sequence) and Tt is the target time (total time of the target sequence). The ATI shows whether a subject speeds up (ATI < 1.0) or slows down (ATI > 1.0) without the target. An ATI of 1.0 indicates the subject has kept time perfectly during a test.

- Inter-Response Index (IRI) = Ri/Rt – Ti/Tt, where Ri is the response time for the ith saccade in a sequence, and Ti is the target time for that saccade. The IRI is calculated for each saccade in a sequence except the last one because the subject remains fixated at that point and there is no measurable end point. The IRI is a measure of how well a subject has kept the rhythm during a sequence; that is, whether the time between each saccade in a sequence is correct relative to the total duration of the sequence. An ITI of 0 indicates the subject has kept time perfectly for that part of the sequence.

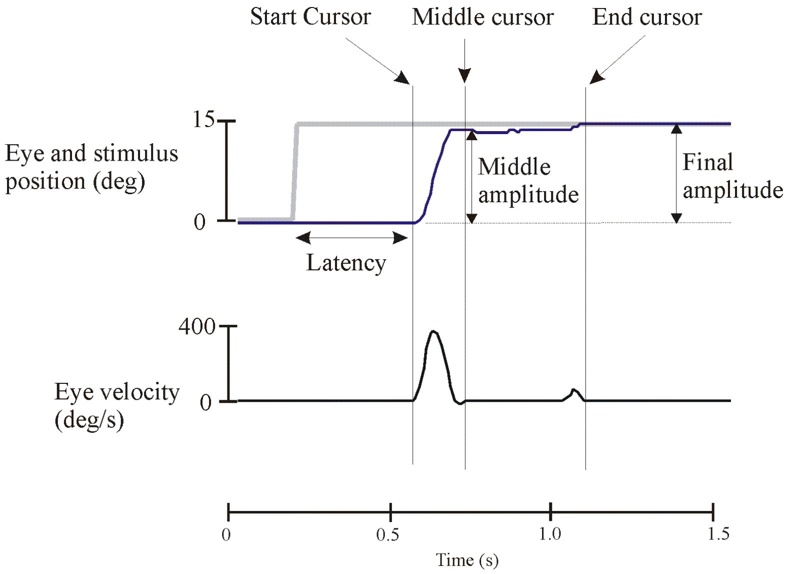

Figure 3. *Measuring the gain and latency of a saccade.*

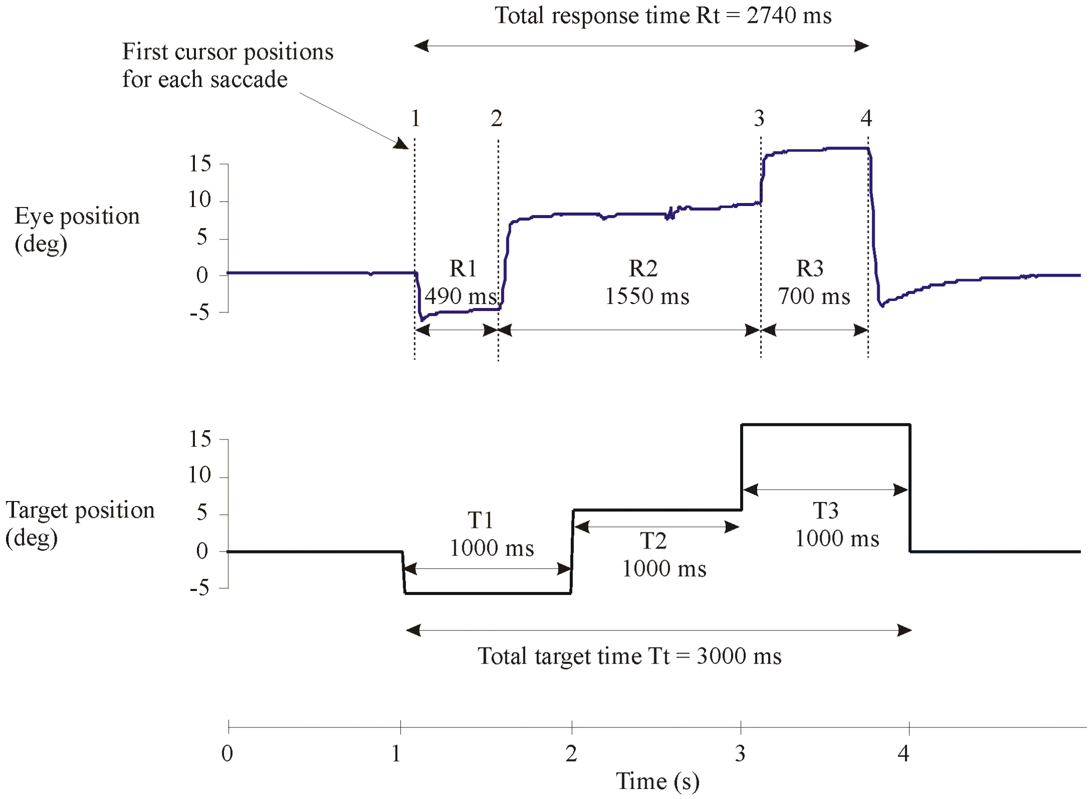

Figure 4. *Calculating the Inter-Response Index (IRI) and Absolute Time Index (ATI) for a sequence test.*
IRI 1 = 490/2740 – 1000/3000 = -0.154
IRI 2 = 1550/2740 – 1000/3000 = 0.232
IRI 3 = 700/2740 – 1000/3000 = -0.078
ATI = 2740/3000 = 0.913

Smooth pursuit

Before making calculations on a smooth pursuit test, saccades and eye blinks can be manually or automatically detected and replaced by a straight-line interpolation (Figure 5). The automatic detection of saccades is achieved using a reference velocity obtained by passing a moving average filter over the raw velocity data with a threshold to exclude the highest velocities from saccades or eye blinks that would otherwise distort the filtering process. The raw velocity is then compared to the filtered reference velocity and if a difference above a preset threshold is found then a saccade is deemed to have begun. Once the difference in velocity falls below the threshold again the saccade is deemed to have finished. A straight line is then placed between the start and end points of the saccade.

The velocity may also be filtered using a fast Fourier transform (FFT) to convert the velocity to the frequency domain, where a frequency cutoff is applied, then the inverse FFT used to convert back to the time domain.

Measures on a smooth pursuit test include:

- Average peak velocity gain (for a sinusoidal target) – the ratio of the mean of the subject's peak velocities to the target's maximum velocity (Figure 6).
- Mean absolute error – the mean of the absolute error between the subject's eye position and the stimulus at each sample in the recording.
- Gain and lag – determined from cross-correlation function of target and response (Figure 7).

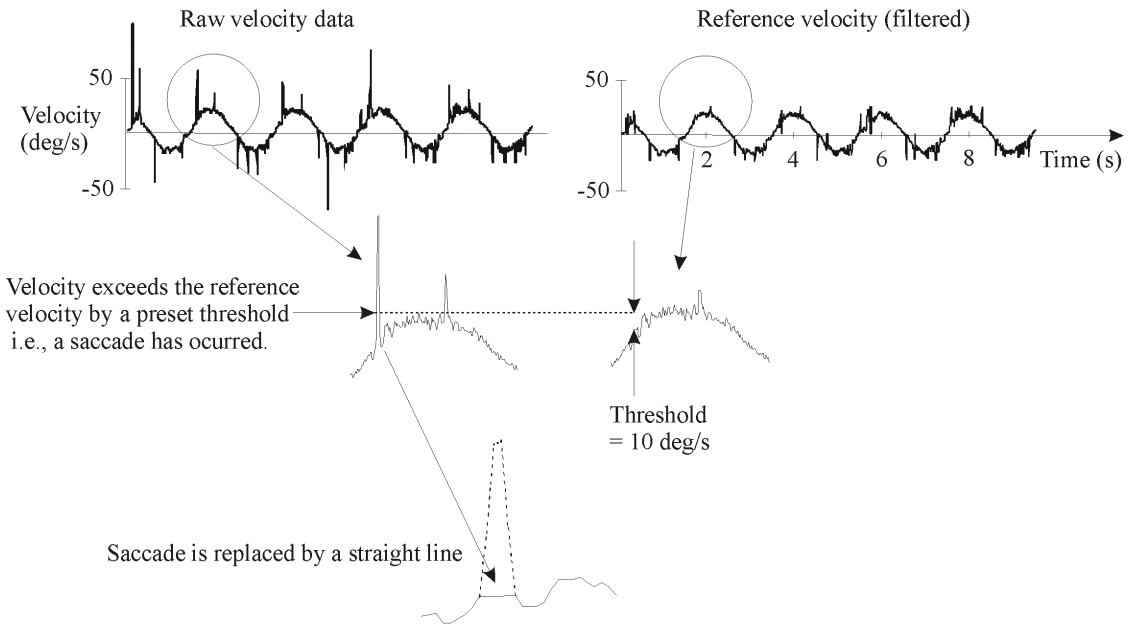

Figure 5. *Automatic saccade detection for smooth pursuit test. The reference velocity is obtained by passing a moving average filter over the raw velocity data, with a threshold to exclude any large saccades that would distort the average.*

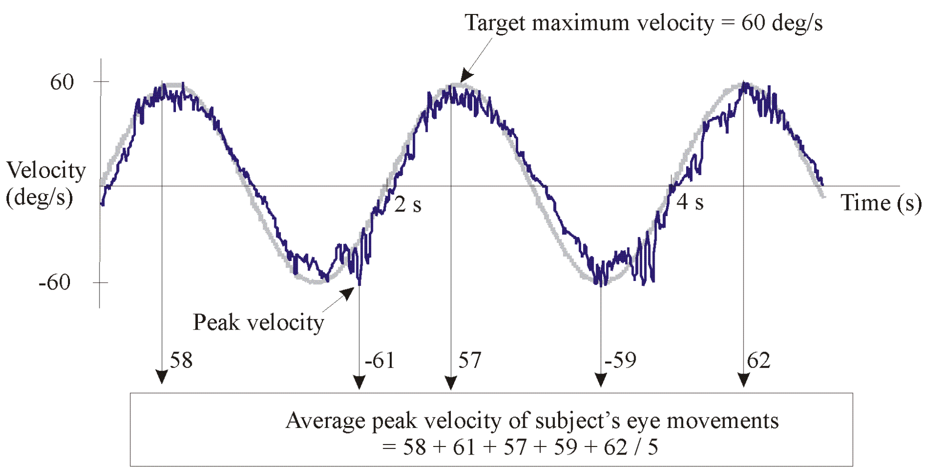

Figure 6. *Calculation of average peak velocity gain for a smooth pursuit test. The target velocity is noisy due to the differentiation of the digitised raw position data.*

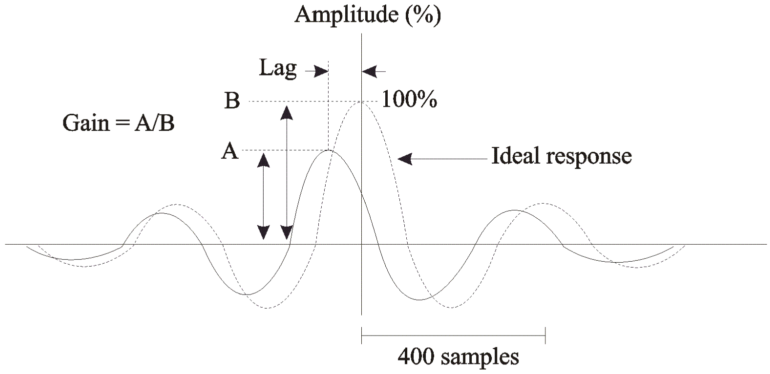

Figure 7. *Calculation of gain and lag from the cross correlation function.*

Clinical and normal research studies

The utility of the EMMA system has been ably demonstrated in a number of research studies on subjects with neurological conditions as well as in investigations of oculomotor and visual phenomena in normal subjects.

The precision and accuracy of the recordings has been shown in several investigations. Small amplitude benign upbeat nystagmus, detectable by clinicians only on inspection by ophthalmoscopy, has been recorded and quantified using the EMMA system[4]. A study of internuclear ophthalmoplegia (INO) required the simultaneous accurate recording of the velocity of each eye during saccades. INO is a disorder, common in multiple sclerosis (MS), which results in the adducting eye having a slower velocity than the abducting eye. Subjects were categorised as having an INO if the ratio of their abducting to adducting eye velocity exceeded the normal range. This objective diagnostic criterion was used in a signal detection study to assess the ability of neurologists and neurology registrars to detect INOs using the traditional clinical method[5]. There was a wide variation in the ability of those clinicians to accurately diagnose the condition.

Saccadic reaction times (latencies) are easier to measure accurately than are eye movement amplitude or velocity, with precision limited only by the sampling rate (generally 200 Hz). In one study, the latencies of MS subjects performing visually-guided saccades were shown to be prolonged relative to controls whereas their auditory-guided latencies were normal[6], confirming that the commonly observed long latency of MS saccades is due to visual delays rather than motor delays. The differences were significant and of the order of 20-30 ms.

The ability of the system to respond to saccades in real time and to change the visual display within the time course of a saccade has allowed us to study oculomotor and perceptual responses to intrasaccadic target displacements. People remain unaware of intrasaccadic target displacements if they are less than a certain size. We have investigated a number of factors which influence the magnitude of the effect[2, 7]. Additional studies have shown that a person with pathologically slowed saccades was able to appropriately modify her saccades in-flight in response to intrasaccadic displacements of which she was not consciously aware[8], and that subjects with Parkinson's disease are less able to modify the size of their memory-guided saccades in response to target displacements[9, 10].

The system has also been utilized in studies designed to look for and characterize oculomotor deficits in persons with developmental stuttering[11], cerebellar disorders[12], and mild closed head injury[13-16].

Conclusion

The EMMA system allows a comprehensive range of eye movements to be tested and analysed with relative ease. The effectiveness of EMMA has been demonstrated in a wide variety of studies of normal and abnormal oculomotor function.

Further development of the system is continuing, with the addition of new tests and analysis techniques, and a migration of further tests to the video rather than LED display.

References

1. Reulen, J. P. H., Marcus, J. T., Koops, D., de Vries F. R., Tiesinga, G., Boshuizen, K., and Bos, J. E., *Precise recording of eye movement: the IRIS technique Part 1,* Medical and Biological Engineering and Computing. 26: 20–26, 1988.
2. MacAskill, M. R., Muir, S. R., and Anderson, T. J.*, Saccadic suppression and adaptation: revisiting the methodology.* In W. Becker, H. Deubel, and H. Mergner Eds, Current oculomotor research: physiological and psychological aspects. Plenum, New York, pp. 93–96, 1999.
3. McLaughlin, S. C., *Parametric adjustment in saccadic eye movements,* Perception and Psychophysics. 2: 359-362, 1967.
4. Anderson, T. J., and MacAskill, M. R., *Upbeat nystagmus on ophthalmoscopy: a benign entity,* International Journal of Neuroscience. 97: 269, 1999.
5. Young, E., Lynch, A., Anderson, T. J., and MacAskill, M. R., *Internuclear ophthalmoplegia in multiple sclerosis,* International Journal of Neuroscience. 97: 270, 1999.
6. Young, E., Anderson, T. J., Carroll, G. J., MacAskill, M. R., and Jones, R. D., *Auditory and visual evoked saccadic latency in multiple sclerosis*, New Zealand Medical Journal. 113: 403-404, 2000.
7. MacAskill, M. R., Anderson, T. J., and Jones, R. D.*, Throwing light upon saccadic suppression of displacement in the dark,* New Zealand Medical Journal. 113: 108, 2000.

8. MacAskill, M. R., Anderson, T. J., and Jones, R. D., *Suppression of displacement in severely slowed saccades*, Vision Research. 40: 3405–3413, 2000.
9. MacAskill MR, Anderson TJ, Jones RD., *Adaptive modification of saccades*. In: J Hyönä, D Munoz, W Heide, R Radach (Eds.), The Brain's Eyes: Neurobiological and Clinical Aspects of Oculomotor Research. Oxford: Elsevier Science, in press.
10. MacAskill M. R., Anderson T. J., and Jones R. D., *Adaptive modification of saccade amplitude in Parkinson's disease,* Brain. 125: 1570-1582, 2002.
11. Anderson, T. J., Gaskill, B., and Ormond, T., *Saccadic eye movements in stutterers*, Journal of Clinical Neuroscience. 2: 371, 1996.
12. MacAskill, M. R., and Anderson, T. J., *Latencies of reflexive and predictive saccades in cerebellar predominant multiple sclerosis,* New Zealand Medical Journal. 110: 401, 1997.
13. Anderson, T. J., Heitger, M. H., Jones, R. D., Ardagh, M. W., and Donaldson, I. M., *Oculomotor deficits after mild closed head injury,* Journal of Neurological Sciences. 187: S432, 2001.
14. Heitger, M. H., MacAskill, M. R., Anderson, T. J., Jones, R. D., Ardagh, M., and Donaldson, I. M., *Subconscious saccadic adaptation is not affected by mild closed head injury,* New Zealand Medical Journal. 114: 480, 2001.
15. Heitger MM, Anderson TJ, Jones RD., *Saccadic sequences as a marker of deficits in closed head injury*. In: J Hyönä, D Munoz, W Heide, R Radach (Eds.), The Brain's Eyes: Neurobiological and Clinical Aspects of Oculomotor Research. Oxford: Elsevier Science, in press.
16. Heitger MH, Anderson TJ, Jones RD, Ardagh M., *Recovery of oculomotor, visuomotor and neuropsychological deficits following mild closed head injury*. New Zealand Medical Journal. In press.