Fusional vergence eye movements in microstrabismus
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5. Methods

5.1 Eye movement recording techniques in general

Several methods have been described in the literature for the recording of eye movements. In general, the following techniques can be distinguished:
- direct viewing
- motion picture recording
- photo-electric viewing
- devices using reflection
- electro-oculography
- electromagnetic search coil
- photo-electric oculography (detailed in 5.2).

The different methods will be explained in some detail now.

Direct viewing and motion picture recording

Movements of the eyes can be measured with a travelling microscope, using blood vessels as reference marks. If the microscope is fitted with a cine camera, permanent recordings of eye movements can be made. With the development of fast cine film it became possible to photograph the whole eye at high speed and thus record rotations about the three axes simultaneously. The time resolution of this method is limited by the speed of the camera and the emulsion, and can hardly be better than 10 msec. The eye positions have to be measured from the film and the corresponding directions of the visual axes have to be calculated. This may be very time consuming. An advantage of this method is that binocular vision can be maintained (no dissociation is used).

Photo-electric viewing

A variety of techniques involve the projection of light on the eye and a photosensitive device that responds to the light reflected from the eye. For instance, a spot of light can be projected on the limbus, with a nearby photoresistor arranged to pick up the scattered light (Blakemore and Carpenter, in Carpenter, 1977). If the reflected light is not all received by the transducer, the quantity of light received by the transducer is more or less proportional to the area of sclera lying under the spot of light. This device can behave linearly over a range of some $10^4$, with a time resolution of 10 msec.

An extension of this method was introduced by Nykiel and Torok (Carpenter, 1977); the eye is diffusely illuminated with infrared and viewed by four photodetectors disposed symmetrically round the orbit. The whole assembly can be mounted on goggles worn by the subject; this eliminates problems related to head movements. This method is an early version of the infrared method used in our study, see section 5.2.
Devices using reflection

Light reflected on discontinuities in refraction index can also be used. Four reflected images can be formed when the light of a bright spot traverses the optical surfaces of the eye. These images are called Purkinje images. The first image is formed by the front surface of the cornea. The back of the cornea and the front and back surface of the lens form the second, third and fourth Purkinje image.

The centre of rotation of the eye is not identical to the centre of curvature of the cornea, therefore a device that observes the first Purkinje image can measure eye movements; it is about half as sensitive as one that, for instance, looks at the border between the sclera and the iris.

A method using the fourth Purkinje image was devised by Cornsweet and Crane (Carpenter, 1977). They use the first and the fourth Purkinje image, because these move in relation to one another on torsional movements. The marked curvature of the cornea makes corneal reflection unduly sensitive to small translations. A plane reflecting device, for instance a mirror mounted on a contact lens, can reduce this sensitivity.

Queré (1981) used electro-oculography (EOG) to study vergence movements. In EOG, movements of the eye are recorded indirectly by periorbital electrodes. The cornea is approximately 1 mV positive with respect to the retina, a situation that creates an electrostatic field that moves with the eye movement. The range of measurement is $1^\circ$ to $40^\circ$ with a resolution of $1^\circ$. Frequent calibration is essential because of non-linearity and drift. For quantitative studies direct-current oculography is required, but it is very difficult to solve problems of baseline drift. For electro-nystagmography, alternating-current coupled EOG is good enough, but stable eye position cannot be recorded in that case.

Robinson (1963) described the scleral search-coil in a magnetic field. When the subject is exposed to an alternating magnetic field, eye position may be accurately recorded from the voltage generated in an 8-shaped coil of wire embedded in a scleral contact lens worn by the subject. Horizontal, vertical and torsional eye movements can be measured. A resolution of 15 seconds of arc and a linearity of about 2 % of full scale is claimed. This is the most accurate and most versatile method available, but it is not a contact-free technique which makes it of limited utility when large groups of young people have to be screened. The contact lens can give complaints of discomfort, certainly when the recording procedure takes several hours, as is the case in our experiments which we will describe below.

5.2 Selected method

Our method of choice had to be contact-free, and suitable to be used for recording eye movements in young children. The infrared photo-electric method can be used for a long time without any discomfort for the subject. This was important because the experiment lasted at least one hour.

Infrared photo-electric oculography ("infrared reflection") is a method based on the
principle of reflection of infrared light by the sharp boundary between iris and sclera, the limbus. A set of infrared light-emitting diodes and a set of infrared-sensitive detectors are mounted on the head in front of each eye so that the receptive fields match the iris-sclera transition, both on the nasal and on the temporal side. Upon horizontal rotation of the eye, for example in the case of abduction, the nasally positioned detector will measure an increased scleral infrared reflection, while the temporally placed detector measures a decreased iris reflection. Subtraction of the nasal and temporal detector signals gives a measure for eye position with respect to head position.

Various reflection systems have been described with several serious drawbacks such as a limited linear range, complicated and time-consuming installation and calibration procedures and poor mechanical stability of the transducer with respect to the eye.

In our experiments, the horizontal eye movements were recorded with the IRIS system (Reulen et al., 1988).

We summarize from Reulen et al.'s paper (1988) the following description of the IRIS system: The infrared light transducer consists of an array of nine infrared light emitting diodes (LED's type Siemens LD 269) and nine phototransistors (type Siemens BPX 69). Maximum infrared-light emission of the LEDs is at a wavelength of 950 nm, and the maximum sensitivity of the detectors lies at a wavelength of 850 nm. So there is a reasonable overlap.

The oscillator generates a square wave signal with a frequency of 2.5 kHz. The wave drives the current source, feeding a 50 mA current through all nine infrared light emitting diodes, which are mounted in parallel in the circuit. To measure horizontal
eye position, the signals picked up by the most laterally located infrared-light detectors, (nasally the numbers 1+2 and temporally 8+9) are summed pairwise and then the sums are subtracted. The resulting signal (marked S1 in figure 5.1) is a 2.5 kHz chopped signal, modulated by the amplitude of the eye-movement signal. This signal passes a bandpass filter (centre frequency 2.5 kHz, rolloff 12dB/octave) and after that the resulting signal S2 is multiplied by the square wave signal to produce S3 (figure 5.1). This signal S3 passes a low pass filter (DC-100Hz; -3 dB) and is amplified, thereby demodulating the eye movement amplitude signal. Using a Labmaster TM40 analogue/digital converter, the amplitude signals were read into an Olivetti M24-SP personal computer. The stimulus signal, the position of each of the two eyes and the signal for the difference in eye position were stored. The sample frequency was 200 Hz for each channel. The vergence signal is derived from the change in the relative position of the two eyes.

For the data acquisition and data analysis, software was used that has been developed by the Neuro-ophthalmological System Group (Dr. G.H. van der Heijde, department of Medical Physics of the University of Amsterdam) and the technical section of the department of Ophthalmology at the University of Groningen. With the infrared device horizontal eye movements can be recorded linearly up to excursions of 30° (Reulen et al., 1988).

Sources of artifact in infrared recording of eye movements were investigated by Truong and Feldon (1987). They used an infrared device with two photodiodes (Texas Instruments) and found a range of linearity from -15° (left) to +15° (right) of the primary position. Non-linearity was found when the photodiodes were displaced horizontally. Displacement of the diodes towards the pupil caused artifacts because of reflection from the pupil and the contralateral iris. These artifacts became more obvious with increasing eccentricity of the eyes from the primary position. This could be confirmed in our own experiments (Koopmans, 1988).
5.3 **Experiment configuration**

![Diagram](image)

**Figure 5.2**
Experiment configuration.

- **A_L** and **A_R**: Transducers and polaroid filters (horizontal and vertical; inserted in the transducers)
- **B**: Polaroid filters (horizontal and vertical)
- **C**: Two pairs of mirrors, one of each pair is mounted on a galvanometer
- **D**: Projectors
- **E**: Galvanometer driver
- **F**: Projection screen
- **G**: Subject

G is the subject, with the transducers in front of the eyes. In each transducer the polaroid filter was inserted (A_L, resp. A_R). The subject had to fixate binocularly on the diagram projected on the screen (F) with polaroid filters in front of each projector. During calibration the polaroid filters B were removed. A step change of disparity could be given by a sudden displacement of one of the mirrors (C) mounted on a galvanometer driven by a galvanometer driver (E). If the mirror corresponding to the right projector moved, the image for the right eye was displaced (corresponding polarisation of A and B). A similar mechanism was used for the left eye. The step change could be given in a convergent and in a divergent direction, and back to the original position. In this thesis back to the original position from convergence is called convergence relaxation. Divergence relaxation means back to the original position from divergence.

5.4 **Target Presentation**

The subject was comfortably seated with his head on a chin rest. After the calibration procedure, crossed polaroid filters were added on the projectors. Two
crossed polariser slide projectors were used and image displacement was induced by rotating a deflecting mirror. Two identical contrast-rich images (figure 5.3) were presented at a distance of 2.86 m. This image was used earlier by Crone (1975). The subjects were instructed to focus on the tip of the nose. The experiment was done in a dark room. The subjects were instructed not to move their heads; they were wearing their own glasses.

![Contrast-rich image](image.png)

**figure 5.3**
Contrast-rich image (Crone, 1975).

A complex image was chosen because simple images such as dots or lines may not induce motor responses when this response has to be based on peripheral fusion. The diameter of the projected image was 33 cm. At a distance of 2.86 m this is seen under an angle of 6.6°.

### 5.5 Calibration

#### 5.5.1 Calibration and data acquisition

After establishing an optimal position for the transducer for the left eye and the transducer for the right eye, the subject had to fixate the image. The unpolarized image was moved in the form of a square wave over a distance of 25 cm on the screen. The distance between the subject and the screen was 2.86 m. This induces eye excursions of 5° (arctan 0.25/2.86). About 12 square-wave stimuli were given with a frequency of 0.25 Hz (T=4 sec). The positions of both eyes were recorded, see figure 5.4.
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5.5.2 Calculation of the calibration signal

Artifacts such as blinks were removed. To exclude an artifact at least one period but possibly more periods had to be removed (figure 5.5).

After this an X/Y plot could be made with on the Y-axis the signal derived from the right eye and on the X-axis the signal derived from the left eye's excursions. Now with least squares analysis, the relation between the signals from the right eye and the left eye could be calculated automatically (figure 5.6).

\[ y = mx + n \]

where \( m \) = slope and \( n \) = offset

\( m \) should be close to one and is the ratio of the amplifications of the two channels.
n represents the correction for the signal from the right eye necessary for obtaining the same reading for both eyes if they fixate at the same spot.

After this procedure, the calibration signal is drawn again, now with the signals for the right and left eye matched (figure 5.7). It is known that excursions of $5^\circ$ are made. Therefore, an absolute calibration can be made in degrees per volt by reading the example values when the cursor is positioned on both the maximum and minimum "equal" levels.
The calibration file was not accepted, and thus the recording rejected, in cases where drift in the signal was seen during recording of one or both eyes, when too many artifacts (blinks) were found in the calibration file, or when the factor m was < 0.5 or > 2.0.

After this procedure the vergence signal was derived from the change in the relative position of the two eyes by subtracting the two eye position signals.

5.6 Recording procedure

After calibration, eye movements were recorded with polarized images during stimulation with excursions of the image corresponding to 2 and 4 prism diopters. Then again a calibration session followed, after which 6 and 8 prism diopter stimulations were recorded. After recording stimulation of the right eye, the same procedure was followed for the left eye. The step change was induced by tilting one of the two mirrors on a galvanometer, as was already shown in figure 5.2. Each stimulus was given 4 or 5 times, or less when the subject reported diplopia. Because diplopia occurred more often in divergence, many more responses occurred when the stimulus was convergence or convergence relaxation, than when the stimulus was divergence or divergence relaxation. See appendix A.
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</tr>
</tbody>
</table>

**Table 5.1**
Prism diopters and corresponding degrees

The starting position of the experiment was an identical projection of each projector (i.e., images superimposed). Because of the distance to the screen (2.86 m) and the pupil distance of e.g. 63 mm this means a convergence of $1.28^\circ$ in the neutral position, and a corresponding convergence angle for other pupil distances.

Just before until about 5 seconds after each stimulus, the eye movements were recorded, (see figure 5.8 trace A and B; variables D and E result from later processing).
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Figure 5.8
Screen dump from recorded signals.
A = right eye
B = left eye
C = stimulus
D = vergence velocity
E = vergence (left eye - right eye)

C = Upward means convergent stimulus in the right eye or divergent stimulus in the left eye, downward means divergent stimulus in the right eye or convergent stimulus in the left eye.

5.7 Derived parameters and descriptors

The following characteristics are calculated automatically, having been indicated manually on the computer screen by means of cursors:

1. Maximum velocity (Vm)
2. Vergence latency (Vl)
3. Response amplitude (Ra)
4. Response duration (Rd)
5. Latency first saccade in expected direction (Sl)

![Figure 5.9](image)

Figure 5.9 shows the location of these dynamic characteristics. A short explanation can be given as follows.

1. **Vergence latency** is defined as the time that elapses after presentation of the stimulus until the first obvious sign of vergence is observed.

2. **Response amplitude** is the absolute value of the first maximum in the vergence amplitude after the stimulus, possibly, therefore, during an "overshoot". In other words, always in the direction of the stimulus.

3. **Maximum velocity**. The vergence velocity is the first derivative of the vergence. Its peak value after the stimulus is the maximum velocity. Usually the vergence velocity also showed a peak value at the moment of the saccade. Peak values that coincided with the saccades were not accepted (see figure 5.9). One reason for this peak value could be imperfect calibration. Another reason is an inequality of the saccade. This has also been described by Hung (1994). The vergence velocity artifact was easy to recognize once the sampling frequency was increased from 100 Hz to 200 Hz, the artifact was then identified as being related to the saccade.

4. **Response duration** is defined as the time that elapses after 10% of the vergence...
response was seen, until 90% of the vergence response was reached.

5. Latency first saccade, this is the time that elapses after the stimulus until the first saccade that occurs and is related to the stimulus (a step-wise stimulus of the right eye in a convergent direction is usually followed by a saccade of the right and left eye to the left and vice versa (Straub, 1989)).

We also scored whether or not the saccade that followed the stimulus was related to the stimulus (in the direction of the shift of the image, see below).

A latency higher then 2000 msec was rare. But the response duration was only limited by the length (in time) of the computer screen, which was 5 seconds. The time that elapsed between two stimuli was usually about 5 seconds (one screen length). The stimuli were given in a random direction at variable intervals. If, incidentally, less than 1000 msec elapsed between two stimuli, only the response to the second stimulus was processed.

![Figure 5.10](image)

**Figure 5.10**
Velocity (=V) (the small amplitude signal), and acceleration (=A), the second derivative of the vergence.
Apart from these five parameters for which numerical values were obtained, several qualitative descriptors were also derived from the recordings:

The shape of the velocity and vergence recording was described in terms of five items:
1. One peak/ more peaks (example in figure 5.11) (vergence velocity)
2. Overshoot or no overshoot (example in figure 5.12) (vergence)
3. Prolonged response (example in figure 5.13) (vergence)
4. First saccade in the direction of the stimulus or not (right eye / left eye)
5. Acceleration related to the stimulus or not (acceleration)

Acceleration, the second derivative of the vergence was computed automatically and displayed. Only accelerations clearly related (in time) to the stimulus were taken into account (see figure 5.10).

figure 5.11
More peaks in vergence velocity (D). (see arrows).
Motor responses were recorded both after stimulation of the eye and after removal of the stimulus, for example convergence and convergence relaxation (C-), which is used to indicate removal of the convergent stimulus. Hard copies of all vergence
recordings were made and the parameters mentioned above were calculated and scored by the same person (the author). The computed data were aggregated for each subject, and groups of subjects were compared.