

## Eye Position Prospectus Prospectus for measuring eye movements

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There are several resources discussing the recording of eye movements in young infants. Of these, Hainline (date; Hainline & Abramov, 1985), Aslin (1985), and Shupert and Fuchs (1988) present the issues involved, and have corresponding reviews of the development of infant eye movement. Several other sources discuss infant eye movement recording with the electrooculogram (EOG) (Finocchio, Preston, & Fuchs, 1987; Regal, Ashmead, & Salapatek, 1983; Shupert & Fuchs, 1988) and corneal reflection techniques (Bronson, 1982, 1983; Hainline, 1981; Hainline & Lemerise, 1985; Haith, 1969, 1980).

Five issues are important in the eye movement research. Transducer: The first question is what measuring device to use to obtain raw (uncalibrated) eye position. With infants, this is a choice between EOG measures and video-based corneal reflection techniques (Aslin, 1985; Shupert & Fuchs, 1988). Calibration: Researchers usually assume that the fovea is the "visual center". However, infants may view a stimulus with foveal or para-foveal areas. Most applications assume that the "visual center" correspond to foveal center, and calibration of raw eye position signals is done against fixated stimuli of known degrees. Head movements must also be restrained, or measured and accounted for, to achieve accurate calibration of EOG measures. Resolution: Resolution is the minimum shift in visual angle that can be detected with the system. To achieve high resolution with adults, the head is fixed in position, allowing large magnification of the eye for corneal reflection. It is difficult to restrict infant head movement, and thus resolution of the eye movement system is a problem. Accuracy: Accuracy is the difference between the actual eye position and the computed eye position. Identifying eye movements: After obtaining eye movement information, the position of the eye over time must be evaluated. This leads to the identification of fixations, saccades, smooth pursuit movements, slow drift, and head movements.

### Transducer: Corneal reflection versus EOG

There are several eye movement techniques that can be used with adults which give sensitive, accurate eye movement positions. Perhaps the most accurate is the use of magnetic coils over the eye, and the measurement of the magnetic field disturbances caused when the eye moves the coil through the magnetic fields. However, the magnetic coils must be implanted (Fuchs & Robinson, 1966; Judge et al., 1980) or placed on the eye with contacts (Collewyn et al., 1975; Kenyon, 1985; Robinson, 1963), making it unsuitable for infant research. With infants, video-based corneal reflection and EOG are the two most practical techniques. Direct comparisons of eye movement techniques have been done with adults (e.g., Abel, Wall, Troost, & Black, 1980; Fey, 1982; Koga & Osaka, 1983; Schlag, Merker, & Schlag-Rey, 1983). Such comparisons do not exist for infant subjects.

The corneal reflection technique is based on video systems. An infrared light is shined upon the eye. The reflection of the fixed light source relative to the camera is compared with the pupil center. If the corneal reflection matches the pupil center, the fixation is directly at the camera. Deviations of the corneal reflection from the pupil center show how much the pupil/eye/fovea deviates from the center. This system has temporal resolution of 30 or 60 Hz, which is sufficient for most eye movements (usually 1 to 5 Hz fastest). The spatial resolution depends on the camera lens size and distance of the eye from the lens. With adults, and fixed head positions (< 2 cm head movement), spatial resolution can be as small as 0.1°. Infant subjects, however, have head movements, errors, and require recalibration. This usually results in resolution of no greater than 3 to 5°.

Another system for measuring eye movements is based on measuring EOG and head movement (Regal et al., 1983; Regal & Salapatek, 1983; Roucoux et al., 1982, 1983). The EOG measures the corneoretinal potential with surface recording electrodes attached to the outer canthi (horizontal) and above and below one eye (vertical). The electrical potential of the cornea is positive with respect to the retina because of the higher metabolic rate of the retina. When the eye moves in the horizontal or vertical direction, the positive pole of the corneal potential approaches one electrode. The other electrode is approached by the negative pole. The potential difference between the electrodes gives the position of the eye relative to the head. If the absolute position of the head is known, the position of the eye may therefore be calculated. Recording of a DC potential difference results in linearity of the response across a wide range of eye movements (40-50°; Fey, 1982; Schupert & Fuchs, 1988). AC recording results in linearity across 30°. The AC linearity depends on the time constant of the AC recording (lower bandwidth), sampling rate, and the speed of the eye movements involved.

The advantage of the corneal reflection and video systems is presumably the increased resolution that can be achieved. Researchers and system manufacturers claim that the resolution of the eye movements with corneal reflection can be as much as 0.05°, whereas EOG resolution may only be 1 or 2°. Resolution in video-based systems is proportional to the magnification of the eye in the video systems. With increased magnification, the field of view of the camera becomes smaller. The resolution of 0.05° is obtained by allowing head movements of 2 cm or less in the vertical and horizontal planes. This can only be achieved with stimulus presentations in a fixed position, e.g., a TV monitor or slide screen. This requires the head to be in a fixed position in order because the field of view of the camera on the eye is very small. This requires head restraint, such as a bite bar. Another advantage of the corneal reflection technique is the existence of computer-based systems which calculate eye position in real-time (usually 60 Hz). This automates the process of giving uncalibrated eye position for large amounts of data. The video basis of the corneal reflection technique can also result in errors due to parallax effects, corneal curvature differences at different eccentricities, video distortion, and effects of the infrared reflective light (Abel et al., 1980; Bronson, 1983; Hainline & Lemerise, 1985; Slater & Findlay, 1975).

There are several reasons that EOG systems may be preferred. Those in the present studies that are of interest revolve around the restricted head movements demanded by the video-based corneal reflection technique. The EOG has the distinct advantage of allowing unlimited head movements. Young infants (and many mammals) accomplish target localization with a combination of head and eye movements. Thus, both eye and head movements must be taken into account for target localization at all but the smallest eccentricities. Infants do not tolerate head restraint well, although it is often used in infant corneal reflection procedures (e.g., Hainline, 1981; Hainline et al., 1984; Aslin, 1981). This may result in 40 to 60% subject attrition rates. While not especially high for infant studies, this may eliminate certain subjects who look away from the central stimulus often, leading to attrition of certain types of infants.

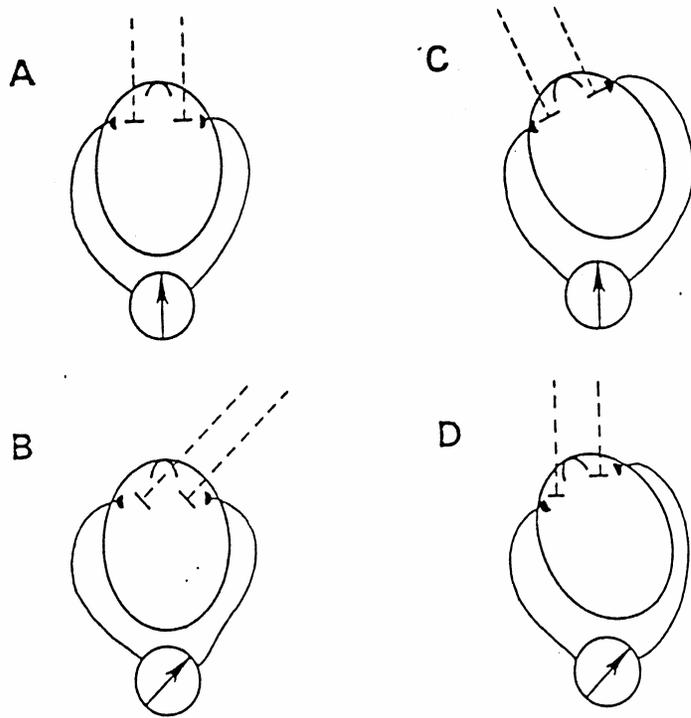


Figure 4. Schematic illustration of the EOG signal, represented by the arrow, recorded from a subject whose head is directed either straight ahead (A and B) or to the left of midline (C and D).

The advantage of allowing head movements for EOG recording is also its disadvantage. As Aslin (1985) discusses, EOG records eye position relative to the orbit, or head position. If the head is stationary, then the recorded EOG values accurately reflect eye movement across the stimulus field (Figure 1, panels A & B). However, different head positions would result in different EOG values even with the eyes fixated on the same

target (Figure 1, panels A & D). Thus, to use EOG, one must account for head movements. This can be done by keeping the head stationary (e.g., Aslin & Salapatek, 1975), or by measuring both head and eye movements (e.g., Regal et al., 1983; Regal & Salapatek, 1983; Roucoux et al., 1982, 1983).

Spatial resolution may actually be better with EOG than corneal reflection techniques, since the former requires only good physiological recording techniques, whereas the latter requires head restraint. Shupert and Fuchs (1988) point out that many eye movement studies with infants assume errors in eye movement measurement of 3-4° (e.g., Hainline & Lemerise, 1985; Hainline et al., 1984), and exclude eye movements smaller than 2°. Effective absolute resolution may be more near 3-4° than the 0.5° which is the highest resolution obtained with the video system. Others have argued that using EOG and head movements for infant subjects results in equal resolution to corneal reflection techniques (e.g., Finocchio et al., 1987). Studies of the infants "visual field" use peripheral target eccentricities of up to 40°. The range of the EOG with head still is near +/- 30° with AC recording, and +/- 40-50° in DC recording, whereas with corneal reflection techniques it is +/- 10-15°. Thus, even with head restraint, EOG may be preferred in certain types of studies (e.g., Aslin & Salapatek, 1975). The temporal resolution video systems is 30 or 60 Hz, which depends on the sampling rate of video signals. Infant (and adult) eye movements typically are in the 5-8 Hz range, so the 60 Hz systems are sufficient. The EOG can be sampled continuously, so any level of temporal resolution can be obtained.

The system for the current studies uses recording of EOG and head movements. The combination of head and eye movement gives both eye position and head position. The eye position is recorded with the EOG, and head position from a video recording of head movements. A calibration procedure similar to that of Harris et al. (1981) and Woestenburg et al. (1984) calibrates the "visual center". The location of the head in space, and the calculated degree deviation of the eyes from the head, provides the criteria against which the EOG is calibrated.

#### Hardware

The EOG measures eye position relative to the head. The EOG is recorded with 6 mm electrodes placed posterior to the outer canthi of the two eyes for horizontal eye position, and placed above and below the left eye for vertical eye position. Biopotential gel (or electrode paste) is the electrical conductor. The electrodes are attached to the skin with adhesive collars (10 mm diameter), and paper tape stabilizes the attached wires. The gain of the amplifiers is the same for all subjects, which seems to capture the potential differences within an eye movement. Amplifiers record the potential difference from DC to 100 Hz with a 60 Hz notch filter. All studies use horizontal eye movement, and DC recording. Some of the studies, which use only horizontal eye movement, record the EOG in the vertical positions for error corrections (e.g., blinks). The vertical EOG in this case are recorded with AC recording techniques, using a 0.01 sec time constant (high pass filter from 16 Hz). The sampling rate of the EOG is 100 Hz (10 msec). The analog-to-digital device has a resolution of 12 bits (0-4095 units). The amplification for EOG for peripheral detection studies is 0.5 mv/cm on a Grass 7 polygraph, which corresponds to 60 ADC units/mv. A comparison was made for 15 subjects with 0.2 mv/cm and 10 subjects with

0.5 mv/cm. It was found an amplification of 0.5 mv/cm, though less sensitive than 0.2 mv/cm, resulted in greater accuracy in the eye movement data. The gain settings on the amplifiers, and the known analog-to-digital converter (ADC) units/voltage can be used to calculate millivolt (mv) potential differences for EOG. However, the relation between ADC values and mv levels is linear and constant, based on the polygraph and ADC hardware. Thus, the raw ADC values can be used. EOG recordings are visual inspected with computer-displays. Obvious error data (e.g., blink or movement artifacts, irregular recording, drifts outside of polygraph range) are discarded.

Since the EOG measures eye position relative to the head (Aslin, 1985), the head must either be restrained, or head movements must be measured (e.g., Regal et al., 1983; Regal & Salapatek, 1983; Roucoux et al., 1982, 1983). We chose to allow head movements, since that is an integral part of target tracking and localization in the young infant. Two methods will be used for head movements. First, EMG will be recorded bi-laterally on a muscle pair responsible for initiating head movements. EMG will be recorded to identify the initiation of the head movement, which should be followed by the overt head movement after some bio-mechanical delay. Slight skin abrading will be used to lower the skin impedance to 50 kohms or less. Miniature electrodes (6 mm) filled with electrode paste or gel will be attached with adhesive electrode collars (SensoriMedics). The electrodes will be placed between .6 and 1 cm apart center-to-center (6 to 10 mm), as close as possible to either the sterno-cleido-mastoid muscles, or the splenius muscles. The sterno-cleido-mastoid muscle acts as a agonist for contralateral horizontal head movement, and the splenius as an agonist for ipsilateral movement. The EMG will be amplified by a Grass 7P3 preamplifier, using a .01 sec time constant (high-pass filter from 16 Hz), and allowed 90% at 10 KHZ and 50% down at 20 KHZ. The EMG signal will be full-wave rectified and integrated, and will be sampled at 1 msec intervals (1 KHZ) with an analog-to-digital conversion. The EMG amplitude will be adjusted for each subject to maximum sensitivity while remaining within the scales of the polygraph and computer. Analog-to-digital units (0-4095) will be used for analyses. The EMG will be analyzed for onset and peak EMG activity latency following the onset of the peripheral stimulus. The agonist muscle activity precedes overt head movement by 40-50 ms, whereas antagonist muscle activity coincides with the overt movement (Zangmeister & Stark, 1982).

Head movements will also be recorded with a full-field camera. The camera is an adjustable "zoom" lens from 11 to 70 mm lens, allowing head movement fields from 53 to 8 cm (39 to 6°) with the infant at 76 cm from the camera. During the recording, the camera lens is kept at the largest magnification possible while still keeping the eyes in the field of view. This can be adjusted for each subject, but remains constant over the experimental trials. The head movements are recorded on a VCR.

Head movements are identified off-line based on a video system. A Panasonic AG6300 VCR plays the recording with frame-by-frame advancing (30 hz, 33 msec resolution). The first frame of the epoch is found with an audio time code, and the VCR is moved to that frame. The beginning frame of each epoch is visually identified to synchronize the audio time code and the video frames within 33 msec. From that point, through the end of the epoch, the observer judges each video frame forwarding the VCR one frame at a time. A

video frame grabber (Tecmar) captures a frame of video data into the computer's random access memory, and allows the display of the video data. Vertical/horizontal crosshairs are superimposed on the video data. The crosshairs represent the horizontal and vertical position of the head. The IBM PS/2 Model 80 mouse, and the OS/2 operating system's Presentation Manager, allows the use of the mouse to simulate crosshairs. A white spot is put on the infant's forehead near the center, and one near the side. The observer positions the crosshairs on the center spot to determine uncalibrated head position. A video frame in the frame-grabber is divided into 640 horizontal units and 480 vertical units (PELS: picture elements). During this judging epochs or frames with problem data (e.g., eyes closed; out of range) can be discarded. Head movements are judged in selected portions of the experimental trial. For example, in peripheral detection experiments, the observer judges those epochs that contain a peripheral stimulus or are control epochs. These epochs are subsequently analyzed for eye movements.

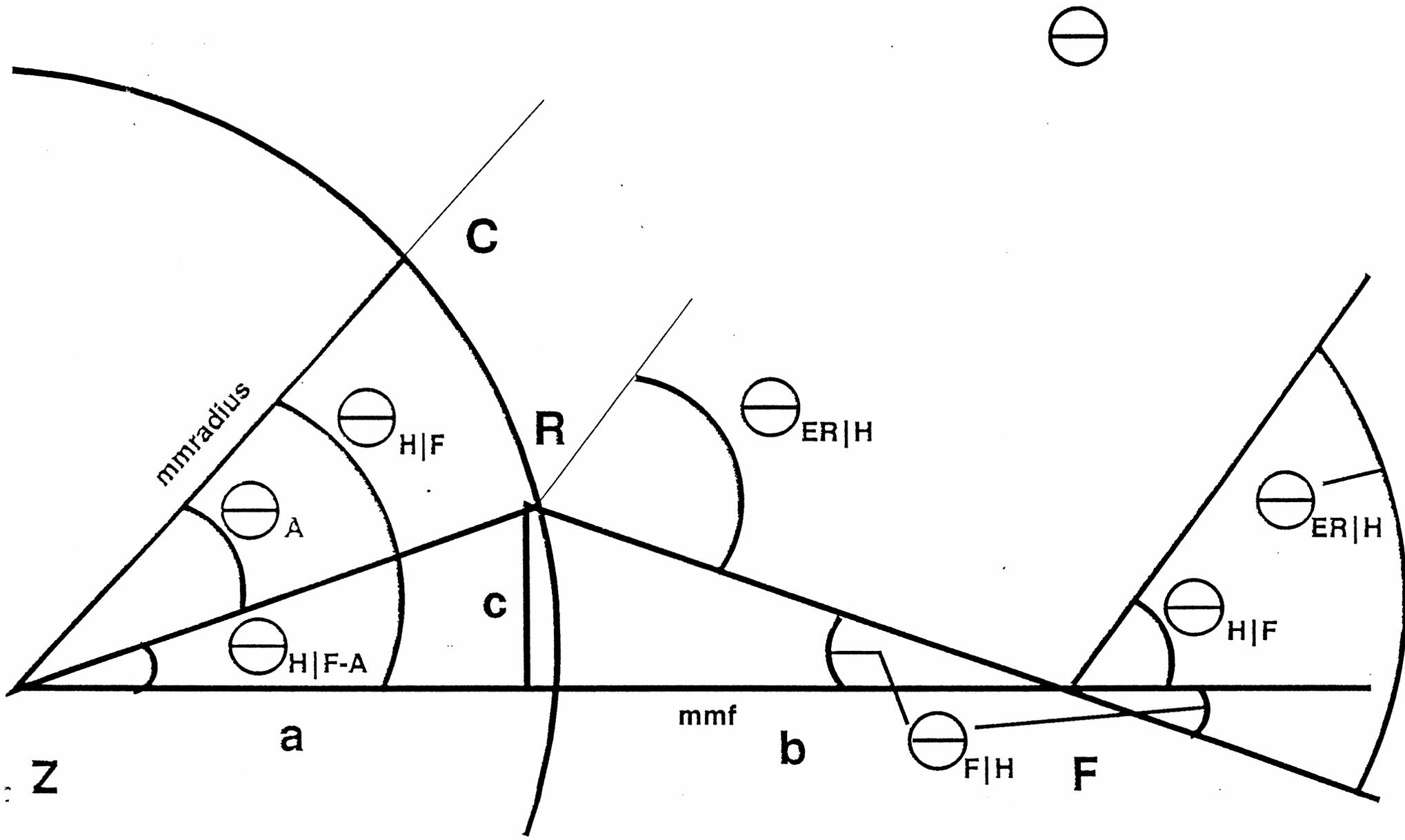
### Geometry of Head and Eye Movements

The EOG measures eye position relative to the head. Therefore, if the head is restrained then the ADC values obtained by sampling the EOG signal can be directly compared against the known eccentricity of the location upon which fixation is directed. If, however, the head is unrestrained, then head eccentricity and target eccentricity determine the eccentricity of the eyes. Formula need to be developed to take into account head and eye movements. It is advantageous to allow head movement in order to increase subject retention rates, particularly in infant subjects. Head movements also are normally used in target localization by infants. The coordination of head and eye movements is thus intrinsically interesting to the study of infant attention.

Figure 1 illustrates that the EOG measures eye position relative to the head. However, it is *not* true that during target fixations head movements and eye movements are identical but simply 180° out of phase. Thus, eye position cannot be simply established by looking at head position, then calculating eye position as the difference between target eccentricity and head position. Head movements and eye movements which preserve target localization are different because of the forward and lateral displacement of the axis of rotation of the eyes relative to the axis of rotation of the head (Collewign, Conijn, Tamminga, 1982; Hine & Thorn, 1987; Wist, Brandt, & Krafczyk, 1983).

The relation between head position, eye position, and target position, are illustrated in Figure 2 (see Hine & Thorn, 1987, or Wist, Brandt, & Krafczyk, 1983, for complementary/alternative formulations). The schematic diagram shows a fixation point (F), the center of the forehead (C), the right eye (R), and the center of rotation of the head (Z). Several angles are marked on the diagram. These include:  $\theta_{HF}$ , the angle between the center of the head and the fixation point;  $\theta_{ER|H}$ , the angle of the right eye with respect to the head;  $\theta_A$ , the lateral displacement of the eye from the center of the head;  $\theta_{FH}$ , the angle between the eye position and the target. If the radius of the head rotation is known (mmradius), and the distance of the target from the head is known (mmf), then the displacement of the eye relative to the head can be calculated from the following formula:

Figure 2: The relation between eye position relative to head, head position relative to target, and target position. C: Center of forehead; R: location of right eye; Z: axis of rotation of head; F: fixated target;  $\theta_{ER|H}$ : right eye eccentricity relative to head;  $\theta_{HF}$ : head eccentricity relative to fixation point;  $\theta_A$ : lateral displacement of eye from center;  $\theta_{FH}$ : eccentricity of fixation point relative to right eye; a, b, c: intermediate values for equations (1) - (8) calculated from other parameters; mmf: distance from fixation point to head; mmradius: distance from Z to head, i.e., effective rotation radius of head.



$$(1) \theta_{ER|H} = \theta_{H|F} + \theta_{F|H}$$

$$(2) \theta_{F|H} = \tan^{-1} (c / b)$$

$$(3) c = \text{mmradius} * \sin (\theta_{H|F} - \theta_A)$$

$$(4) z = \text{mmradius} * \cos (\theta_{H|F} - \theta_A)$$

$$(5) b = \text{mmradius} + \text{mmf} - z$$

$$(6) b = \text{mmradius} + \text{mmf} - \text{mmradius} * \cos (\theta_{H|F} - \theta_A)$$

$$\text{mmradius} * \sin (\theta_{H|F} - \theta_A)$$

$$(7) \theta_{ER|H} = \theta_{H|F} + \tan^{-1} \frac{\text{mmradius} * \sin (\theta_{H|F} - \theta_A)}{\text{mmradius} + \text{mmf} - \text{mmradius} * \cos (\theta_{H|F} - \theta_A)}$$

This set of equations shows that the degree of the eye relative to the head is based on its forward placement, center of the head's rotation axis (mmradius), its lateral displacement from the center of the head ( $\theta_A$ ), and parameters based on the head's degree and distance relation to the fixated target (mmf,  $\theta_{H|F}$ ). With recording of the EOG on both eyes, the displacement of either eye from the head can be determined. However, EOG recording on the outer canthii of both eyes results in an electrical potential summed over both eyes (such as a point at the center of the head). The estimate of the deviation of the "center eye" is derived from (7) by eliminating the angle between the eye and head. This would result in a value representing the "Cyclopean eye" representing the center head at the forward placement of the eye (C in Figure 2),  $\theta_{EC|H}$ . (Simulations of this value compared with the sum of the deviation from the right and left eyes showed nearly identical estimates of eye position)

$$\text{mmradius} * \sin (\theta_{H|F})$$

$$(8) \theta_{EC|H} = \theta_{H|F} + \tan^{-1} \frac{\text{mmradius} * \sin (\theta_{H|F})}{\text{mmradius} + \text{mmf} - \text{mmradius} * \cos (\theta_{H|F})}$$

Figure 3 shows a model of the measurements that are taken on each subject in order to obtain the mmradius and mmf variables. They include the frontal-occipital diameter at the level of the mastoid (mmfodia), the mastoid-mastoid diameter (mmmastdia), the mastoid-mastoid circumference in the front (mmmastf) and the rear (mmmastr). The lateral of the head occurs near the mastoid-mastoid diameter (Kapandji, 1974). Rotation :

other axes (e.g., saggital rotation, "roll", translation of axes) has a negligible effect on (8) (Hine & Thorn, 1987; Kapandji, 1974). Thus, the distance from the mastoid-mastoid axis to the front of the head is taken as the radius of head rotation (mmradius in (8)). The distance between pupils is measured (mmpupils), and the distance between a white spot placed on the center and sides of the forehead (mmobj). Also measured at the beginning of the experiment, is the distance of the TV monitor at its center from the center of the forehead. The distance from the TV center to the video camera, and the computed distance from the fixation point on a stimulus to the TV center, can be used to estimate the distance of the center spot from the camera or from the fixated stimulus (mmf in (8)). The distance from the infant's head to the center is measured at the beginning of the experiment. It is updated if the infant moves forward or backward relative to the stimulus, by comparing the number of PELS between the two white spots on the forehead relative to their known distance apart.

The application of these relations between head position, eye position, and target position, to the present studies with infants, is shown in Figure 4. The C in Figure 4 represents the center of the stimulus setup and the F is the fixation point. The distances (mmradius, mmf, and distance from head to center) involved and the angles of head position are known. The eccentricity of the "center eye" can be determined by the relation of the center head spot to the fixated target, judged from the video recording of head movements during the experiment.

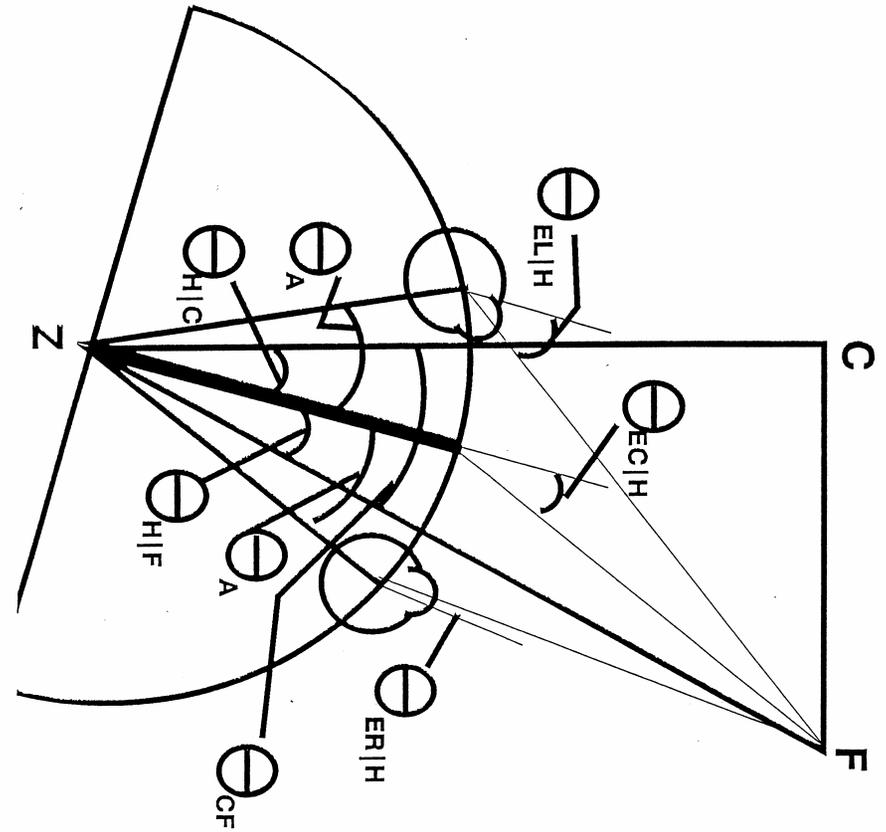
Given the parameters from (8), and a known fixation on a target and the target eccentricity, the deviation of the eye from the head is known. Thus for rotating head movements, for lateral head movements, or for fixed head positions, the eye deviation is computed from (8). It does not matter whether the head is moving or whether the head is still, as long as the infant is fixating on the target. Also, the deviation of the eye from the head does not change for other positions of the head as long as the variables in (8) are measurable.

The range of deviations that could be computed with these methods, compared to just assuming that eye movement was equal to head movements but out-of-phase, was calculated over a range of head sizes and distances. There are changes in head circumference, interpupillary distance, and other parameters important to equations (7) and (8) from the ages of 6 to 26 weeks (Roche & Malina, 1983). There is an increase in head circumference from ages 6 weeks through 26 weeks, from approximately 350 mm to 425 mm (Figure 5). Interpupillary distance also changes, thus increasing the lateral placement of the eyes from the center of the head ( $\theta_A$  in (7)). Thus, the values of mmradius which are important to the equation (7) and (8) might change over this age range. Figure 6 shows the relation between hypothetical changes in head eccentricity with respect to a target at 500 mm for a 20 week old, and the necessary deviations in the eye eccentricity with respect to the head, to continue fixation on the object. The data are plotted separately for left and right eyes, and a "center eye". It can be seen that the relationship is nonlinear over the estimated range of head movements. Also, if estimation

**Figure 3: Head measurements necessary for determining radius of head rotations.**

SUBJECT NUMBER:

Figure 4. Application of head/eye/target eccentricities to peripheral detection experiments. C: center of TV stimuli; F: Fixation point; Z: center of head rotation;  $\theta_{ERH}$ ,  $\theta_{ELH}$ : deviation from head of right and left eyes;  $\theta_{ECH}$ : deviation of head of "center" or "cyclopean eye";  $\theta_{HC}$ ,  $\theta_{HF}$ : deviation of head axis from center of TV, and from fixation point;  $\theta_{CF}$ : eccentricity of fixation point from center;  $\theta_A$ : lateral deviation of eye from center of head.



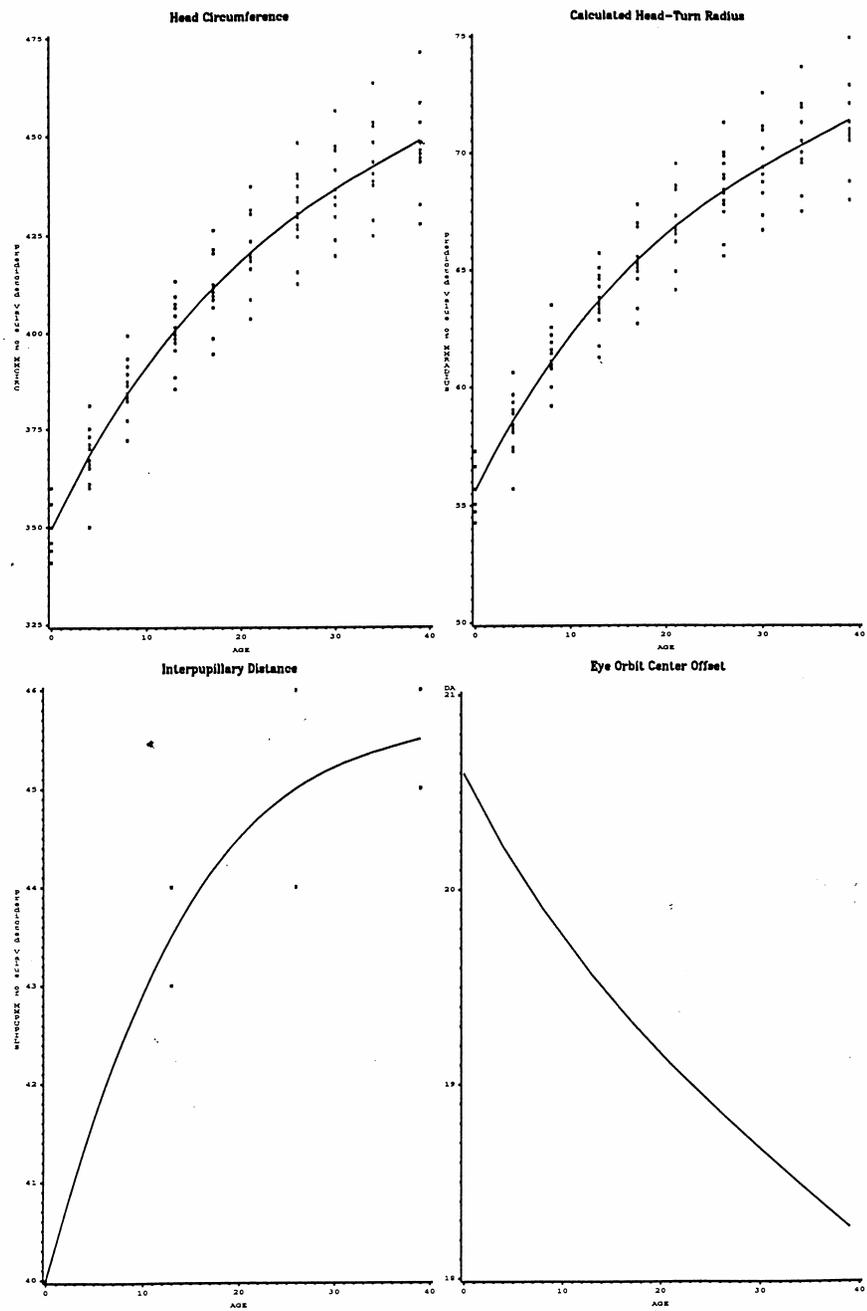
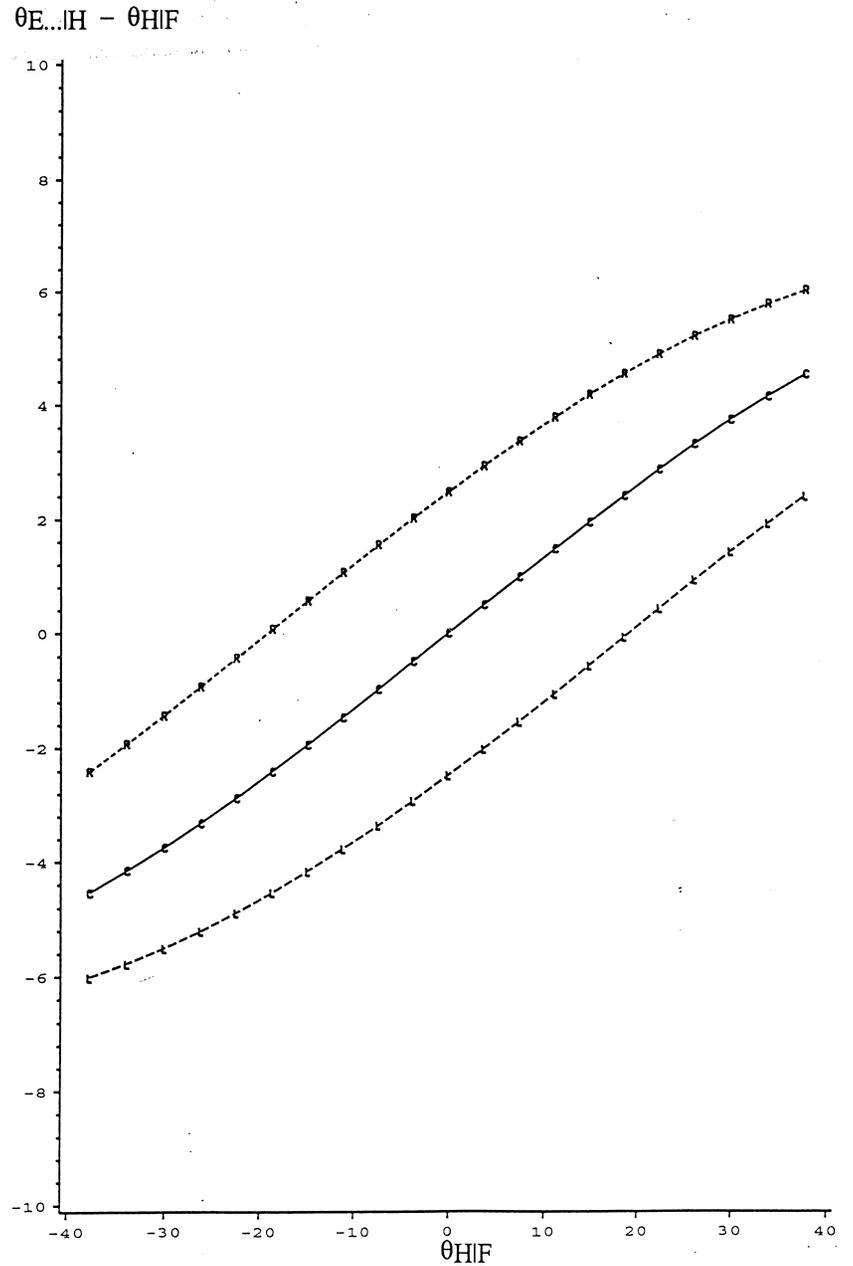


Figure 5. Changes in head circumference (and radius) and interpupillary distance as a function of age from birth to 40 weeks.

Figure 6. Difference between eye eccentricity ( $\theta_{ERH}$ ,  $\theta_{ELH}$ , or  $\theta_{ECH}$ ) and head eccentricity ( $\theta_{HF}$ ) during head movements and eye movements which retain target localization. Data are for right eye, left eye, and "center eye", with the expected values of head size of a 20 week old, and the target at 500 mm from the head.

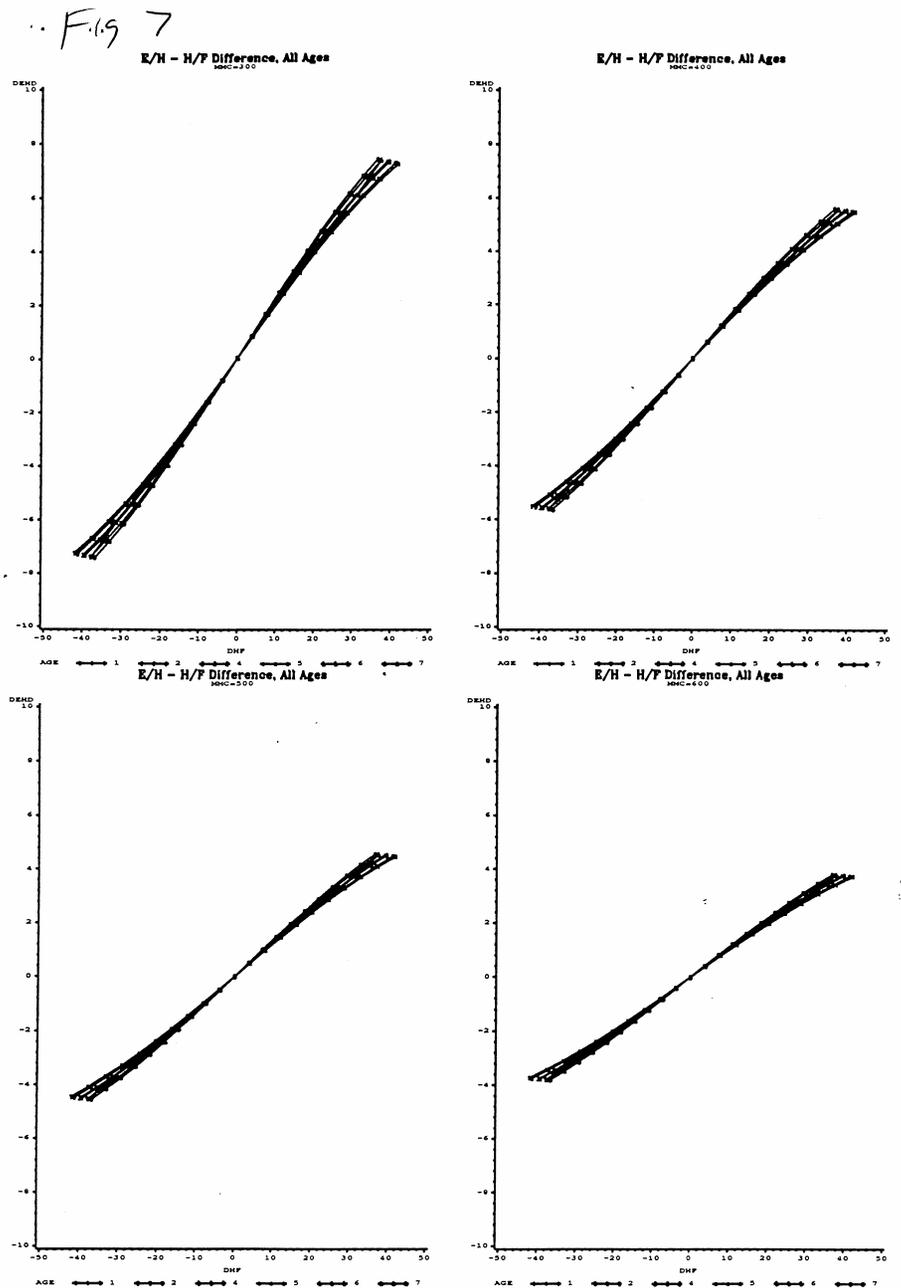


of the eye position is made strictly on the location of the head relative to the target, errors as large as  $6^\circ$  would be made when target localization is near  $40^\circ$ .

From the changing values of head circumference and interpupillary distance, the potential changes over the age range from 6 to 26 weeks was computed. This was done for target distances of 300, 400, 500, and 600 mm. Figure 7 shows the results. The target distances are plotted on separate plots. It can be seen that as target distance increases the difference between eye position eccentricity and head position eccentricity becomes smaller (e.g.,  $8^\circ$  at 300 mm;  $4^\circ$  at 500-600 mm). The target distances in the current studies are between 500-600 mm from the infants, which shows little difference. Each plot in Figure 7 contains the "center eye" estimate for ages 6, 8, 10, 12, 14, 20, and 26 weeks. There is little effect across the ages of the increasing circumference of the head on the relation between  $\theta_{ER|H}$  and  $\theta_{HF}$ . The largest influence is the distance from the TV. Similar simulations manipulating TV distance, rotational vs lateral head movements, "roll" in head movements (lateral rotation mixed with rotation in another axis), had little effect on the estimates shown in Figure 7 (cf., Hine & Thorn, 1987; Kapandji, 1974)

### Calibration

A calibration procedure computes the "visual center" by regressing eye position to fixated stimuli of known degree deviation (Harris et al., 1981; Woestenburg et al., 1984). On each trial a small stimulus ( $1^\circ$  square) is illuminated. Observers judge (to 33 msec resolution) when the infant begins to look at the fixation point, and for how long the infant maintains fixation. This fixation position is the  $0^\circ$  viewing position. Similarly, on each trial with a detection of the peripheral stimulus, the observer judges when the infant is fixating on the peripheral stimulus. Since the peripheral stimulus is at known eccentricities from the first fixation point (e.g.,  $10, 20, 30, 38, 40^\circ$ ), the absolute distance is known. The angle of deviation of the head center from the fixation point ( $\theta_{HF}$ ) is calculated from the head spot location, and the known distances of the head from the TV monitors. The calculated necessary deviation of the "center eye" relative to the head is also calculated ( $\theta_{EC|H}$ ). Head and eye position occur for every sample period of fixation on either the first stimulus or the peripheral stimulus. Then, separately for each infant, the raw position ADC values from the EOG are regressed on the known degrees with a polynomial equation. Irregularly large prediction errors (predicted minus actual) are discarded. The computation of the polynomial, and discarding of the errors, is done iteratively until the errors converge to some small level. This polynomial therefore translates the coordinate systems of ADC values into degrees of eye position. This polynomial can then be used to estimate the degree of deviation for eye movements when the fixation point cannot be determined by observer judgements. This would occur, for example, on unknown fixations, or for saccadic eye movements, or smooth pursuit tracking. Thus, the "main sequence" relation between saccade size and velocity can be estimated, or smooth pursuit accuracy can be estimated. This system does not assume that this "visual fixation center" is absolutely found in the visual center of the infant eye (e.g., Bronson, 1975; Slater & Findlay, 1975). It assumes that the relation between the true visual center and the computed visual center remains constant within an infant across fixations.



This procedure was used for several infants in a peripheral stimulus detection study (horizontal eye movements only). The saccade (or multiple saccades) to localize the stimulus was the EOG value corresponding to the coordinate of that peripheral stimulus. Across all localizing saccades, regression coordinates were obtained for each subject, and the ADC units were converted to degrees for each saccade (regression weights--degrees/ADC unit). Head movements toward the peripheral stimulus often followed the initial localizing saccade. Compensatory ocular responses often accompanied the localizing head movement. The ADC values for EOG while fixating on the first fixation stimulus represented the initial fixation point. The final fixation on the peripheral stimulus, after all head and eye movements, represented the second fixation point. The degree of head movement was computed by knowing the distance of the head from the TV and camera, and the movement of the head spot across the video field. Eye movements were estimated by the calibration analyses. The gaze eccentricity was the sum of head and eye movements in degrees. Gaze eccentricity could be calculated for looks on the first and second fixation stimulus, and final fixations on the peripheral stimulus.

A second pilot study was done to test several infants in a paradigm involving smooth pursuit and saccades. The stimulus occurred in a 35° area, so head movement was not a factor in the localization. The stimuli consisted of a small moving rectangle in predictable (sine or square wave) or unpredictable (random error on sine wave path) paths. The stimulus stopped at the right or left end of each path, and at various locations during the path. The observer judged at least 1 second of fixation on the stationary stimulus (corroborated by the off-line observer), and the stimulus was restarted. These fixation points allowed the collection of vertical and horizontal EOG data at several known stimulus positions on each trial. Regression of the raw EOG data on the fixation points provided a transformation equation. The regression equation then was used to transform the other data from the trial to determine the degrees of fixation at each 10 msec of the trial.

In summary, the essential basis for "visual center" calibration in any experiment is 1: the known eccentricity of selected stimuli presented in the study; 2: the measured location of the head, the distance of the head from the TV and camera, and the computed head eccentricity relative to the fixation target; 3: observer-judged epochs of time when the infant is fixating on the stimulus, resulting in computed eye deviations; and 4: estimated eye eccentricity for periods of time when unknown fixation or eye movements were occurring, from the regression equation established in the calibration. The calibration procedure involves the regression of the uncalibrated EOG against the degrees. The resulting regression weights translate the ADC units into degrees for eye position.

### Resolution

Resolution is the minimum visual angle that can be detected by the system. The resolution for the EOG depends on the gain of the EOG amplifier, i.e., the sensitivity of the amplifier relative to the degree of eye movements. The EOG is sampled with a 12-bit analog-to-digital converter (4096 units), and thus the °/ADC can be computed. Alternatively, one could use the amplifier gain to calculate the electrical potential in volts, and calculate °/mv. However, the regression equation relates the uncalibrated eye

position and the eccentricity of the fixated stimulus. The regression procedure provides an equation given any unit of measure, so the arbitrary ADC units work as well as the voltages. Since the transformation from ADC units to mv units is linear, the standardized regression coefficients of the raw ADC units would be identical to the coefficients of the mv units. The unstandardized coefficients of the multiple regression equations give the resolution of the system.

For the head movement, the resolution depends on the distance of the head from the camera, and the size of the head and head spot in the video frame. A video frame in the frame-grabber is divided into 640 horizontal units and 480 vertical units. The unit of measure is "PELS", e.g., "picture element". The number of PELS taken to move the head from the 0° to a peripheral stimulus can be used to calculate the head movement resolution in °/PELS.

Two pilot studies for a peripheral stimulus detection study generated some sample EOG resolution data. In the first, EOG ADC values were regressed against the known deviation of the target with respect to the head without computing the deviation of the eye relative to the head. The EOG measurements were very sensitive. The resolution was better than 0.5 °/ADC unit for all subjects (range = 0.044 to 0.39 °/ADC). In the second pilot study, the deviation of the head with respect to target, the deviation of the eye with respect to the head, were computed (e.g., "Geometry of Head and Eye Movements"). The resolution improved, being better than 0.2°/ADC unit for all subjects (range = 0.056 to 0.134 °/ADC). These two pilot studies compare well to eye movement studies using corneal reflection and video based systems (Shupert & Fuchs, 1988). The sensitive EOG resolution in the present study was a result of high amplification and good recording techniques (e.g., proper skin preparation, well-secured electrodes and wires, sufficient biopotential gel, minimal subject movement due to high interest in stimuli and procedure). The resolution of the head movements in the first pilot study ranged from 0.09 to 1.45 °/PELS. The resolution of the head movements in the second pilot study ranged from 0.043 to 0.066 °/PELS. A third pilot study involving the tracking of a moving stimulus also generated some sample resolution data. As with the second study, the resolution for eye movements was better than 0.2 °/ADC unit for all subjects (range = 0.025 to 0.10 °/ADC).

### Accuracy

Accuracy is the computed eye movements relative to actual eye derivation. Absolute eye position cannot be measured in this context, so true accuracy cannot be assessed. However, it can be assumed that the fixations judged to be on the stimuli of known degrees are absolute positions. Calculated eye position on these trials can then be compared with the absolute degree deviation to assess how well the calibration computes fixations of known eccentricities.

Two sets of pilot studies examined the accuracy of the procedures. These were done with a pilot study for a peripheral stimulus detection study. In the first pilot study, we used procedures where the raw ADC values for the EOG were regressed against the difference between fixations on the first stimulus and fixations on the peripheral stimulus. Figure 8 shows the accuracy measures. Mean error level for eye position or gaze position was

small (means  $< 1^\circ$ ). However, the mean level is small due to the regression method upon which the estimation is based. The error in estimated eye position (Figure 8a) ranged from  $-9.64$  to  $8.0^\circ$  (S.D. = 3.06), and gaze position (Figure 8b) ranged from  $-4.76$  to  $7.34^\circ$  (S.D. = 2.29). The gaze accuracy worked well, with no overlap in the gaze estimates across conditions. However, the fixation at the time of the shift in gaze could not be accurately determined. The infants were looking at a large stimulus ( $10^\circ$ ) or a small stimulus ( $1^\circ$ ) before looking toward the peripheral stimulus. The error may have resulted from infants looking at the edges of the stimuli rather than the center. Thus, the regression of the ADC values on the degrees was inaccurate because the knowledge of where the infant was looking was lacking.

The second pilot study was done with the estimates of head eccentricity and eye eccentricity relative to the head, computed as discussed in "Geometry of Head and Eye Movements". The amplifier gain was also set to 0.5 mv/cm, which though less sensitive, resulted in better accuracy. Multiple measures of eye eccentricity relative to the head location were obtained for each fixation on the first blinking spot ( $1^\circ$ ) and the fixation on the peripheral stimulus ( $2^\circ$ ). Since head movements often occur during fixation on either target, there was a changing eye/head relation and more data was available to use in the regression equation. Since the fixations on the large stimulus ( $10^\circ$ ) were not necessary to the calculations, more accuracy could be achieved in estimating the eye/head eccentricity. Figure 9 shows the accuracy measures. The error in estimated eye position ranged from  $-6.62$  to  $6.19^\circ$  (S.D. = 2.02). Gaze position shows similar levels. More than 90% of all estimates had the estimated position within  $\pm 2.5^\circ$  of the peripheral stimulus eccentricity. Not only that, as shown in Figure 9b, about 97% of all estimates had error levels which were less than 0.25% of the gaze eccentricity. This accuracy was preserved across the entire range of eye movements (Figure 9a).

The measures of accuracy reflect good measurement of eye and gaze position with EOG. Thus, EOG can be sensitively measured (resolution), with a degree of accuracy acceptable to the relative size of the eye movements in the study. The accuracy limits the total system, suggesting eye movements of  $2^\circ$  (S.D. level) or less should not be analyzed, since they are less than the error of the system. The limit of eye movement measurement by accuracy is a characteristic of both EOG and corneal reflection measurement methods (cf., Hainline & Lemerise, 1985; Hainline et al., 1984; Shupert & Fuchs, 1988).

### Identifying eye movements

Three types of eye movements can be estimated in infant eye movements: saccades, smooth pursuit, and slow drift (Harris et al., 1988). Infants also show compensatory ocular responses (Regal et al., 1983; Regal & Salapatek, 1983). These are a combination of vestibulo-ocular response, cervico-ocular response, and smooth pursuit movements. Compensatory ocular responses aid in continuing eye fixations during localizing head movements. Fixations are the lack of eye movements.

There are several methods to identify saccades. Saccadic eye movements have an accelerative component, and are easily identified using the second derivative (acceleration) or the third derivative. Additional external information can be used to

identify saccades or fixations. For example, in the peripheral detection studies, the observer judges the infant to be fixating on the first stimulus. The observer also judges the approximate time when the localizing eye and head movements occur towards the peripheral stimulus (see Aslin & Salapatek, 1975). While saccades may occur at other parts of the EOG record, only those used for stimulus localization are important. The variables which are analyzed for saccades include the onset and offset latencies, average speed, maximum speed, and the degree of the saccade path.

The identification of eye movements during the peripheral detection pilot study was much easier than those during the smooth pursuit study. The primary means of localizing a stationary stimulus is with saccades, and the non-moving stimuli result in few saccades after fixation. There are no smooth pursuit eye movements that occur to stationary stimuli. Therefore, the essential distinction was between fixation, slow drift, and saccadic eye movements. Given the accelerative nature of saccadic eye movements, we could easily distinguish between the saccades and the slow drifts. The observer judgments of fixation periods and localizing eye and head movements aided this process.

The identification of eye movements during the smooth pursuit stimuli was much more difficult. The predictable/unpredictable, and slow/fast stimuli elicited saccadic and smooth pursuit motor movements. The changes in eye position are therefore a combination of smooth and saccadic eye movements. Almost all procedures first identify saccadic eye movements, and then remove the saccadic movement from the raw eye position signal, leaving the smooth pursuit component. Many procedures separate saccades from smooth pursuit eye movements by setting criteria for saccades as fast (e.g.,  $> 40^\circ/\text{sec}$ ) and having a minimum duration (e.g., 20 ms) (Barnes, 1981; Bergenius, 1984; Baloh et al., 1976, 1980, Bittencourt et al., 1982). Other algorithms use quantitative or mathematical properties of saccades (e.g., acceleration, main sequence relation) to separate slow pursuit and saccadic eye movements (e.g., Allum, Tole, & Weiss, 1975; Matsuoka & Harato, 1983; Matsuoka & Ueda, 1986; Yasui & Young, 1984). The composite eye movement data was analyzed by an algorithm presented in Matsuoka and Ueda (1986; also Matsuoka & Harato, 1983). This algorithm has the advantages over others in that it identifies potential saccades as eye movements showing changing acceleration relative to current speeded smooth pursuit movements. This allows "fast" smooth pursuit eye movements which occasionally occur. This algorithm uses a third order differential equation to identify saccades, and removed the saccades from the composite eye movement data. Figure 10 shows the algorithm graphically. A third order derivative provides a differential filter which transforms the raw eye movements (composite eye movements, Figure 10a). A tripolar output (Figure 10b) identifies saccades in the composite signal. The velocity of the smooth pursuit movement is estimated from the velocities preceding and following the saccade, and a smooth pursuit signal is interpolated between the beginning and ending points of the saccade (Figure 10d). The difference between the interpolated smooth pursuit signal and the composite signal is the resultant saccadic component (Figure 10e).

The studies of smooth pursuit used predictable sine wave stimuli and unpredictable sine wave with Gaussian random components. The gain and phase lag for both types can be

estimated with spectral analyses of the stimulus, response, and coherence functions (Bahill et al., 1980; Matsuoka & Ueda, 1986; Wolfe et al., 1978; Yasui & Young, 1984).

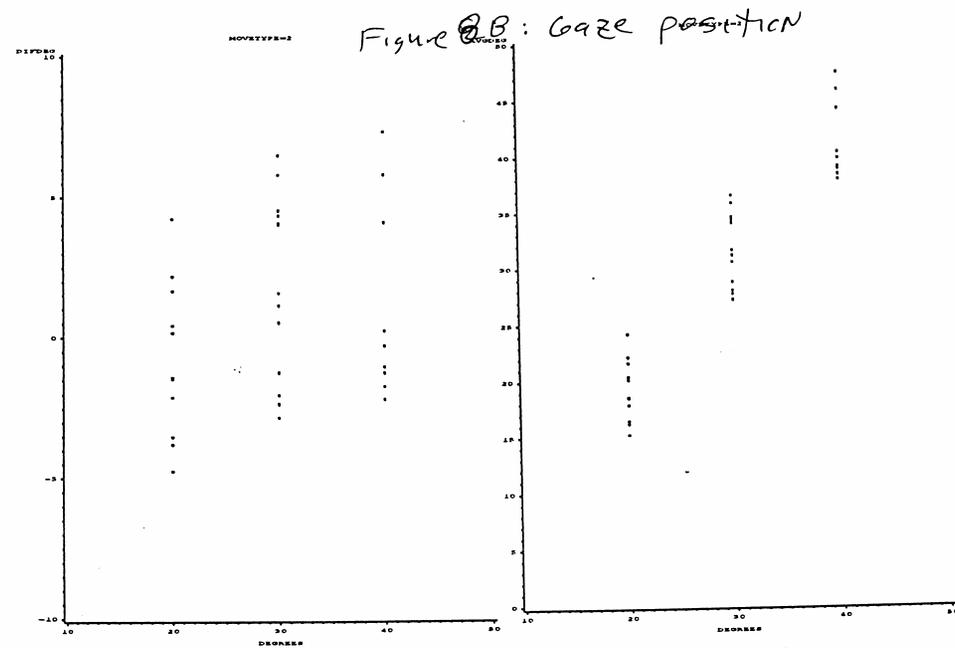
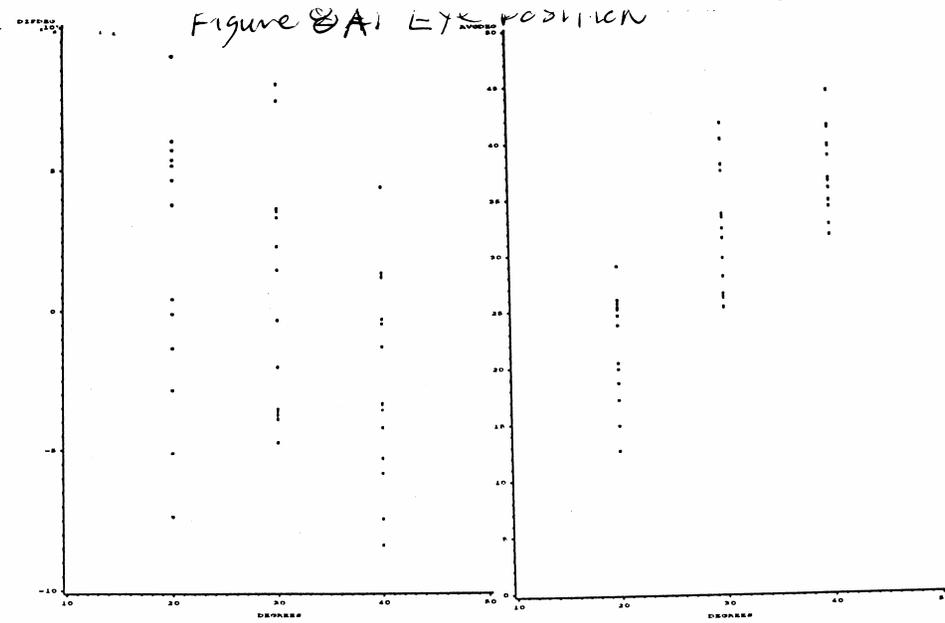


Figure 9a: Nominal eye eccentricity from known eye/head/fixation parameters (Y-axis) as a function of eye position computed from EOG and regression calibration (X-axis)

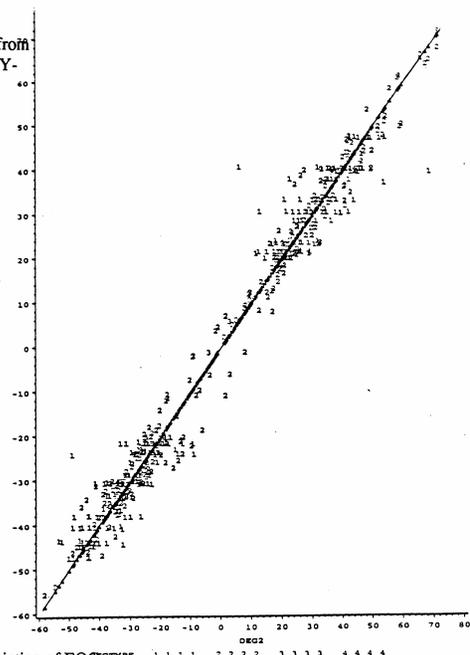


Figure 9b: Distribution of percent deviation of EOG computed eye position from nominal eye position (i.e., (computed eye position - nominal eye position) / nominal eye position).

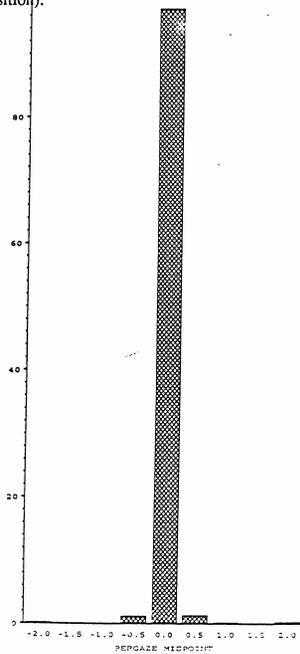
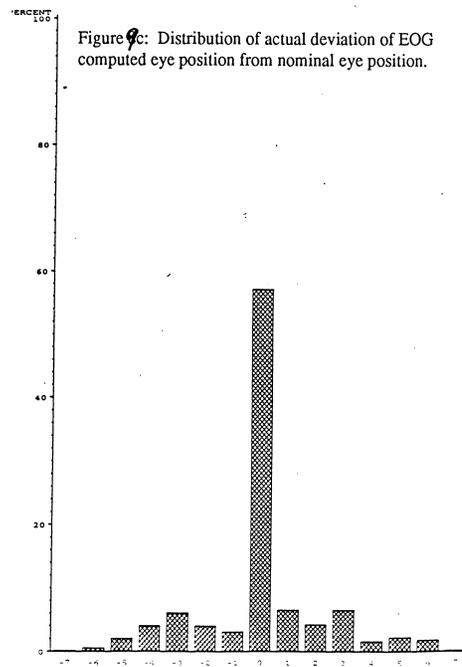


Figure 9c: Distribution of actual deviation of EOG computed eye position from nominal eye position.



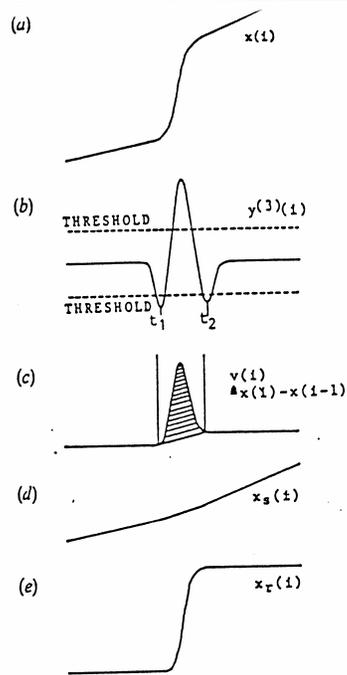


Figure 9 Method of separating the smooth and saccadic components: (a) raw eye movements, (b) third-order derivative, (c) velocity, (d) smooth component, (e) saccadic component.

The gain and phase for the sine wave stimuli can be directly examined from the known amplitude and phase of the stimulus and the eye movement data (Matsuoka & Ueda, 1986). Gain and phase relations can be examined for saccadic eye movements, smooth pursuit eye movements, and the composite raw eye position.

Slow drifts in eye position also occur. In slow drifts the eye moves but has a small and constant speed. Thus, there is a constant linear slope in either vertical or horizontal position, but no acceleration (e.g., first derivative is constant, second and third derivatives are zero). Fixations may be distinguished from slow drifts based on the first derivative. Fixations may have some change, but the first derivative changes from positive to negative over periods. This shows that the eye position remains around a fixed position over some period of time. Fixation changes may be due to small oscillations in the eye, or may represent errors in the recording system. Slow drifts often occur as a result of compensatory ocular responses due to head movements. For example, in the pilot data, some compensatory eye movements accompanying localizing head movements did not meet the criteria for saccadic movements. However, they clearly represented a large deviation of the eye position over time.

Infants localize stimuli with a combination of eye and head movements, for which the eye movements usually precede the head movements (Regal et al., 1983; Regal & Salapatek, 1983; Roucoux et al., 1983, 1984). Head movement initiation probably occurs at the same time as eye movements (e.g., simultaneous neck EMG and saccades, Zangmeister & Stark, 1982), and the delay of head movements may be because of biomechanical lag rather than neural differences. Adult saccades to target eccentricity less than about 20° occur without head movements, whereas target localization to larger eccentricities usually involve head movement (Tomlinson & Bahra, 1986a, 1986b). It is unknown whether target eccentricity has a similar effect in infants. In our pilot studies of peripheral detection we classified 5 types of eye/head movement combinations. 1: Eye movement only; 2: single eye and/or head movement; 3: multiple saccades and/or multiple head movements; 4: compensatory eye movements accompanying head movements which move the eyes toward the orbital center, keeping eye-stimulus localization to compensate for head localization. Over 90% of all movements consisted of 1: Eye movements only, or 4: Eye movement initiates, head movement follows, and compensatory ocular responses. Also, very frequently, after successfully localizing the stimulus with a saccadic eye movement, the infant would slowly move its head, with a corresponding slow compensatory movement of the eyes in the opposite direction. Regal et al. (1983) report that occasionally head movements preceded eye movements. In over 300 localizing movements, we never detected head movements alone with no localizing eye movements, or head movements preceding eye movements.

Head movements complicate the identification of eye movements in two ways. First, the head movements without accompanying compensatory ocular responses would change the position of the eye away from a localizing stimulus. Thus, the eyes rotate in a direction opposite from the head rotation in order to retain fixation. However, due the lateral and forward displacement of the eyes, the rotation is not simply a rotation that is 180° out-of-phase, but differs in magnitude (see section: Geometry of Head and Eye

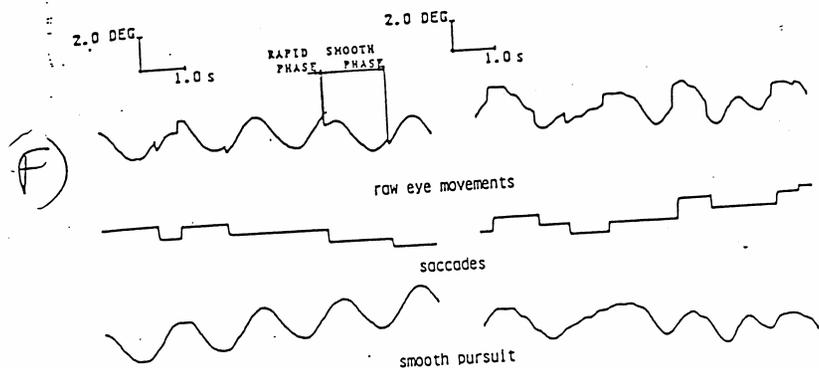


Figure 9. Examples of separating two components from raw eye movements.

Fig 9 to Matsuoka & Ueda

Movements). This may occur slightly prior to the head movement, but usually synchronously with the head movement (Barnes, 1979; Uemura, Arai, & Shimazaki, 1980; Zangmeister & Stark, 1982). This is not a problem for stationary stimuli. This produces complicated composite eye movements when saccades or smooth pursuit eye movements are tracking a moving stimulus.

Second, the movement of the head, and compensatory ocular responses, make calibration based on EOG an important issue. The EOG represents the position of the eye relative to the position of the head. Thus one has to take into account head movements in order to get the absolute fixation point of the eye (e.g., Figure 1). The present studies measure both eye movements and head movements in order to capture absolute eye position. Video-based systems (e.g., corneal reflection techniques) capture the absolute position of eye in space, rather than relative to the head, and thus do not have this problem. Some studies of eye and head movements simply add eye and head values to achieve "gaze position" (e.g., Regal et al., 1983). However, the eye and head values must be calibrated separately and transformed into degrees before gaze position can be obtained (e.g., Roucoux et al., 1983, 1984).

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