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BUQUET C. , CHARLIER J.R.

U279 INSERM, LILLE

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A- INTRODUCTION

During the past 30 years, studies of oculomotor responses greatly contributed to the evaluation of sensory visual functions in non verbal children.

These developments result from a better understanding of the oculomotor behaviours of infants and from the introduction of objective techniques for measuring their eye movements. For this reason, we will first review the foundations of methods based on eye movement responses to study the detection and discrimination of visual stimuli.

Second, we will present the various techniques which are available today for measuring eye movements in children.

Third, we will summarize how these developments have been applied to the evaluation of sensory visual functions.

We do not have the ambition to make a thorough analysis of all these subjects. They involve so many scientific disciplines as far apart as neurophysiology, psychology, system engineering, medicine... that this could only be devised as a collaborative work of specialists from these various disciplines.

Therefore our purpose will be to provide a framework with references to the different reviews made in each of these specialties.

B- MEASURING SENSORY VISUAL FUNCTIONS WITH OCULOMOTOR RESPONSES

The rationale behind the use of oculomotor responses for testing sensory visual functions is based on the fact that the oculomotor system is driven, at least partially, by visual input information. oculomotor responses found in young infants -

Visual stimuli can elicit a wide variety of eye movement responses at the earliest ages (Maurer and Lewis 1979).

- Newborn infants can fixate a stationary stimulus (Bryan 1930).
- They can make saccades in the direction of stimulus localized in the periphery (Tronick 1972).
- They can track a stimulus in motion (Beasley 1933).
- They also present optokinetic nystagmus (OKN) to a moving repetitive pattern (Mc Ginnis 1930).

How do these responses reflect the information processing which takes place at the sensory level ?

At the present time, there are no clear cut answers to this fundamental question. Many issues are still a matter of debate and the actual knowledge on the different processes involved and their maturation is fragmentary.

mechanisms involved in the oculomotor responses -

The oculomotor responses obtained from young infants are different in many aspects from those obtained from attentive adult subjects.

- In young infants, fixations present dispersions which are considerably larger than adults.

- When viewing simple geometric forms, they make slower, hypometric saccades (Aslin 1985; Hainline et al. 1984).
- They track a smoothly moving target with mainly saccadic movements and only some short episodes of smooth pursuit (Kremenitzer et al. 1979).
- Their OKN shows a tonic deviation in the direction of the field movement (Kremenitzer et al. 1979) and a temporo-nasal asymmetry under monocular viewing conditions (Atkinson & Braddick 1981)

The mechanisms responsible for these immature oculomotor behaviors have not yet been clearly identified. It is likely that the developments of sensory, motor and attention mechanisms contribute together to the maturation of these oculomotor responses (Aslin 1981). The reduced performances of infants with respect to the spatial, temporal and velocity attributes of the visual stimulus may affect their oculomotor responses. Other factors such as the sensori-motor controls and the mechanical properties of the oculomotor "plant", including viscosity, frictions and inertia may also be involved. Selective attention is also likely to play a major role : numerous attention-preference studies have demonstrated that infants are capable of some, low level, degree of attention by using their sensorimotor apparatus to select among the available input information (Haith 1978).

Even if the effect of attention on infants oculomotor responses has not been demonstrated, it is worth to note that infant's eye movements strikingly ressemble those of non attentive adults, i.e. adults who stare at the stimulus rather than look at it or who perform passive rather than active viewing. In inattentive adults, the quick phase of OKN becomes the primary component, resulting in a mean ocular deviation in the direction from which the movement is coming (Carpenter 1988). The velocity of saccades is reduced (Becker 1991). The gain of visual pursuit decreases and its phase augments (Pola & Wyatt 1991).

It is very important for practical reasons to control attention phenomena as they make examination techniques less sensitive and less reliable by introducing large variations in their results. If such precautions are not taken, the absence of oculomotor response is difficult to interpret as it may result from several causes (Aslin 1985) : a lack of detection of the visual stimulus by sensory processes, a failure in programming an oculomotor response or an absence of attention.

For this reason, we will now review different approaches which have been attempted to reduce or control the influence of attention phenomena.

In the following section, we will study the possibility of using oculomotor responses which are independent from attention mechanisms. We will next review the question of controlling the state of wakefullness in order to perform visual tests under optimal conditions. Then we will analyse the influence of attention on estimations of sensory visual processing and in a final paragraph, we will discuss the possibility of maintaining an optimal level of attention by reinforcement techniques providing rewards to the subjects according to their performance.

oculomotor responses which are independant from attention mechanisms -

Numerous physiological and anatomical studies suggest that the oculomotor system is fundamentally split into two mechanisms named by Carpenter (1991) gaze shifting and gaze holding.

These mechanisms process specific visual information, respectively velocity and position, and imply specific neurological centres. The gaze shifting mechanism is the consequence of the non uniformity of the spatio-temporal properties of the visual system across the retina. It acts to form the image of a visual stimulus over the fovea, where the spatial resolution is much higher than anywhere else on the retina. This is accomplished either by fast, saccadic movements when a visual stimulus is detected in the periphery or by slow, tracking movements when the displacement of the stimulus relative to the fovea is small. It is important to note here that although the macular region is not mature in young infants, it presents a higher spatial resolution than the peripheral retina (Sireteanu et al. 1984). The gaze holding mechanism acts to maintain the retinal image of a visual stimulus still and so avoids the degradation of spatial information resulting from motion. Such optokinetic responses are evoked by movements of the visual scenery. There is much evidence that the gaze holding and gaze shifting mechanisms are differently affected by attention : "the response to target motion is continuously variable as a function of attention whereas the response to target position is switched on when a deliberate effort is made to look at the target" (Pola and Wyatt 1991).

Oculomotor responses which imply movement of the stimulus are less dependent on attention than others which are static. In fact, optokinetic responses cannot be completely suppressed in the absence of a stationary target. Furthermore, they cannot be voluntarily initiated in the absence of a moving target. According to Kowler (1990), these results "make it quite sensible to regard smooth eye movements as a sensorimotor reflex, operating under the control of the stimulus rather than free will". It should be noted however that optokinetic responses cannot be obtained when a subject is sleeping, even when his pupil is directed toward the stimulus (Gardner and Weitzman 1967), which demonstrates the need for a minimum level of wakefulness. Nevertheless, most studies performed on babies have demonstrated the presence of optokinetic responses in almost all of them (McGinnis 1930; Gormann et al. 1957). The use of these responses as a mean of testing sensory visual functions has been criticized (Fantz 1962) on the basis that optokinetic responses may not involve retino-geniculo-cortical pathways and structures.

If this judgment is true, the sensory visual performances of subjects estimated from these responses would be much lower than what would be obtained if the cortical processes were involved (Pasik and Pasik 1980). In fact, recent studies indicate that optokinetic responses involve both cortical and subcortical components (Kowler 1990). It is probable that when the subjects' arousal level is low their performances correspond to subcortical processes and that optimal performances can only be achieved if cortical processes which are under the control of attention are involved (Bushnelle et al. 1981). On this basis, it may be concluded that optimal estimations of sensory visual functions cannot be obtained from oculomotor responses independently of attention mechanisms.

control of the state of wakefullness -

It is worthwhile to mention that a number of environmental conditions are required in order to maintain a suitable state of wakefulness in infants. Such conditions involve, for example, the amount of ambient light and posture (Grenier 1981). Furthermore, infants are known to exhibit cyclic patterns of sleep and wakefulness. Scales have been developed in order to grade these different states of behaviour by Brazelton (Horowitz and Brazelton 1973) and by Prechtl (Prechtl et al. 1973). Several studies have shown that responses to sensory stimuli are more reliable and reproduceable when the test is performed in a specific behavioural state, for example, in Prechtl's state III (calm awakeness with opened eyes, absence of large body movements and regular respiration).

influence of attention mechanisms on estimations of sensory visual processing -

We have seen previously that attention mechanisms play a key role in the elaboration of the oculomotor responses to visual stimulation. If the influence of these mechanisms is not identified, there is no guarantee that the subject's sensory threshold can be estimated reliably from oculomotor responses. We will first give some examples of the influence of attention which demonstrate the need to take its effect into account in the design of the evaluation procedures as well as in the interpretation of their results. We will then consider the possibility of estimating the level of attention as an attempt to provide reliability criteria for these interpretations. Our first example will be concerned with the analysis of fixation duration. The idea that infants spend more time fixating a portion of space where they locate a stimulus which captures their attention was introduced by Chase (1939) and developed by Fantz (1956; 1962). It was later popularized under the name of preferential looking. Subsequent studies demonstrated that this measure is greatly affected by the novelty and the familiarity of the stimulus (Saayman et al. 1964). Many infants seem to prefer novel stimuli but some may actually favor stimuli which are familiar. Therefore time of fixation influences the attractivity of the stimulus in an uncontrolled manner and cannot be used as a reliable indicator of sensory visual processing. Our second example will deal with the analysis of gaze orientation responses. The preferential looking technique evolved with the replacement of time of fixation as a measure of preference by the estimation of gaze orientation toward the stimulus, i.e. a peripheral localization task. This approach was named forced choice preferential looking (Teller et al. 1974) indicating the use of a forced choice paradigm to eliminate observer biases in the evaluation of gaze orientation responses : the observer determines on which side of a screen the stimulus is presented by looking at the infant's eye movements. This technique has since had a wide diffusion for research and clinical applications such as the assessment of visual acuity, with consistent results across many laboratories and with other techniques (Vital-Durand and Hullo 1989).

However, these responses have been shown to be affected by ill-defined characteristics of the stimulus described as complexity, salience or conspicuousness (Berlyne 1958). Furthermore, Held et al. (1979) have shown that infants do not exhibit preference to stimuli presented near threshold. These two examples illustrate the fact that attention mechanisms may cause large variations of the oculomotor responses to a given visual stimulus. The same problem affects other oculomotor responses such as OKN and visual pursuit. Nevertheless, there is an important difference : these last responses cannot be produced in the absence of a moving target, whereas fixations and saccades can be made with an empty visual field (Kowler 1990).

In any case, the problem of interpreting the absence of oculomotor response in the presence of a stimulus remains unsolved with all oculomotor responses. There is no guarantee that the subject demonstrates his maximum sensitivity level and there is no evidence that the infant sensory threshold is reached (Teller 1985). It is therefore important to estimate the level of attention of subjects for the interpretation of oculomotor responses. A well trained experimenter may be able to do so but such an evaluation is very dependant on individual skill and experience. Another possibility is to use features of the oculomotor response which characterize the attention level. For example Charlier and Buquet (1994), in an experiment involving the pursuit of a pattern stimulus by young infants, have shown that infants with reduced spatial discrimination do not present smooth pursuit or have reduced visual pursuit gains. They suggest that this the quality of visual pursuit might be influenced by the attention level, but further research is needed to substantiate this hypothesis. Other possible indicators of attention level may be thought of for other oculomotor responses, such as, for example, the dispersion of fixations or the latency of saccadic responses (Hainline et al , 1984, Hainline and Harris, 1990).

feedback procedures to maintain attention -

Another approach is to maintain attention by reinforcing the infants behaviour according to the appropriateness of their responses. Operant conditioning techniques are often needed for the examination of infants after the age of 5 months as they get bored very fast by repetitive stimulations. Rewards such as the appearance of an animated toy or the gift of food cereals have been used successfully (Mayer and Dobson 1980). A major difficulty in applying these techniques is that there are large variations of behaviour between subjects which result from factors such as age, sex as well as cognitive and cultural development. Their application may be again very dependant on the individual skill and experience of the experimenter. Feedback techniques based on an automated analysis of the "quality" of the oculomotor responses may improve considerably this approach and are possibly a promising orientation for future research.

C- TECHNIQUES FOR MEASURING EYE MOVEMENTS

Several arguments demonstrate the need for an objective recording of oculomotor responses in children. Direct viewing of a subject's eyes does not allow a precise determination of the gaze orientation. It is dependant upon the observer skill and does not provide an objective documentation. Furthermore, it is not suitable for the analysis of dynamic responses. Our purpose is not to make an exhaustive description of the numerous techniques which have been proposed for measuring eye movements. Such descriptions can be found elsewhere (Young and Sheena 1974; Maurer 1975; Aslin 1985). We will rather present the major requirements which have to be met in order to make recordings from infants and estimate how these requirements are fulfilled by the techniques which are presently available. A suitable sensor for infants eye movements would be non invasive, easy to implement, easy to calibrate, highly reliable and available at an accessible cost. Other technical specifications will depend upon the type of eye movements which is studied.

The analysis of fixations and slow movements such as pursuit requires absolute measurements and can be made with rather low sampling rates (5 measures per second for example) whereas the analysis of fast movements such as saccades requires higher sampling rates. Another important consideration is the ability of the technique to separate eye movements from head movements. For the evaluation of sensory visual functions, it is necessary to evaluate the correlation between the oculomotor response and the position and movement of the visual stimulus. Techniques which make measurements relative to the head are not suitable for the evaluation of fixations and slow eye movements relative to a visual target, except if the head is kept steady, which cannot be achieved in infants within a suitable range. Specific adaptations have to be made to the techniques designed for adults in order to obtain recordings from infants as most infants will grasp any object at a reachable distance in their visual field and, after the age of 5 months, many will not tolerate anything in touch with their eyes or head.

Table 1 gives a summary of these characteristics and we will now comment the specifications which are given.

technique	electrooculography	magnetic coils	limbus reflectance	HIRSCHBERG
invasiveness	skin electrodes : risk of skin abrasion	contact lenses : blurring effect and risk of corneal abrasion	goggles : visual field limitation no horizontal measurements	rather limited head movements
horizontal measurements	yes	yes	yes	yes
vertical measurements	unreliable (eye lid movements contamination)	yes	unreliable(masking of iris margin by eye lids)	yes
torsion measurements	no	yes	no	some possibility by image analysis of the iris margin in primary position of gaze
measurement reference	head	fixed	head	fixed
analysis of fixations and slow movements	unreliable (electrode drift, head movements)	yes	limited (head movements)	no
analysis of fast movements	limited (30 Hz effective bandwidth due to noise)	yes	yes	limited (60 Hz sampling frequency)

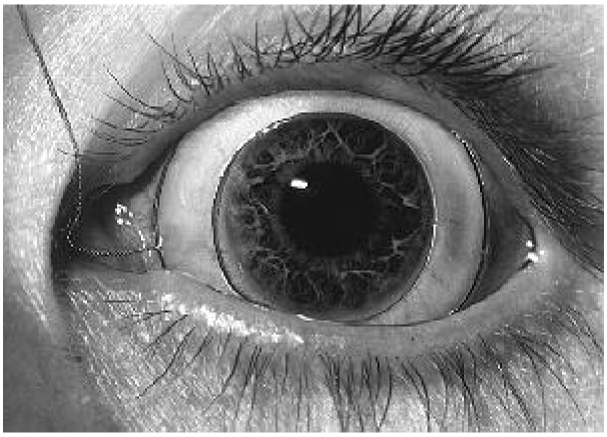
the electro-oculography technique -

Electro-oculography (Marg 1951) was probably the first technique used for recording eye movements in infants (Dayton et al. 1964). It consists in measuring differences in electric potential between electrodes placed on the skin around the eye. These potentials result from the electric field between the retina and the cornea of the eye and are modulated by rotations of the eye relative to the head. They are affected by a number of artefacts such as drifts of the electrode potential and heterogeneities of the bioelectric field (Zao et al. 1952) which impede absolute measurements and reduce considerably its reliability along the vertical and oblique axis.

set-up used for electro-oculographic recordings

the magnetic coils technique-

The magnetic coils technique (Robinson 1963) is frequently used, on account of its accuracy and sensitivity, in eye movement research on animals or adult humans. It is based upon electric currents induced in a small coil by a magnetic field. These currents are modulated by rotations of the eye relative to the magnetic field. The small coil is usually embedded within a scleral lens with small wires making the connection to the recording apparatus. This arrangement is extremely difficult to apply and potentially harmful for infant subjects.



scleral lens used with the magnetic coil technique

the limbus reflectance technique-

The limbus reflectance technique (Torok et al. 1951) consists in the measurement of the amount of light reflected by the border of the iris. The variation of reflectance between the iris and sclera produces a modulation of this signal by movements of the eye. This technique does not allow eye movements to be separated from head movements. As a result of the masking of the iris margin by the eyelids, it is limited to horizontal eye movements.

Techniques based on the Hirschberg's principle -

Methods based on Hirschberg's principle (Hirschberg 1885) measure the position of the image of a light source over the cornea (corneal reflex) relative to the pupil. These measurements do not necessitate contact with the subject and are not sensitive to translation movements of the head. They are directly related to the gaze direction by the geometry of the eye anterior chamber. As a consequence, they allow an isotropic and absolute evaluation of the angular eye rotation. Without any calibration, locus of fixation can be estimated with an absolute precision better than 5 degrees (Buquet and Charlier 1993) Due to these interesting characteristics, this method was used in early studies of infant fixations (Fantz 1956) with the instrumentation which was available at that time : photographic recordings. However, the measurement rate was not quite enough to allow the analysis of successive fixations. The advent of cinematography allowed higher sampling rates and a suitable temporal resolution. However the analysis of these recordings was extremely time consuming (1 minute of recording at a sampling rate of 30 Hz represents 1800 images to score !). Recent technological developments of near-infrared video sensors, electronics and microprocessors have permitted the increase of sampling rate and the automated analysis of these eye images, first "offline" (Haith 1969) and thereafter in "real time" (Merchant et al. 1974; Charlier 1980; Aslin 1981; Hainline 1981). At the present time, the performance of video sensors and image processors is still limited and an optimal precision can only be achieved with a camera viewing field of about 25 mm. It is therefore necessary to track the recorded eye in order to maintain its image on the sensor and compensate the body movements of the subject (Hainline 1981 , Buquet et al. 1992).

set-up used for recordings with the Hirschberg technique

D- APPLICATION TO THE EVALUATION OF SENSORY VISUAL FUNCTIONS

We will now study the different possibilities offered by the oculomotor responses obtained in infants for the evaluation of each of the main sensory functions. Any visual function can be studied with almost any oculomotor response, given the choice of an appropriate stimulus. For example, an eye tracking response can be elicited by a moving grating, allowing the evaluation of spatial discrimination or by a moving sterogram for the determination of stereopsis. However, there are many constraints to be met, advantages and drawbacks for each solution that will be discussed in the following paragraphs. visual acuity

Before reviewing the various methods which have been proposed for the estimation of visual acuity, we would like to stress two important points.

The first point is that the best spatial discrimination can only be obtained with specific spatio-temporal properties of the stimulus. In human adults, spatial discrimination decreases sharply when the stimulus is projected away from the central part of the retina and when its retinal image is in motion (Carpenter 1988).

A second point which is worth mentioning is the difficulty of obtaining a "pure" visual stimulus, i.e. one which is really testing what it is supposed to test. The problems which are most frequently encountered are the contamination of high spatial frequency gratings with lower frequency components, mismatches of luminance between a local stimulus and its background and apparent edges where the grating is delineated from the background (Schor and Narayan 1981; Robinson et al. 1988). Such problems have explained erroneous results in several past studies and are often difficult to solve, even with today's technologies.

Attempts to estimate visual acuity have been made with all the oculomotor responses that have been described in infants. These responses include OKN, visual exploration and visual tracking of a moving target.

Optokinetic nystagmus -

Optokinetic nystagmus (OKN) is a rhythmic oculomotor response which occurs when a subject is watching a repetitive pattern in motion at a constant speed. It is made up of a characteristic succession of slow and fast movements in opposite directions. OKN responses have occasioned a large number of studies in the 50s and 60s and have been the object of several reviews (Reinecke and Cogan 1958; Delthyl et al. 1968; Goddé-Jolly and Larmande 1973). They have since been almost abandoned as their results were often found unreliable in infants. Two major approaches have been described : induced nystagmus and nystagmus arrest . In induced nystagmus, visual acuity is estimated as the smallest separation between the bars of a grating in motion which can elicit a nystagmic response. This approach permits evaluations of visual acuity which are consistent with those obtained with other techniques for infants with ages up to two months (Gunther 1948; Gorman et al. 1957). As far as we know, reliable results have not been obtained in older subjets.

There are a number of reasons which may account for this. The first reason is that it is technically extremely difficult to realise a "pure" stimulus with high spatial frequencies covering a large visual field. A second reason is that, as the spatial frequency of the grating is increased, its velocity has to be reduced so that the temporal repetition of bars does not exceed the critical frequency of fusion (Collewijn 1991). As an example, the velocity of a grating of 5 cycles per degree, suitable for estimating the visual acuity of a 5 months child, has to be reduced to less than 4 degrees per second in order to keep the repetition rate under 40 Hz. Such a velocity is probably too low to maintain attention and elicit an optokinetic response involving the cortical processes.

The second approach, **nystagmus arrest**, is based upon the finding by Dodge and Fox (1928) that the optokinetic movement generated by a large moving grating can be easily inhibited by fixation of a target superimposed on the stripes. This observation was later applied by Ohm (1932, 1956) to realise objective estimations of visual acuity in adult by measuring the threshold of nystagmus arrest obtained by adjusting the visibility of a target. The major problem with this technique is that the selection between tracking the moving grating and fixating the target is governed by selective attention (Kowler 1984) and therefore the subject has to be instructed to fixate the target. Therefore, it is not surprising that studies in infants have obtained unreliable results (Delthyl et al. 1968).

Visual exploration-

The exploration of a visual scene which is static is made through a succession of eye fixations and saccades. In infants, these changes of fixation do not operate randomly, but respond to visual information from the peripheral retina (Aslin 1985). In adults, they are controlled by complex perceptual and cognitive functions which probably have already some effect at the earliest ages. One implementation of visual exploration for the assessment of visual acuity is the preferential looking technique. In the usual set-up, the infant is placed in front of a screen which comprises two zones, one with a grating of a given spatial frequency and the other uniform. The two zones are luminance matched and separated by a visual angle of about 20 degrees from border to border. The test is based upon the fact that subjects direct their gaze toward the stimulus that they find most interesting. This implies that they are able to detect the stimulus before they can exert a preference. This is possible only if the stimulus is brought in the macular area where the spatial discrimination is higher than in the periphery (and becomes more and more so with age). The projection of the stimulus on the macular area can be obtained by chance, if enough time is given to the subject to scan through the visual scene. If the infant is old enough, he can be conditionned with operant techniques to scan through the two areas of interest. A third solution proposed by Brown and Yamamoto (1986) consists in attracting fixation on the stimulus presented at the centre of the scene before displacing it toward the periphery. This solution is quite similar to the tracking approach that will be presented in the next paragraph.

Visual tracking of a moving target -

Visual tracking is made by a set of ocular movements which aim at keeping the image of a moving target on the macular area. These movements include slow movements called smooth pursuit and fast saccadic movements which occur when the gain of smooth pursuit is insufficient or when smooth pursuit is absent.

The first attempts to use visual tracking as a measure of visual acuity in infants have been made by using moving objects of decreasing sizes. Such objects included steel wires fitted on the swinging arm of a metronome (Schwarting 1954) or polystyrene balls (Sheridan 1963). However, in these situations, it is not clear whether the response is affected by a local change in stimulus luminance or by a change in stimulus resolution. A solution to this problem has been proposed for measurements of acuity in adults by Goldmann (1943) and later by Millodot and Harper (1969). It consists of a moving grating of limited size, with a luminance matching that of the background. This last approach was first tested on young infants by Delthyl et al. (1968) who used the Goldmann apparatus and later by Atkinson and Braddick (1983). These preliminary studies were based on direct observations of the oculomotor responses.

The application of the electro-oculographic technique (Charlier et al. 1987) and of a technique based upon the Hirschberg principle (Buquet et al. 1992) allowed a more precise analysis of the oculomotor responses obtained with small moving gratings. This last study reported high success rate in eliciting visual tracking : 82 % of babies at birth, 98 % at two months and

100% at 4 months. The use of tracking oculomotor responses for the assessment of visual acuity raises several questions. A first question is the appropriateness of moving targets for a spatial discrimination task. It may be worthwhile to remember that, under normal viewing conditions, there is no such thing as a static stimulus. The oculomotor system continuously exerts visual tracking to achieve a precise compensation of body and head movements. A second question concerns the velocity limit imposed by the critical frequency of fusion, a problem which was mentionned previously with OKN responses. Actually the velocity of the retinal image of the stimulus is low when the eye is tracking the stimulus continuously. The problem rises when the stimulus is put in motion and it can be solved by increasing velocity progressively. Evaluation of other sensory visual functions Oculomotor responses have also been used for the assessment of many other sensory visual functions. Visual field has been studied by detecting gaze shifting responses to peripheral targets (Tronick 1972, Harris and MacFarlane 1974). Color discrimination has been evaluated with OKN (Anstis et al. 1987), light adaptation with preferential looking (Dannemiller and Banks 1983) and stereopsis with the visual pursuit of a random dot stereogram (Fox et al. 1980; Simons and Moss 1981) and with forced choice preferential looking (Birch et al 1985). These techniques have been used only for research purpose and are still not available to the clinic.

E- CONCLUSION

In this review, we have emphasized the major problems involved with the evaluation of infants sensory visual functions with oculomotor responses. At the present time, very promising results have been obtained in research laboratories. However, there is still no widespread application of these techniques in the clinical world. On major barrier is the extremely high level of expertise which is needed actually to conduct the examinations and to interpret their results. There is some hope for future improvements of the present status by a better understanding of the neurophysiology of sensory and attentional processes. Other possible evolutions may come from the technological development of eye movement sensors adapted to infants. Such techniques allow more objective and precise analysis of oculomotor responses and might be used to ensure a better control of attention effects.

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