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"Binocular Vision"

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Binocular Vision

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9 Development of Binocular Vision and Stereopsis

Richard Held

Introduction

Developmental studies become particularly interesting when systematic changes in function with age can be demonstrated. The process of change can be revealing of the manner in which mature organization and function are achieved. Such indeed appears to be the case for the achievement of binocular vision. This chapter will focus upon recent research which casts light on mechanisms which may account for the abrupt onset of binocular vision and the consequent rapid increase in resolution of the stereoptic system in human infants.

The difficulties of investigating development are not to be underestimated. Human infants have relatively limited response capabilities and must be tested with special psychophysical procedures often resembling those used in animal studies. Response measures are limited and easily fatigued. These difficulties constrain the acquisition of information about the development of binocular vision. Yet within these limitations a significant amount of knowledge has been obtained and some intriguing questions have arisen from it.

During the last two decades progress in research on vision in human infants has accelerated rapidly. Many visual and oculomotor functions have been studied in infants and their changes during development have been tracked. Brief reviews can be found in Atkinson (1984), Gwiazda *et al.* (1989a), and Boothe *et al.* (1985). Reviews of research up to 1980 on the development of depth and binocular vision can be found in Aslin and Dumais (1980), and Fox (1981). A recent review of both animal and human research on development of depth vision is to be found in Timney (1988) and a review of visual space perception in Yonas and Owsley (1986).

The 1980 Watershed

Although much relevant research had been done earlier on depth perception, including a few attempts to study stereopsis, the year 1980 witnessed major progress towards understanding the development of human binocular vision. During that year several laboratories independently confirmed the finding that adultlike binocular vision is apparently lacking in infants during the first few months of life. It has an abrupt onset beginning on average at three to four months of age. Consequently, it differs from other forms of spatial vision which appear to be present at birth, however poor their sensitivities may be. This result gained a striking degree of credence because its discovery was made more-or-less contemporaneously by several different laboratories using different methods and procedures.

Braddick *et al.* (1980) used a dynamic random-dot display in which the interocular relation alternated between correlated and anticorrelated states. They recorded the time-locked visually-evoked response to the alternation and found that it did not appear before an average age between three and four months. (Evoked potential techniques are reviewed by Regan (1989)). Petrig *et al.* (1981) used a similar procedure to measure response to the alternation between interocularly correlated and disparate states. Their results showed a similar age of onset of the time-locked response. They added the caution that the random-dot procedures do not efficiently distinguish responses to binocular, as opposed to the more specific disparity-sensitive channels. In these procedures disparity alternates with non-disparity but so does interocular correlation and decorrelation between corresponding retinal loci thereby confounding the two. Fox *et al.* (1980) used the infant's direction of gaze in pursuit responses to motion of disparity-produced targets in dynamic random-dot stereograms with similar results.

Although dynamic random-dot displays have the advantage of eliminating monocular cues to depth, they have the disadvantage mentioned above as well as requiring global stereopsis to resolve the ambiguity of correspondence (Chapter 3). As an alternative Held *et al.* (1980) used line stereograms, separated by polarization, in a two-choice preferential looking procedure. One side of the dis-

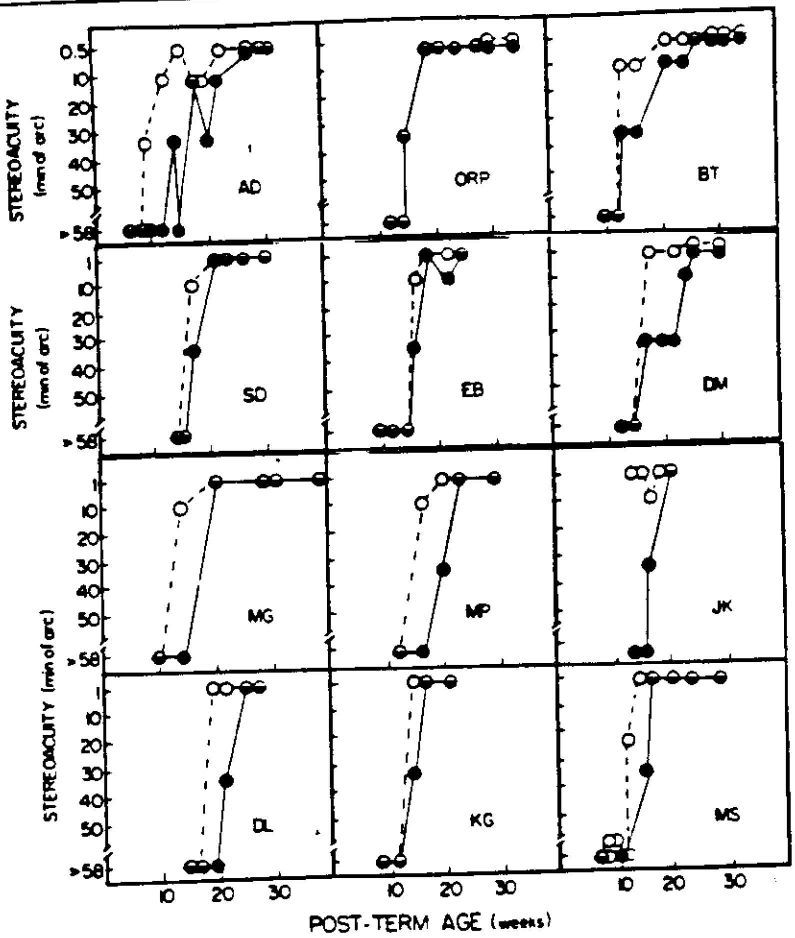

Fig. 9.1 *Development of uncrossed (●) and crossed (O) stereoacuity. The smallest disparity presented was 0.5' for infants A.D., O.R.P., B.T. and D.M. and 1.0' for the others.* Figure adapted from Birch *et al.*, (1982).

play had a disparity, ranging from 1–58', the other side had zero disparity. In this procedure a trial is initiated when the infant, held by the mother, gazes directly at a flashing LED centred in the display, whereupon the bipartite stimuli are presented and the LED turned off. An observer, blind to the display, watches the infant and within a few seconds decides which side the infant prefers. Over a series of trials, the disparity is varied and a stereoacuity threshold obtained. Suitable controls against discrimination based on non-disparity cues to depth were added. In a longitudinal study, the subjects were run at least once every two weeks. The results agreed with previously mentioned research in showing that the onset of stereopsis occurs at an average age of 14 weeks. The fine time-grained analysis revealed that stereoptic discrimination may appear less than two weeks after none had been found on the previous test (Fig. 9.1). It also showed the considerable range of ages over which infants show acquisition of stereopsis. This age range is shown in cumulative curves (Fig. 9.2) of percentage of infants showing stereopsis (Birch, 1983; Teller, 1982). Following the onset of coarse stereopsis, the disparity threshold measures revealed that stereoacuity rises within a few weeks to 1' (Fig. 9.1), the resolution limit of the testing device used by Held *et al.* (1980). It also revealed the first evidence that the onset of crossed stereopsis antedates that of uncrossed stereopsis.

The agreement of ages of onset among these experiments gave no ground for believing that there are developmental differences among several aspects of binocularity tested. Both tests of global and local stereopsis revealed ages of onset that do not appear to be different. The results obtained comparing correlogram (correlated *vs* non-correlated stimuli) with stereoptic discrimination also did

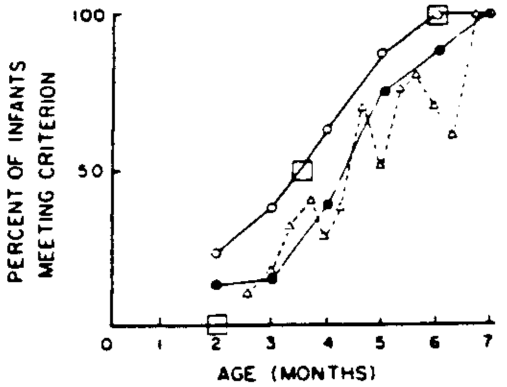

Fig. 9.2 *Summary of three studies of the development of detection of binocular disparity. The circles show data from Birch et al. (1982) for crossed disparities of 58′ (open circles) and 1° (closed circles). The large open squares show data from Petrig et al. (1981) taken with the VEP. The open triangles include the data of Fox et al. (1980) plus unpublished data supplied by R. Aslin (personal communication).* Figure taken from Teller (1982).

not reveal significant differences in age of onset (but see section on a two-stage model).

The convergent results of the early 1980's set the stage for further understanding of issues in the development of binocular vision. An equally important contribution came from animal studies of which most have been concerned with the fine anatomical structure of the visual projection system. The one exception is the study of the development of depth discrimination in kittens by Timney (1981) in which kittens are shown to have a rapid rise in stereoacuity at the same age as the appearance of disparity selective cells in their visual cortices (Pettigrew, 1974).

Progress in the 1980s

Following the burst of results in the early 1980s, a number of new and sometimes unexpected findings have been made. Using the reaching test technique developed in the Yonas laboratory, Granrud (1986) showed that four-month-old infants who had shown stereopsis by the Held *et al.* (1980) test reached significantly more often for the nearer of two visible objects than did those who did not show stereopsis. Such reaching behaviour is suggestive of true depth discrimination and not just discrimination of disparity.

The extensive data of Birch *et al.* (1982) confirmed that crossed disparity discrimination antedates uncrossed discrimination by several weeks and further revealed the fine time course of acquisition. A confirmation of the priority of crossed over uncrossed discrimination was also made by Reuss (1981). Recently Gwiazda *et al.* (1989) demonstrated the continued superiority of crossed over uncrossed stereopsis in the form of persistently higher stereoacuity during childhood. These results add to the list of differences found between these two forms of disparity and suggests that there are two separable processes involved. See Mustillo (1985) for review and chapter 11 by G. Poggio for further discussion of this difference.

Another result obtained by Birch *et al.* (1983) showed that the improvement of control of vergence did not explain the onset of stereopsis in the infant. They showed that the onset age of stereopsis was unaffected when tests were made with large redundant stereograms in which the registration of disparities was minimally influenced by errors of vergence.

In still another report Birch *et al.* (1983) showed that when binocularly rivalling stimuli are paired with non-rivalling (fusible) stereograms, a preference for the fusible stimulus appears at about the same age as does stereopsis. This result was used in a further test of pre-stereoptic vision discussed below (Shimojo *et al.*, 1986). Improvements in stereopsis and vernier acuity have been shown to continue through the early years of childhood (Birch and Hale, 1989) and until about nine years of age although grating acuity reaches asymptote several years earlier (Gwiazda *et al.*, 1989a). This result suggests that the continued improvement is not a matter of behavioural responsivity but of true visual development. Otherwise why would similar and equally difficult behavioural tasks mature at different rates?

Recently, significant differences between the sexes in the ages of onset of both stereopsis and response to binocular rivalry were discovered (Gwiazda *et al.*, 1989b). Females tend to show earlier onsets than males. These results followed upon the discovery of such sex differences in the development of vernier acuity (Held *et al.*, 1984). Since the differences are not found in grating acuity measurements, suspected of being heavily constrained by retinal factors, their discoverers have suspected that they are specific to processes going on in cortex (Held, in press). This conclusion has been confirmed in the auditory modality in which the precedence effect in localization shows a significant sex difference in the same direction while no such difference is found in auditory localization (Muir *et al.*, in press). Held *et al.* (1984) speculated that the neurotrophic influence of the high levels of testosterone present in males during the early months of life, combined with the intense synaptogenesis of this period may account for the sex difference. Measurements of the level of plasma testosterone have since been reported to be correlated with the age of onset of mature binocularity as measured by the age of shift of the fusion–rivalry preference (Held *et al.*, 1988).

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Developing Loci in the Visual System

As has been discussed elsewhere in this volume, the achievements of binocular vision depend upon a sequence of transmission and processing mechanisms beginning with the light stimulus and terminating with a perceptual or other form of response of the system. Consequently its development will depend upon the status of these mechanisms, most of which show developmental changes. We shall first consider the sources of these changes.

Dimensional Growth

Growth of the head is of course accompanied by growth of the distance between the eyes. This interocular distance increases from birth to adulthood by an average of 60% (Aslin, 1988), with 36% of the change occurring during the first six years (Fledelius and Stubgaard, 1986). The increase requires an increased amount of vergence to maintain bifixation on targets. Since vergence may be controlled by a number of mechanisms including retinal disparity, foveal fixation responses, and the accommodative linkage, it is necessary to factor out the contributions of each. With other variables held constant, growth of the interocular distance proportionally increases the size of retinal disparities. If the depths perceived by both infant and adult are correct, the former corresponding to the neonatal disparity and the latter to the increased adult disparity, we must infer that some sort of adaptive process occurs during development. It is needed to recalibrate the relation between disparities and the magnitudes of the perceived depths that they produce. We have no direct evidence for such a developmental process in adults although there is some evidence for an adaptive process in adults in response to an artificially increased interocular distance (Wallach *et al.*, 1963). Analogous effects must occur in sound localization with growth of the interaural distance (Clifton *et al.*, 1988).

Ocular Media

Like most other visual abilities, the first order dependency is on the quality of the light transmitted and refracted by the ocular media. Beginning at birth, these media appear to be at least as clear as in the adult except in cases of pathology. Infant eyes do tend to have greater cylindrical astigmatism than those of adults with consequent production of meridional amblyopia (Gwiazda *et al.*, 1986) but unknown consequences for binocularity. The focusing capabilities of the eye of the neonate are not at the adult level. The accommodative efficiency of the lens of the eye appears to be less than that of the adult, although the visual consequences of this inefficiency are mitigated by the relative insensitivity of the system to fine detail (Banks, 1980). Furthermore, by the age at which mature binocular vision begins the accommodative system has already begun to function quite adequately.

Retinal Transduction

Given an image focused on the retina, the next step is transduction by the receptors of the retina. Recent findings concerning anatomical development of the receptors and their connections in the human retina show profound changes occurring during the first few years of life (Hendrickson and Yuodelis, 1984; Yuodelis and Hendrickson, 1986). Although the detailed consequences of these changes are subject to alternative interpretations, the general conclusion is that they account for a considerable increase in resolution (Banks and Bennett, 1988; Wilson, 1988). Such increases have important consequences for further processing of spatial properties of stimuli including some of those entailed in binocular vision (see below).

Neuronal Transmission

From the retina the axons of ganglion cells leave the eyeballs in the optic nerves. In normal brains, those from the nasal half of the retina cross the midline in the chiasm to the contralateral side of the brain while those from the temporal half remain on the same side (ipsilateral). These fibres then form the optic tracts and terminate on synapses in eye-segregated layers in the lateral geniculate nuclei. Cells of the geniculate then send their axons through the optic radiation. The gross aspects of these structures appear adultlike at birth except for size. Cells are known to increase their size for several years after birth (Hickey and Peduzzi, 1987). From geniculate cells efferent fibres form the optic radiations which terminate for the most part on entry-level cells in layer IV of the striate visual cortex. Our knowledge of the detailed structure of connections in the brain comes largely from studies of animals of which the closest to man is of course the monkey. In the absence of detailed knowledge of human brain structure and functions our best guess is that they resemble those of monkey. However, the rates of development of man relative to monkey differ by a factor often estimated as close to one-fourth.

Visual Cortex

Since the first important convergence of signals from the two eyes occurs in the striate visual cortex, it is here that processes crucial to the analysis of binocular differences have their inception. In recent years a fairly clear picture of the cortical levels and loci concerned with binocular

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vision in the monkey has emerged. In the mature monkey the geniculocortical inputs from each eye remain segregated in layer IV C of striate cortex (area 17) and available evidence suggests that this state is also true in human cortex (Hickey and Peduzzi, 1987). Consequently, binocular combination of signals must occur outside of this layer as a result of convergence of outputs from the eye-specific columns. Some empirical evidence for this supposition comes from work of Levay and Voigt (in press). Yeshurun and Schwartz (1987) have provided a theoretical account of the process. Of great interest for development is the fact that these segregated ocular dominance columns are either not present or are incompletely segregated at birth in cat, monkey, and man (Hickey and Peduzzi, 1987); Levay *et al.*, 1978; 1980). They segregate in early life and consequently are candidates for explaining the development of mature binocularity. Layer IV C is subdivided into two lamina, alpha and beta. This division is important for our purposes because it is the further projection from IV C alpha via layer IV B which appears to be concerned with stereopsis (Hubel and Livingstone, 1987). Efferents from IV B connect with cells in the broad stripes of area 18, cells which are very frequently selectively sensitive to binocular disparities, the basis of stereopsis. Significant is the fact that these cells are also invariably selectively sensitive to the orientation of edges in their receptive fields. From cells of the broad stripes connections are made to area MT which also has afferents from IV B. In that region are found many cells responsive to disparities as well as interocular rivalry, as has recently been discovered (Logothetis and Schall, in press).

Apart from the retina, it is in the cortex that the most evident developmental changes in the visual nervous system occur and present candidates for explanation of visual development. Particularly evident is the process of segregation of the ocular dominance columns which in cat, monkey, and man show incomplete segregation, if any, at birth. In human visual cortex the rate of post-natal synaptogenesis peaks between two and six months of age and the total number of synapses is greatest at ten months for the entire life span (Huttenlocher *et al.*, 1982). Wilson (1988) has argued that during this period inhibitory connections become established resulting in sharpened tuning for the several forms of spatial discrimination.

Hypothetical Mechanisms of Binocular Development

Given the known developmental changes occurring at various loci that determine binocular vision, can we assess which make major contributions? In the following paragraphs we consider the pros and cons of several non-exclusive possibilities adducing additional data relevant to them.

Vergence

The developent and maintenance of accurate control of vergence has been suggested as determining the onset of mature binocularity. Such control has a reciprocal relation to stereopsis in the sense that under normal conditions of vision vergence is necessary for accurate and precise registration of disparities, hence stereopsis, and at the same time, disparities drive vergence. The control of vergence movements is far from adultlike in infants less than four months of age (Aslin, 1988). They have difficulty in following all but the slowest movements of targets changing distance from the eyes. This deficiency appears to reflect a lack of open-loop control such as would be possible after the development of vergence control by disparity (Held, 1988). Good control of vergence is in fact achieved at about the same age as the onset of stereopsis although as yet this correlation has not been experimentally verified. Consequently, as Aslin has suggested (1988), the achievement of good vergence control might account for the onset of stereopsis. Here there are two possibilities. First, the stereoptic mechanisms might be present but not evident because of inaccurate vergence. Second, chronically accurate vergence might be required for development of the mechanism. However, these possibilities are contraindicated by several experimental results. The most direct of these is the result of Birch *et al.* (1983), discussed above, demonstrating that the onset of stereopsis is not affected by testing with stimuli that are insensitive to vergence. Another counterindication comes from the finding that crossed emerges before uncrossed stereopsis (Held *et al.*, 1980; Birch *et al.*, 1982), a result that counters the implication that the accuracy of vergence accounts for both. In addition, that related indicant of mature binocular vision, the onset of response to binocular rivalry (Birch *et al.*, 1983; Shimojo *et al.*, 1986) occurs at roughly the same age as stereopsis (Gwiazda *et al.*, 1989b) and its testing is also minimally dependent upon the accuracy of vergence. Consequently, although appropriate eye alignment, produced by vergence, can be crucial to accurate binocular vision and its maintenance (see below), its perfection does not appear to determine the onset age of mature binocularity

Spatial Resolution

Spatial resolution at both the retinal and cortical levels improves markedly from birth. Banks has claimed that changes at the receptor level alone improve contrast sensitivity and may improve hyperacuity measurements (vernier acuity) by an even greater amount (Banks and Bennet, 1988). There is every reason to suspect that this improvement should also apply to stereopsis where the limit of stereoacuity is close to that of vernier acuity and the achievement of levels of hyperacuity occur concomitantly (Shimojo *et al.*, 1984). It is less obvious how the abrupt onset of stereopsis might be explained solely by improved resolution. As mentioned above, this onset is correlated with that of response to rivalry (Gwiazda *et al.*, 1989b). The rivalling grating may be quite coarse and far above the resolution threshold. Moreover, the transition from pre-stereoptic preference for stereograms with orthogonal gratings to the post-stereoptic preference for non-rivalling fused gratings occurs abruptly within a week or two (Shimojo *et al.*, 1986). Can an incremental improvement in resolution such as might occur in a week or two be the cause of onset of stereopsis? To be fair, one must ask the same question of any neuronal change suspected to account for such an abrupt behavioural change (see section on two-stage model). Improvement in resolution is also contraindicated by the significant differences in the ages of onset of crossed and uncrossed stereopsis (Held *et al.*, 1980; Birch *et al.*, 1982). The sex differences found in the age of onset of stereopsis (Gwiazda *et al.*, 1989b) as well as the fusion-rivalry response (Bauer *et al.*, 1986) can hardly be explained as a result of different rates of increase of resolution since there is no evidence for sex differences in the development of grating acuity during this period (Held *et al.*, 1984). Any such differential increases in resolution should have been evidenced by sex differences in grating acuity.

It is possible that orientational resolution might play an important role in both the onset and development of mature binocularity. Evidence from several sources suggests that coarse orientational discrimination is present by at most six weeks of age (Braddick *et al.*, 1986; Held *et al.*, 1989). Recent results suggest that orientational tuning does not reach an asymptote until three to five months of age (Held *et al.*, 1989). Since disparity sensitive cells appear always to be orientationally selective as well, one may suspect that their development proceeds together. Further research is required to examine this possible relationship.

A Two-Stage Model

Another possible explanation for binocular development is derived from the observation that the ocular dominance columns of layer IV C are either not segregated or are incompletely segregated at birth (Held, 1985; Shimojo *et al.*, 1986). Prior to segregation the right and left eye inputs to visual cortex are topographically arranged and those from corresponding retinal loci overlap. Moreover, many of the axonal endings from both eyes synapse upon the same cells in layer IV (IVC in monkey) (Levay *et al.*, 1978; 1980). Depending upon the nature of the synaptic connections, signals from the two eyes might either summate or inhibit or have more complex interactions within this layer. Consequently, the system may have a considerable degree of binocularity of a primitive sort. Held (1988) has distinguished this primitive binocularity from the mature binocularity which follows segregation of the columns and has proposed a two-stage model of the development of binocularity. The model (Fig. 9.3) incorporates a claim that it is only when segregation is achieved that signals from the separate eyes may be combined so as to form circuits which compare inputs from the two eyes. Such circuits could underlie both binocular disparity discrimination and binocular rivalry. According to the fragmentary information available, that segregation occurs in the human visual cortex during the first few months of life (Hickey and Peduzzi, 1987). The proposal then is that segregation of the columns is a necessary but not sufficient condition for mature binocularity. In addition, further connections must be made to produce circuits that analyse for disparity, up to hyperacute levels (approx. 10" or better), rivalry and other binocular properties of the mature system.

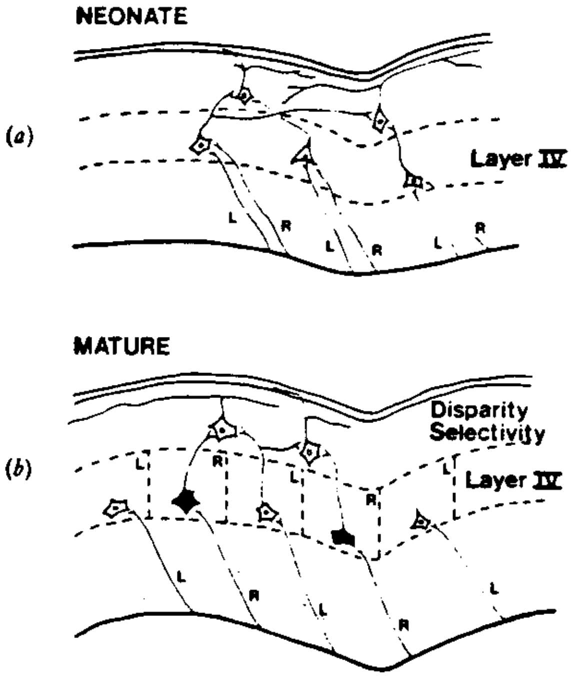

Fig. 9.3 *(a) Geniculostriate afferents from both eyes (R and L) synapse on the same cells in layer IV thereby losing information about the eye of origin. (b) Geniculostriate afferents are segregated on the basis of eye origin (R and L) and consequently recipient cells in layer IV may send their axons to cells outside of that layer so as to synapse on cells which may be disparity selective.* Figure taken from Held (1985).

As has been discussed, another test said to indicate binocularity is the visually evoked response (VEP) to alternation of binocularly correlated and uncorrelated dynamic random-dot patterns. The onset of this response, specific to binocular interaction has been claimed to occur concomitantly with that to stereoscopic disparity (Braddick and Atkinson, 1988). Moreover, preferential looking tests have agreed with this conclusion insofar as the preference for correlated over uncorrelated stimuli occurs concomitantly with the onset of stereopsis (Gwiazda *et al.*, 1989b). Recently, Eizenman *et al.* (1989) recorded the binocular VEP using liquid crystal shutters to present correlated and uncorrelated dynamic random-dot stimuli. Previous investigators used anaglyphic colour separation. Eizenman *et al.* reported time-locked VEPs to the alternation at a few weeks of age and before any such response to disparate stimuli had appeared. This result is predictable from the binocular mixing that appears to occur in layer IV C before segregation of the ocular dominance columns (Held, 1988). That mixing could result in differences between correlated and uncorrelated patterns. After segregation binocular interaction can only occur outside of layer IV C and some of it must occur at disparity selective sites.

The preceding discussion suggests that a primitive form of binocularity exists before the achievement of mature binocularity marked by the onset of stereopsis and binocular rivalry: hence the two-stage model. It was just this suspicion that suggested the experiment on pre-stereoptic binocular vision carried out by Shimojo *et al.* (1986). If geniculocortical afferents from both eyes synapse on common cells in layer IV C, the simplest assumption in combination of post-synaptic excitation (Fig. 9.3). If the summed excitation is within the linear range of the cell's activation, the outcome should resemble the superposition of two images. By stereoscopic methods Shimojo *et al.* (1986) presented orthogonal gratings to the separate eyes paired with parallel (fusible) gratings in a two-choice looking preference. The summed excitation assumption should yield the appearance of a plaidlike figure for the orthogonal gratings paired with an ordinary appearing grating for the parallel gratings. Infants of various ages prefer a plaid to a grating with other factors held constant. However, as discussed above, binocularly rivalling stimuli are avoided in favour of fusible stimuli at and after the onset of mature binocularity. In the Shimojo *et al.* experiment pre-stereoptic preference was for the plaid. But a sudden (within one or two weeks) shift to preference for the fused grating occurred at the expected age of onset of stereopsis. This result is then a partial confirmation of the existence of primitive early binocularity. Gwiazda *et al.* (1989b) confirmed that the age of onset of this preference shift occurs at roughly the same age as the onset of stereopsis and is significantly correlated with it across infants. The result again shows that increasing accuracy of vergence control is not involved in the age of onset of mature binocularity.

Binocular summation of visually evoked potentials has been regarded as an index of cortical binocularity (Shea *et al.*, 1987). These authors recorded monocular and binocular VEPs in a group of young, mostly pre-stereoptic infants, and a group of older infants, presumably with stereopsis. When tested with a counterphased checkerboard (26′ square checks) they found that binocular VEP exceeded monocular VEP by approximately 185% in the younger infants. However, the older infants, responding like adults, showed binocualr superiority of only 40%. Although in their introduction the authors suggest that this result might indicate that cortical binocularity is present in infants prior to the onset of stereopsis, they nevertheless conclude that their results are best accounted for by summation of two independent pools of monocularly driven neurones. They were apparently driven to this conclusion by the great amount of binocular summation in young infants prior to the onset of stereopsis. Their conclusion is, however, contraindicated by their data. In principle, summation of independent pools of monocularly driven neurones cannot yield more than 100% superiority of binocular over monocular VEP and 185% is substantially in excess of that. Part of this large superiority might be accounted for by the relatively low monocular VEP shown by the younger group of infants. But this too would probably entail interaction between the two eye channels requiring synaptic contacts. These results are more consistent with the two-stage model of binocular development, which, in principle, could provide binocular facilitation during the early months, than with the interpretation of Shea and Aslin (1987). As those authors suggested, but did not accept, young infants may well be binocular in the primitive sense discussed above. Just as correlated inputs to the two eyes summate to produce greater excitation than uncorrelated inputs in the very young infant (Eizenman *et al.*, 1989), so binocular input may act with respect to monocular input. In the latter case, signals from the two retinas will have a considerable degree of decorrelation because of the intrinsically noisy retinal discharge from an occluded eye. More sophisticated VEP procedures may help disentangle the origins of binocular interaction (Regan and Regan, 1989).

The two-stage model has its problems (Held, 1988). The onset of mature binocular vision is very abrupt, much quicker than the process of segregation of the ocular dominance columns. Some thresholding device must be invoked. Another objection comes from comparison among animals who appear to have binocular vision and stereopsis without evident ocular dominance columns. Here one can only look for other types of mechanism. Despite its shortcomings, the two-stage model currently appears to account for more data than the alternatives.

Looking Ahead with Both Eyes

Where do we go from here? I would suggest that several topics need exploration. The first of these concerns two types of stereoptic stimuli whose developmental course has not been established. So far only positional disparity has been studied and we cannot assume that orientational and motion disparities show the same developmental timing. There is evidence that static disparity and stereo motion in depth are processed in different psychophysical channels, that different types of neurones are sensitive to static and changing disparities, and that changing disparity neurones are comparatively insensitive to static disparity (chapter 8). It has been suggested that there are two ranges of disparity mechanisms: coarse and fine (Poggio chapter 11). Although we have no evidence that large disparities may show a developmental course different from that of fine disparities, the possibility should not be overlooked. Study of the global versus local difference is also in order. Only a first step has been taken in understanding what binocular vision is like in the very young infant before the onset of mature binocularity. It seems unlikely that the inputs from the two eyes merely summate as has been suggested by Held (1985) and Shimojo *et al.* (1986). A particularly important question concerns the relation between disparity selectivity and vergence movements of the eyes. These are mutually dependent but correlations between their developmental time courses have not been studied empirically.

Since the onset of infantile strabismus (a developmental disorder of vergence control) is reported to occur at roughly the same age as that of mature binocularity (Nixon *et al.*, 1985), one might suspect that the link between vergence control and binocularity is implicated. Finally, further study of the development of binocularity under pathological conditions should be pursued. Clinical evidence shows that deficits in binocularity follow even brief periods of binocular asymmetry during infancy resulting from strabismus, anisometropia, monocular occlusion, or other eye disorders. However, there are only a few prospective studies of the developmental course of these losses. The existing evidence suggests that mature binocularity develops initially within the normal age range (Bechtoldt and Hutz, 1979; Birch and Stager, 1984; Mohindra *et al.*, 1985). It is also possible that, in some cases, early failure to develop stereopsis, hence disparity control of vergence, plays a role in the origin of infantile strabismus. However, this possibility may be contraindicated by the existence of only one report of such a failure (Held *et al.*, 1980) among large numbers of infants tested for stereopsis. We do not know how many such failures may have gone unreported. For clinical purposes, as well as scientific interest, we should like to gain further knowledge of the process by which the normally developing binocularity is disrupted. Clearly, there is much to be done in this area.

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"The Development of Eye Alignment, Convergence, and Sensory Binocularity in Young Infants"

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The Development of Eye Alignment, Convergence, and Sensory Binocularity in Young Infants

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Joseph A. Bauer, and Richard Held**

Purpose. To measure and compare the development of ocular alignment, sensory binocularity, and convergence in infants during the first 5 months of life.

Methods. Healthy infants were tested between 2 and 21 weeks of age. Ocular alignment was measured by the Hirschberg test; convergence was determined by visual examination as an illuminated toy approached an infant's face; and sensory binocularity was measured by preferential looking for fusible versus rivalrous gratings. In experiment 1, we compared the proportion of infants at different ages demonstrating orthotropic ocular alignment with those showing convergence. In experiment 2, we compared the age of onset of convergence to that of sensory binocularity.

Results. Experiment 1: Most infants were orthotropic during the first month, and almost all of the others showed small amounts of exotropia. None of the infants showed accurate convergence until 6 weeks of age. By 4 months of age virtually all were orthotropic and had good convergence. Experiment 2: The onset of sensory binocular fusion occurred at 12.8 ± 3.3 weeks. Full convergence did not occur until 13.7 ± 3.2 weeks, although the first signs of convergence occurred slightly earlier. For individual infants there was a high correlation between the age of onset of sensory binocularity and convergence, and both onsets occurred earlier in girls than in boys.

Conclusions. Ocular alignment did not require the development of binocularity mechanisms, and the development of binocularity mechanisms did not await the onset of good ocular alignment. The relatively sudden onset of binocularity, both sensory (preference for fusion and stereopsis) and motor (convergence) at about 3 months of age and the high correlation between these measures indicate a common causal mechanism that probably involves refinements in striate cortex circuitry. Invest Ophthalmol Vis Sci. 1994;35:544–553.

Normal binocular vision requires orthotropic alignment of the eyes and the binocular mechanisms for disparity-controlled convergence, sensory fusion, and stereopsis. Many studies indicate that these different aspects of binocularity approach adult levels by 4 to 6 months of age.[1–5] However, differences in data and interpretation concerning the development of ocular alignment, convergence, binocular fusion, and stereopsis have made it difficult to determine the causal relationships among these components of binocularity.

The most consistent binocularity data are for sensory binocularity. Preferential looking toward binocularly fusible rather than rivalrous stimuli occurs suddenly in individual infants between 6 and 16 weeks of age. Previous studies show that young infants prefer viewing binocularly orthogonal gratings that are seen as rivalrous by adults who have normal binocularity. Older infants prefer the fusible grating.[3,6,7] Stereopsis tested with preferential looking,[2,8] motion tracking[9] or visual evoked potentials[10,11] also occurs with a sudden onset at this time. The onsets of binocular fusion and stereopsis occur at the same average age[3,7] and at the

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same relative age for individual infants within a sample as shown by the high correlation between the two onsets.[12]

The development of convergence is more complex because the convergence response is driven by several cues including accommodation, retinal disparity, and "proximity."[13] Under some conditions partial convergence can be demonstrated to occur intermittently in infants during the first month. It is believed that this sporadic convergence is triggered by accommodation.[1,14] According to Aslin and Jackson,[1,15] very young infants show inaccurate, inconsistent convergence to an approaching object but by 3 to 4 months their convergence is accurate and consistent.[1,15] Held[16] proposed that this accurate convergence results from the acquisition of disparity control mechanisms within the visual cortex. Using electro-oculograms, Mitkin and Orestova[4] demonstrated a sudden improvement in convergence between 12 and 15 weeks of age. The age of this sudden improvement matches the age of onset of stereopsis and suggests that retinal disparity plays an essential role in the improvement of accurate convergence.

Base-out prisms placed before the eyes provide retinal disparity cues that induce convergence in adults but do not trigger convergence in infants before 6 months of age.[1,17] This does not mean that disparity is not an effective convergence cue before this age. However, the disparity induced by a prism is in direct conflict with the information for convergence provided by accommodation and proximity cues. Thus, the prism technique may simply show that disparity cues cannot dominate over competing accommodative and proximity cues until 6 months of age.

Until recently, the literature concerning the temporal development of ocular alignment has also been relatively consistent. Most laboratories using corneal reflections from a fixation light have shown that, when large angle kappas (8° to 10°) are assumed, most infants are approximately orthotropic during the first month.[1,14,15,18] Data that demonstrated small consistent amounts of exotropia in young infants using a similar technique[19,20] have since been explained by the infant's large angle kappa.[21] Recently, Sondhi and colleagues[22] and Archer and colleagues,[5] using the examiner's face as a fixation target, reported that infants up to 2 months of age tend to have very large angles of exotropia ($> 40\Delta$) and then become orthotropic during the 3rd and 4th months. The cumulative percentage increase in orthotropia with age coincides with that of stereopsis and has led some authors to speculate that there might be a causal relationship between the basic alignment of the eyes and binocular fusion.[23] But, these findings differ sharply from those in which a standard Hirschberg test was used.

Because of their crucial importance in understanding the development of binocular mechanisms, we have examined the relationships among the development of eye alignment, convergence, and sensory binocular fusion in young infants. By comparing the presence of orthotropic ocular alignment and convergence in young infants we hope to determine if convergence is delayed until the eyes are aligned (consistent with Sondhi and colleagues[22] and Archer and colleagues[5]) or if the eyes are aligned at a much earlier age[1,14,15,18] and convergence develops according to its own mechanisms. By comparing the development of binocular fusion preference and convergence, both of which involve binocular circuitry, we hope to determine if these two processes develop together in an infant. If they do, this suggests that two similar mechanisms are developing in unison or that the onset of these two functions awaits the development of a shared binocular mechanism.

METHODS

This research followed the tenets of the World Medical Association Declaration of Helsinki. Informed consent was obtained from parents after the nature and possible consequences of the study were discussed. The research was first approved by the Massachusetts Institute of Technology Committee on the Use of Human Experimental Subjects.

Experiment 1

Subjects. Thirty-four healthy infants, who were the product of uncomplicated pregnancies and deliveries, were examined. All births had occurred within 3 weeks of the expected due date. In accord with the previous convention of the laboratory, all ages cited are relative to due date rather than the actual date of birth. This convention is used because grating acuity, the most widely studied visual standard for infants, has been shown to be best predicted by gestational age rather than postparturitional age.[24]

Each infant was examined during several visits (one to seven visits; mean 3.2 visits) usually on a weekly or biweekly schedule (mean time between visits 1.8 weeks). The mean starting age was 6.6 weeks (range 0 to 12 weeks). Two infants were excluded because they already demonstrated convergence (9 and 11 weeks of age). In this group, 22 infants were girls and 12 infants were boys.

Procedures. Eye Alignment: A standard Hirschberg test was performed in a dark room by two experienced examiners, one optometrist (FT) and one ophthalmologist (AC), at a distance of 1 m using a transilluminator. This fixation light was jiggled and flashed to obtain the infant's attention and fixation. It was never directed toward his or her eyes for more

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than a 2-second period without jiggling or flashing because young infants' orienting reflex often habituated so that it could be difficult to elicit repeated fixations.

The observer's score sheet had a series of three drawings of a pair of eyes. On each trial for which the observer believed the infant was fixating the target light, he carefully drew the position of the corneal reflections on a pair of eye drawings. Infants' pupils had approximately a 4-mm diameter (between 3.5 and 4.5 mm for six infants whose pupils were measured) and a conversion for the Hirschberg test of 20 Δ/mm was used.[21,25–27] Because an infant's angle kappa is normally 8° to 10°,[21] we considered decentered corneal reflections to indicate exotropia only when they were more than midway from the pupillary center to the nasal pupillary margin. We believe this method provides an accuracy significantly finer than 0.5 mm per eye ($< 5.7°$ or 10Δ). A comparison of interocular differences is even more accurate ($< 3°$ to 4°). Unmeasured interocular differences in angle kappa might introduce additional uncertainty. However, Barry and colleagues,[28] using the first and third Purkinje images of three infrared lights to precisely measure the angle alphas of infants and children, have demonstrated asymmetries of less than 1° in infants. Accordingly, we are confident that our estimates of ocular alignment are accurate to within 10Δ. Such an estimate allows us to measure eye alignment accurately enough to state that alignment is adequate for binocular fusion or coarse stereopsis, but we cannot estimate if the eyes are aligned well enough for fine stereopsis.

The unilateral cover test could resolve the problem of interpreting the Hirschberg test, but it is difficult to perform a cover test on young infants because they normally withdraw from or look at the cover placed before one eye. Examiner FT performed a standard unilateral cover test on 12 unusually cooperative infants between 4 and 8 weeks of age whom he judged to be orthotropic by the Hirschberg test despite a slightly nasalward position of the corneal reflex.

Convergence: An examiner (FT) jiggled an illuminated toy in a dark room approximately 0.5 m from the infant's face until the infant fixated on it. It was then moved slowly toward the bridge of the infant's nose while the examiner observed the infant's eyes. Convergence was classified as none, the first sign of convergence (any bilateral adduction), and full (complete binocular pursuit to within 12 cm of the face). The toy used for a fixation target was a brown rubber pony, the face of which was internally illuminated by the transilluminator. The toy's face was approximately 2 cm in diameter and contained no fine details. The data for the second observer were not included because he often used a different criterion.

Experiment 2

Subjects. Fifty-nine infants (23 girls and 36 boys) were included in this experiment. Fifteen of these also participated in experiment 1. The infants had a mean of 6.5 visits. The mean age for initial testing was 7.5 weeks (range was 1 to 11 weeks). As in experiment 1, all ages are relative to due date.

In order to compare the ages of onset of convergence and binocular fusion preference, we have included in our data analysis only the infants who completed both tasks after showing neither response on their first visit (n = 59). We did not include infants who started the study at an age more than 11 weeks after their expected due date (n = 11, first visit between 11.5 and 16 weeks), infants who did not complete one or both tasks because they did not return before the expected onset of binocularity (n = 2), infants whose onsets were so late that the parents tired of the study (n = 5, discontinued between 22.5 and 29 weeks), and infants who already demonstrated one or both of the binocular responses on their first visit (n = 4, first visit between 7 and 11 weeks). The exclusion of these infants should not alter the overall mean onsets significantly but may truncate our distribution of onsets by eliminating primarily infants with very early or very late binocularity onsets. This truncation would be expected to reduce variance of onset age and therefore reduce the correlation between convergence and binocular fusion onsets.

Procedures. Convergence: Convergence was tested by one examiner (FT) using the same procedures described in experiment 1. The age of onset for the first sign of convergence was the earliest age at which any bilateral adduction was observed in response to the approaching illuminated toy; the age of onset for full convergence was the earliest age at which complete binocular pursuit to within 12 cm of the face was observed.

Binocular Fusion: Sensory fusion was tested by the fusion-versus-rivalry preferential looking technique.[6] During this procedure the infants sit on their mothers' laps and wear lightweight goggles containing crossed-polarized filters. They view a screen from a 70 cm distance. Flashing fixation lights are used to bring an infant's attention to the center of a dark 3.6° vertical region bounded on both sides by 17°-horizontal by 27°-vertical screens. One screen side has crossed-polarized superimposed vertical gratings, which are readily fused by normal adults; the other side has nonfusible crossed-polarized orthogonal gratings, a vertical grating viewed by one eye and a horizontal grating viewed by the other, which are not fusible by normal adults. Gratings consisted of a rectangular wave of 0.40 cycles per degree.

The criterion for the onset of sensory binocular

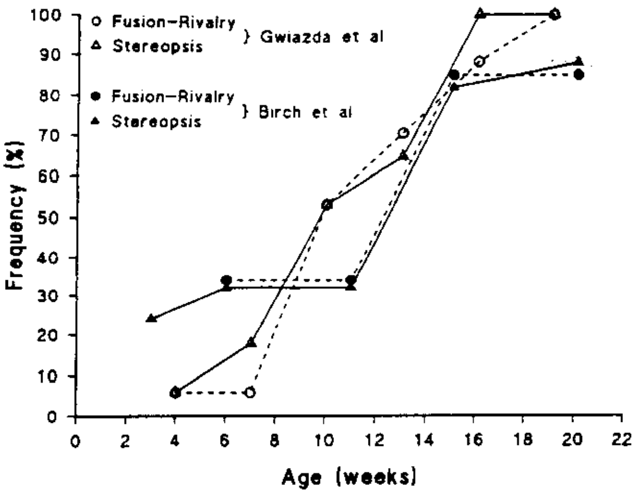

FIGURE 1. Cumulative proportion of infants showing stereopsis and fusion preference as a function of age. Data from Gwiazda and colleagues[7] (n = 17) and Birch and colleagues[3] (n = 9).

fusion is the age at which an infant first has a looking preference for the binocularly fusible gratings on 12 or more of the 15 trials in one session provided that the infant preferred the fusible gratings on 21 or more of the 30 trials during that session and either the preceding or following session. Both the single session and two session performance levels have been chosen because the probability of reaching either is less than 0.05. The experimenter performing the binocular fusion preferential looking testing (JG) was unaware of the results of convergence testing, and the experimenter performing convergence testing (FT) was unaware of the fusion preference results.

Preference for binocularly fusible versus rivalrous patterns normally switches suddenly from a preference for viewing binocularly orthogonal gratings, that are seen as rivalrous by normal adults, to a preference for the fusible grating[3,6,7] at about the same age as the onset of stereopsis.[3,6,7] The similarity in fusion and stereopsis development is shown in Figure 1 using data from Birch and colleagues[3] and Gwiazda and colleagues.[7] The original data from these articles have been grouped into 3-week intervals in the same way that we have grouped our data in experiment 1. In both studies data from individuals show that the onsets of stereopsis and binocular fusion preference occur within 1 week of each other for a majority of the infants. This laboratory generally uses the binocular fusion–rivalry preferential looking test rather than stereopsis because it requires simpler instrumentation and calibration and because it is designed to be unaffected by significant amounts of ocular misalignment even though it is highly correlated with stereopsis. It is also easier to score.

Quantifying the Relationship Between Convergence and Fusion Onset: We have quantitatively related the age of onset of full convergence to that of binocular fusion preference. Such a relationship is usually calculated by means of a linear regression equation. However, a linear regression equation is only valid when relating a dependent variable that was actually measured to an independent variable. Our data involve the measurement of two dependent variables. The simple linear regression function, which assumes that the measurements on the x axis at given points are without significant variance, minimizes variance on the y axis only. This leads to a slope that is always less than it would be if realistic assumptions had been made about variance on the x axis. Therefore, we have calculated a mutual regression function based on the best-fit line of principal axis analysis to compare the age of onset of full convergence to that of binocular fusion preference.[29]

RESULTS

Experiment 1

The proportion of infants showing orthotropia and convergence is plotted in 3-week intervals in Figure 2. At less than 6 weeks of age, most infants showed orthotropia, but none showed full convergence. The age at which 50% of the infants demonstrated full convergence was 11.9 weeks.

The discrepancy between the observations of the two examiners can be accounted for as follows. The

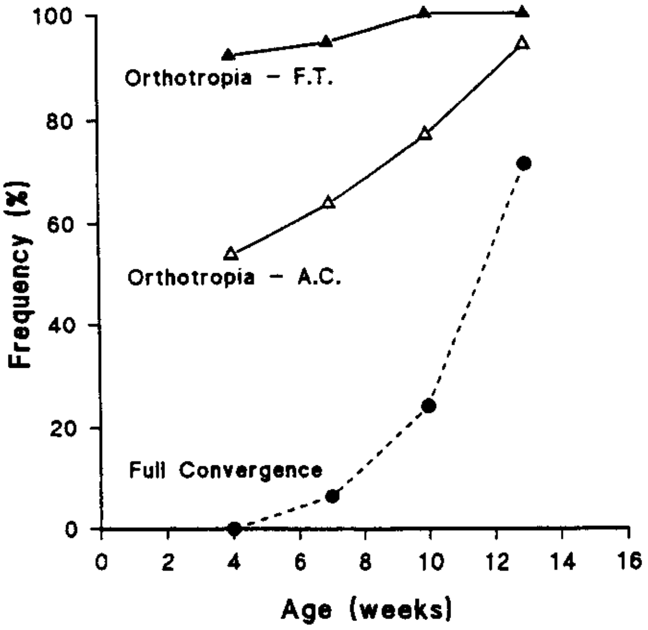

FIGURE 2. Proportion of infants demonstrating orthotropia according to two examiners and demonstrating full convergence, as a function of age.

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two examiners judged about the same total amount of nasal decentration of the corneal reflection for almost all infants. Often this was about halfway from the pupil center to the nasal margin of the pupil because of the infant's large angle kappa. If both reflections were less than half way from the pupil center our criterion for orthotropia was reached. If one was closer to the pupil center and the other closer to the nasal margin of the pupil, then it was judged that the reflections were asymmetrical and that an exotropia occurred. Thus, the difference between an orthotropia and a small exotropia involved a subtle measurement difference (usually within our measurement error range). One observer accepted symmetry of corneal reflections more often than the other (for infants less than 1 month of age, 93% versus 56%). It should be noted that both corneal reflections always fell within the pupillary margins for both observers, indicating that exotropias were never more than 30Δ.

During the 80 subject visits when an infant was seen by both examiners, they agreed that the infant was orthotropic 62 times and exotropic two times. Examiner FT judged exotropia only twice when examiner AC judged orthotropia, but examiner AC judged exotropia 14 times when examiner FT judged orthotropia. During 32 visits the infant was too uncooperative for one of the examiners to make a judgment. On these visits, the successful examiner showed the same proportion of orthotropic judgments as when both examiners were able to make successful judgments. One infant was judged to have intermittent esotropia on all four of his visits.

The unilateral cover test was performed successfully on 10 of the 12 infants tested between 4 and 8 weeks. In each case, the infant's fixation did not move when one eye was covered, indicating that the infants were indeed orthotropic.

Experiment 2

Figure 3 shows cumulative onset functions for binocular fusion preference and the two criteria for convergence (first sign of convergence and full convergence) with each data set being fit by a Gaussian integral. The three best-fit functions are very similar with the same slope.

There were no positive responses before 5 weeks of age. The mean onset for binocular fusion preference was 12.8 ± 3.3 weeks. Fusion preference is preceded by the first indication of convergence (mean 12.1 ± 3.2 weeks) and followed by the onset of full convergence (mean 13.7 ± 3.2 weeks). These onsets for binocular fusion are slightly later than in previously published studies[3,4,7] and these convergence onsets are significantly later than those in experiment 1. This discrepancy is partially explained by the fact that most studies calculate the population onset age as the age when 50% of the infants achieve a particular behavior. Because the distributions for the data in this experiment are positively skewed normal distributions, the 50% achievement criteria occurs earlier than the means (fusion preference 12.1 weeks, first sign of convergence 11.4 weeks, and full convergence 13.1 weeks). This age of onset estimate is 0.6 to 0.7 weeks earlier than the calculated means. The other identifiable factor is that, through chance differences in scheduling, most of the infants in experiment 2 were boys, whereas most of those in experiment 1 were girls (see below).

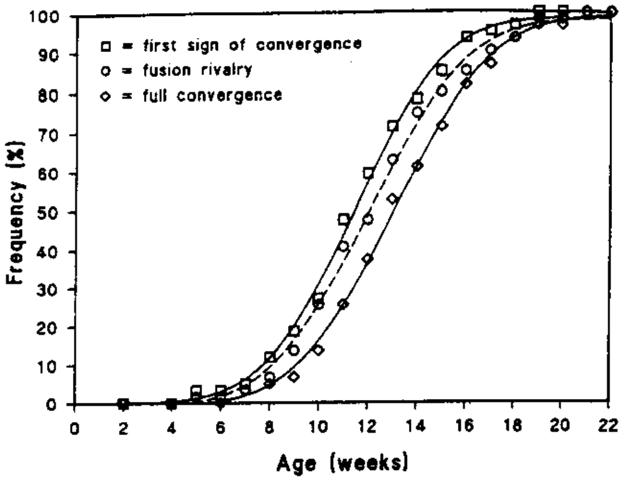

FIGURE 3. Cumulative proportion of infants showing the onset of partial and full convergence and binocular fusion–rivalry preference, as a function of age.

For individual infants both the preference shift from rivalry to fusion and from no convergence to full convergence occurred during a brief period, normally less than 2 weeks. For 53% of the infants, the first sign of convergence was full convergence pursuit. Although the onset of fusion occurs only 1 week before full convergence, the difference is statistically significant (paired $t = 2.43$, $P = 0.018$ two-tailed).

The similar onset functions for the group as a whole are reflected in the individual data. The onsets for sensory fusion and full convergence for the individual infants showed a significant correlation ($r = 0.59$, $P < 0.0001$), as shown in Figure 4. The magnitude of this correlation is somewhat limited by a narrow distribution of onset ages (SD 3.1 weeks). The principal axis best-fit line for this scatter plot is $C = 0.941\ (F) + 1.668$, where C is onset age of full convergence, and F is onset age of fusion preference, both in weeks of age. The slope of this best-fit line is not significantly different from 1.0. The age of onset of the first sign of convergence also demonstrated a significant correlation with the age of onset of binocular fusion ($r = 0.54$, $P < 0.0001$).

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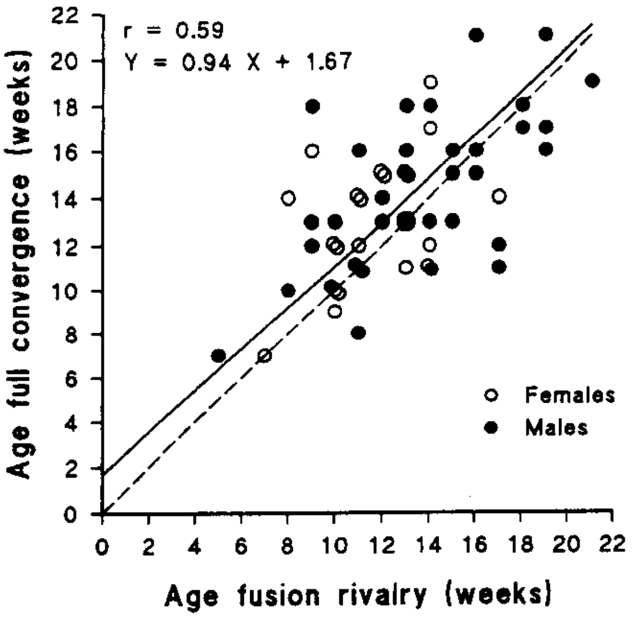

FIGURE 4. Scatter plot for age of onset of full convergence and binocular fusion–rivalry preference for all 59 infants in experiment 2. Open circles, girls; filled circles, boys.

As in earlier studies,[7,30] girls have an earlier mean onset age than boys for binocular fusion preference (11.6 versus 13.5 weeks). The mean onset of full convergence also occurred earlier in girls (13.0 versus 14.2 weeks). A two-dimensional analysis of variance shows that girls have a significantly earlier onset than boys for these binocular measurements ($F[1,57] = 4.329$, $P = 0.042$) and that fusion preference occurs significantly earlier than convergence ($F[1,57] = 6.584$, $P = 0.013$). However, there is no significant interaction effect between gender and the visual task ($F[1,57] = 0.838$, $P = 0.364$). The lack of an interaction suggests that a subject's gender does not induce a significant difference between the ages of onset of the two tasks even though t tests show that girls precede boys by a highly significant amount for binocular fusion ($t = 2.26$, $P = 0.014$ one-tailed) and a not quite significant amount for convergence ($t = 1.44$, $P = 0.078$ one-tailed).

DISCUSSION

Our data show that the onset of convergence and sensory fusion can neither be the cause nor the result of good eye alignment because most infants' eyes are orthotropic or very close to orthotropic during the first month. On the other hand, the close link between convergence and sensory fusion onsets is unmistakable. The two onsets occur at about the same time and the correlation between the two onsets is highly significant. This suggests a common causal factor, which we believe is the onset of functioning fusion and disparity mechanisms in the central visual system.[12]

Factors in Judging Ocular Alignment

Our ocular alignment data are similar to those in most previous studies.[1,14,15,18] However, our examiners considered the differentiation between orthotropia and small angles of exotropia to be the most difficult judgment that they performed. The four major sources of uncertainty or error in making these judgments are: the large angle kappa of infants, the absence of convergence, difficulty in judging when an infant is looking at a fixation target, and the infant's arousal level. All of these factors can increase the likelihood that aligned visual axes will be judged as exotropic.

The basic factor confounding the interpretation of an infant's ocular deviation is the angle kappa. We might expect the reflection of a light on a subject's cornea to be centered in the pupil when the subject fixates the light, but this is rarely the case. The corneal reflection is usually displaced relative to the optical axis or pupillary center by an amount denoted as angle kappa. Slater and Findlay[21] showed (using photographs of corneal reflections during monocular viewing) that the mean empirical angle kappa of neonates is 8°, consistent with the 8.5° angle kappa calculated on anatomical considerations. This finding implies that, based on the Hirschberg test, neonates would appear to have a 30Δ exodeviation when their eyes are perfectly aligned on a distant target.

The lack of convergence shown by young infants can add to the illusion of an exodeviation, because an infant must be tested with a relatively near target. We have tested as far away as we deemed practical (1 m). If the interpupillary distance of an infant is assumed to be about 40 mm, this viewing distance would add 4Δ exo to a nonconverging infant's apparent exodeviation. The nearer viewing distances (25 cm to 50 cm), that are commonly used in testing infants, also add to the appearance of an exodeviation (16Δ and 8Δ, respectively).

The calibration of a zero point for the Hirschberg test is very difficult because we can never be certain of precisely where an infant is fixating. We believe the primary reason that our two observers did not always agree with each other is that infants do not always look at the fixation light. For example, if an infant looked directly at the fixation light on each of three fixation trials, each eye would have a corneal reflection decentered nasally by about 8° from the center of the pupil. If the infant looked just 8° to the side of the fixation light on one trial, the corneal reflection would be centered in one eye and 16° nasal in the other eye, and this infant would be categorized as having an intermittent small-angle exotropia. Thus, judgments of when

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the infant is fixating the light or off to the side are crucial. Photographic or video records of the Hirschberg test appear to provide a more accurate measurement of eye alignment than simple direct viewing as used in our study.[1,14,15,18-20] These techniques provide a hard copy of the infants' looking behavior and therefore allow for repeated precise measurements. But, the key factor causing inaccuracies in using the Hirschberg test on infants is the judgment of where the infant is looking and this must be made by an observer. The unilateral cover test can resolve the problem of interpreting the Hirschberg test when fixation and the size of the angle kappa are uncertain. For the ten infants under 8 weeks of age on whom the unilateral cover test was successfully performed, the infants were indeed orthotropic even though large angle kappas made the interpretation of the Hirschberg test difficult.

Finally, an infant's arousal level can influence eye alignment. Rethy[31] used the Hirschberg test to measure eye alignment in sleeping neonates. He judged 37% of his premature and 43% of his full-term sleeping infants to be orthotropic with the remainder showing 15° to 35° of exodeviation. He believed that this tendency toward exotropia approximates the anatomical position of the eyes at rest, noting that when the neonates awoke their exotropic eyes would often assume an orthotropic position. By 3 weeks of age most infants showed an orthotropic alignment during testing due, he believed, to increased wakefulness, accommodative convergence, and stronger fixation behavior.

Using a Face as a Fixation Target

Recently, a group used a very different technique for measuring the ocular alignment of young infants.[5,22,32] The examiner held the infant on his or her arm with the head in the examiner's hand so that the infant could fixate on the face of the examiner. The examiner then used the corneal reflection of his or her own face, which appears as a dark silhouette against a light background. Thus, rather than judging the position of a small light spot on the cornea tested from a 0.4- to 1.0-m viewing distance, the examiner judged the position of a large dark area against a slightly lighter background from a 0.2 to 0.25 m viewing distance. The rationale for this technique was that infants attend to a face better than to a light. However, our examiners found the task of judging the position of their own reflection from an infant's cornea to be far more difficult than the Hirschberg test.

Nixon and colleagues,[32] using the novel technique described above, report that 58% of 1031 testable newborn infants were orthotropic and 39% exotropic. Sondhi and colleagues,[22] using the same technique, found that 30% of 2271 newborns were orthotropic and that almost all the others were exotropic. These proportions remained constant through 6 weeks of age. There was then a rapid increase in orthotropia to 75% at 3 months and 97% at 6 months. Archer and colleagues,[5] again using the same technique on 3316 newborn infants, found that fewer than 25% were orthotropic with 72% showing an exotropia. At 3 months, 75% were orthotropic and at 6 months 97% were orthotropic. We do not know why Nixon and colleagues[32] found a much higher percentage of orthotropic neonates, because this study involved the same group of experimenters using the same technique as the two subsequent studies. In Archer and colleagues'[5] study moderate exotropias (defined as a corneal reflection falling more than halfway to the limbus from the pupillary center) were seen in 52% of newborn infants and 30% of 1-month-old infants. If the infant's pupillary diameter is 4 mm, the horizontal width of the infant's cornea from limbus to limbus is 10 mm, and we assume 20Δ/mm angular deviation, then this deviation amounts to 40Δ to 100Δ of exodeviation, which most examiners would consider a large-angle deviation, and is in direct contradiction to all the other studies cited.[1,14,15,18]

Because of the large samples used in these studies,[5,22] the findings have received considerable attention. Thus, it is important to try to understand why they differ from our findings and those of so many others. A large angle kappa and a lack of convergence for a near viewing distance can account for about a 45Δ exodeviation. However, if the infant is alert and fixating on the examiner's eyes, the corneal reflections would be approximately symmetrical and the examiner would interpret this as orthotropia with a large angle kappa. We think the unusual confounding factor, when using the examiner's face as the fixation target, is that the facial features on which the infant fixates change with age. Infants younger than 2 months of age tend to fixate on the largest high contrast feature of the head, namely the hair line and the silhouette of the head.[33-36] In Archer and colleagues'[5] procedure, the room lighting comes from behind the examiner so that features of the face are especially dim relative to the silhouette of the examiner's hair. If Archer and colleagues'[5] young infants fixated on the lateral hairline and silhouette, then the examiner would be 15° to 20° (26Δ to 35Δ) eccentric to the line of sight and would conclude that the infant was highly exotropic. By 4 months of age, infants act more like adults, spending most of their time looking at the features of the face[33-36] with special attention on the eyes.[37]

It is surprising that the cumulative distribution of the age of orthotropia onset from Archer and colleagues'[5] study is so similar to the cumulative distribution of the age of onset of stereopsis and binocular fusion[5,6–8,23] and convergence (Figs. 1, 3) if Archer and colleagues' data are due to a mechanism as seemingly unrelated as the change in an infants' strategy for facial scanning. A portion (about 15Δ) of the reduction they show in exotropia during the 3rd and 4th month can be explained by the onset of consistently accurate convergence. The similarity in the development of facial scanning and binocularity may be explained by the findings of Kleiner and Banks.[38] They have shown that the proportion of time that 2-month-old infants look at a drawing of a face versus a competing pattern is related to the phase spectrum of facial features rather than the contrast spectrum of the pattern. It is the phase spectrum of borders within a picture or drawing, not the contrast spectrum, that allows adults to recognize faces and other objects although an altered contrast spectrum may degrade the visibility of the face or object.

Our laboratory has demonstrated that vernier acuity, which measures sensitivity to phase changes within a pattern, develops in parallel with stereopsis and binocular fusion preference.[39] In fact, vernier acuity is similar to stereopsis and binocular fusion in that girls develop it at an earlier age than boys.[40] We have hypothesized that vernier acuity develops parallel to binocularity because it also depends on the development of the visual cortex. Thus, the serendipitous parallel development of binocular mechanisms and eye alignment as described by Archer and colleagues[5] may represent the development of mechanisms within the visual cortex both as they relate to fusion-induced convergence and to the phase-sensitive mechanisms needed for adultlike facial scanning.

Eye Alignment Versus Sensory Binocularity

Most young infants are within a few prism diopters of orthotropia even though functional binocular mechanisms do not develop until about 3 months of age. Thus, it is clear that binocular mechanisms are not necessary for good ocular alignment in early infancy. The question of whether good ocular alignment is necessary for the development of binocularity is not as clear. We know that surgically induced exotropia in kittens[41] and infant monkeys[42] during the critical period for susceptibility to abnormal visual experience causes a loss of cortical binocularity and therefore a loss of the mechanisms required for fusion-induced convergence. However, the critical period for the development of sensory binocularity in humans with strabismus does not start at birth but at about 6 months of age.[43,44] In addition, Birch and Stager[45] have shown that infants who become strabismic have as high a probability of developing stereopsis before strabismus onset (between 3 and 5 months of age) as do normally developing infants. Thus, it may be that good ocular alignment is not necessary for the development of the neural mechanisms underlying binocularity, although the maintenance of these binocular mechanisms requires good alignment.[45] Because good eye alignment exists in most young infants, this is difficult to test.

Convergence Versus Eye Alignment and Sensory Binocularity

Convergence involves ocular alignment and sensory binocularity because the function of convergence is to align the eyes for different viewing distances using binocular information. Ocular alignment is important for fusional convergence because fusional convergence cannot be expressed if the eyes deviate excessively, even if the necessary retinal disparity control mechanisms exist in the brain. Similarly, stereopsis and binocular fusion cannot normally be expressed if the ocular deviation is excessive or if convergence does not allow bifixation at a near distance. Our data indicate that convergence depends on mechanisms similar to those of sensory fusion and stereopsis. These similarities include the gender difference in which girls develop earlier than boys. Thus, just at the time binocular mechanisms require reinforcement as they enter into their critical period, fusional convergence is initiated to provide this fine control of ocular alignment at all viewing distances.

Cortical Control Mechanisms

The visual cortex, as well as other cortical areas of postnatal infant primates, continues to develop along a number of parameters including neuron size, neuropil density, dendritic spine density, and the number of synapses.[46,47] Although these quantitative changes imply functional change during the postnatal period, they do not lend themselves to an analysis of the functional neural refinements expected to be associated with visual refinement. The ocular dominance columns of the striate cortex provide a model system for visualizing refinement of columnar circuitry. In the newborn rhesus macaque, ocular dominance columns are readily identified in layer 4 of the striate cortex but the boundaries between adjacent columns are highly blurred. This indicates a diffuse lateral geniculate nucleus input to layer 4 that crosses the functional borders that must be maintained for proper binocular function.[48] In effect, the information from the two eyes is mixed together at their entrance into the striate cortex so that the interocular comparison needed for retinal disparity comparison would be scrambled.[16,23]

By 2 months of age the boundaries between adjacent columns are sharply delineated and the monkey's stereopsis can approach adult levels. In humans, ste-

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reopsis suddenly develops in individual infants at an average age of 3 months, consistent with a refinement of the ocular dominance boundaries.[49] At the same time infants stop preferring a pattern containing orthogonal gratings to the two eyes and start to look preferentially at binocularly fusible gratings. Shimojo and colleagues[6] suggest that in the young infant the orthogonal gratings may be integrated into a preferred grid pattern and that only when the information from the two eyes is segregated within layer 4 of the striate cortex can the two gratings be disengaged so that one can be suppressed by the other through binocular rivalry. At that time the fused (or summed) parallel gratings would suddenly be preferred to the rivalrous pattern.

The parallel between the development of vernier acuity and the sensory binocular functions is expected if vernier acuity also depends on a refinement of cortical columns (though not ocular dominance columns). In this case, precise relative monocular position sense (or spatial phase) rather than a precise relative interocular positional sense between the two eyes develops rapidly at about the same age. This refinement of the positional sense appears to underlie the mature facial scanning behavior of the 3- and 4-month-old infant that allows an examiner and parents to observe the infant looking directly at their face.

Conclusions

Most infants are orthotropic at 1 month of age; almost all the others are just slightly exotropic. Thus, the results of this study indicate that early infantile ocular deviations cannot delay the development of binocularity mechanisms, nor can the binocular mechanisms that develop at about 3 months of age have an effect on the initial alignment of the eyes. The relatively sudden onset of binocularity, both sensory (preference for fusion and stereopsis) and motor (fusional convergence), at about 3 months of age and the high correlation between these measures suggest a common causal mechanism. We hypothesize that this important benchmark involves the refinement of circuits in the cerebral cortex, especially those of the ocular dominance columns.

Key Words

infants, ocular alignment, binocular fusion, convergence, binocular vision

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