Lecture 20 - Normal Binocular Development

(Steinman Chapter 9; Schwartz Chapter 17)

INTRODUCTION TO BINOCULAR VISUAL DEVELOPMENT

Many visual problems are the result of abnormal development of the visual system during the formative early years. If we understand the normal course of binocular visual development, we will be able to better isolate the causes of these problems and intervene to protect the visual development of these patients.

Much work has been done in the past several decades, but much is still unknown. Infant vision research (as well as infant eye exams) presents special challenges:

- Infants are difficult to communicate with.
- They are easily distracted.
- They fatigue quickly.

Therefore, special test procedures have been developed, some of which resemble tests designed for animals.

TECHNIQUES USED TO STUDY SPACE PERCEPTION & BINOCULAR VISION IN INFANTS

One classic technique is the **visual cliff**. The infant is placed on an elevated surface, which has a steep drop-off at one edge. The drop-off is covered with a thick sheet of glass to protect the infant from falling, but since it is transparent, the dangerous precipice will be visible if he approaches the edge. This was originally designed to test infants who were old enough to crawl. When called by their mothers, most babies would proceed along the surface but stop at the edge. This showed that they could perceive depth. For infants too small to crawl, their response to the visual cliff could be tested by monitoring their heart rate as they were placed near the edge. See the illustration from the Scientific American article by Gibson and Walker (1960). See Fig. 1 to the right and **Steinman Fig. 9-4**.

Figure 1. Visual cliff

Some researchers studied infant responses to the impending collision of objects, or they assessed their skill in reaching for objects. These studies showed that depth perception improved as a function of age, but by these tests, it was hard to distinguish how much of this was just an improvement in the child's attention or the actual development of vision. It is also difficult, at this age, to distinguish the influence of monocular and stereoscopic depth cues.

More recently, the **preferential looking** technique has been used to test the infant's perception of binocular disparity. An example is shown in **Adler's Fig. 24-39 (**9th edition). An infant wearing polaroid spectacles is presented with two targets. One contains a random-dot stereogram, while the other is just a flat random dot pattern. The assumption is that the baby will prefer to look at the stereogram if he can perceive the stereoscopic depth. If he has no stereopsis his gaze will be random. A commercial version of the preferential looking stereoacuity test, called the Randot Stereo Smile Test, is available from Stereo Optical Company (http://www.stereooptical.com/), the same company that sells the Stereo Fly test.

When viewing the random dot stereogram, the infant sees disparate images in each eye. This can be thought of as a special kind of **uncorrelation**, but it is not random uncorrelation; the disparate portion has been shifted horizontally. Does the visual system of young infants truly detect stereoscopic disparity, or is it simply detecting uncorrelation between the two images? This was tested experimentally by comparing how infants responded to pairs of images that had either horizontal or vertical disparities. In both cases, a similar kind of uncorrelation existed between the right and left images. They found that infants with apparent stereopsis showed no preference for vertical uncorrelation. This indicates that they are truly detecting stereopsis, and not just uncorrelation.

Figure 2. The Randot Stereo Smile Test

Another way to study binocular vision in infants is to record the **VER** (visually evoked response) while the child is presented targets that contain binocular disparities. When targets are visible, the electrical response of the visual cortex is apparent in the VER trace.

TIME COURSE FOR THE DEVELOPMENT OF NORMAL BINOCULAR VISION

The critical period

There is a critical time period for the development of normal vision, which begins several months after birth and continues until an age of 6-8 years. If a person is to develop normal binocular vision, both eyes must receive good quality, correlated retinal images (i.e., no cataracts or large uncorrected refractive errors, no strabismus) during this time. If the quality of either image is poor, this will lead to **amblyopia**. If the images are of good quality, but are highly uncorrelated (for example, due to strabismus), then visual acuity may develop normally, but binocular fusion will not develop normally.

In the case of monocular deprivation, **reverse occlusion** (occluding the better eye), if started early within the critical period, can prevent the development of amblyopia and may restore normal binocular development (assuming there is no strabismus). After the critical period, the abnormal development of the binocular system will be permanent and reverse occlusion or other treatments will not restore binocular vision.

The critical period for binocular development does not begin until *at least two months after birth*, which is fortunate, since this is when the oculomotor system develops enough that motor fusion becomes possible. Quoting from Steinman (p. 275)

> *If the critical period were to begin exactly at birth, the diplopia that the infant would experience from the uncorrelated eye movements could have a strong detrimental influence on visual development, in particular the development of binocularity. This would almost certainly ensure that every infant would develop binocular visual problems. It would be advantageous for the visual system to wait, that is, to hold off the critical period for the development of binocularity until precise extraocular muscle control could be exerted by the infant. This is, in fact, what happens. The critical period for binocular vision does not begin immediately at birth, and binocular vision takes months to begin to develop. For example, human infants do not develop amblyopia from the presence of cataracts or strabismus before 2 months of age.*

The critical period in humans appears to be divided into two phases:

- Infantile phase - several months after birth to about 8 months of age
- Post-infantile phase - from about 8 months to 9 years of age

During the initial infantile phase, visual functions appear to develop rapidly, but during the post-infantile phase the rate of development slows. During the infantile phase, visual acuity improves quickly and stereopsis develops during this time. Anatomic studies confirm that this is a time of rapid growth (**Adler's Fig. 24-48**). The top graph shows the steep increase in cerebral cortex volume and the density of synapses per cubic mm during the first 10 months of life. The improvement in visual acuity is shown in the lower graph.

Growth in the magnocellular system begins sooner and proceeds more quickly than the parvo system. Therefore magno functions, such as motion perception, develop faster than parvo functions, such as fine visual acuity or fine-static stereopsis.

Motor fusion and eye movements
A prerequisite for sensory fusion is motor fusion. **Adler's Fig. 24-44** shows that newborns normally have unstable ocular alignment, and intermittent strabismus is common. The majority of babies in this age range have an intermittent exotropia (top curve); some vary between intermittent exo and eso deviations (middle curve); a small number tend to show occasional esotropia only (lowest curve). Notice that there is a steep decline in ocular misalignments between 3 and 6 months of age. By about 6 months of age, the majority of these infants are fixating normally.

It is important to understand that this variable, intermittent and temporary strabismus (usually exotropia) is part of normal binocular development for most babies. A mother visiting your office might be concerned that her 3-month old baby's eye's appear to turn out occasionally. You can assure her that this is common in that age range, and as the visual system matures, the occasional exotropia usually ceases and normal binocular vision develops. Quoting from Tychsen (Adler's, p. 808),

> *Vergence in neonates is unstable, wavering between under- and overconvergence. Errors of underconvergence are more common. Vergence becomes remarkably accurate by 6 months, implying substantial development of input to the motoneurons encoding convergence.*

At first the oculomotor system shows a preference for pursuit movements for targets that are moving from the temporal field toward to the nasal. This can be appreciated by occluding one eye and observing the fixating eye. See **Fig. 24-43 in Adler's** (9th ed). By about 3-5 months, the normal infant develops the ability to smoothly follow targets moving in either direction. Quoting from Adler's Fig. 24-43:

> *When a handheld toy is moved from temporal-to-nasal before the fixating eye, pursuit is smooth. Pursuit is absent or cogwheel when the target moves nasal-to-temporal. The movements of the two eyes are conjugate, and the direction of the asymmetry reverses instantaneously with a change of fixating eye, so that the direction of robust pursuit is always for nasally directed targets in the visual field. ... The asymmetry indicates immaturity of binocular motion processing connections in visual cortex.*

Sensory fusion and stereopsis
During 1-3 months of age, the infant's visual system becomes capable of simultaneous perception of images (Worth grade 1 fusion). By 3 months they show an aversion to rivalry, which indicates that they have the ability to flat fuse images (Worth grade 2 fusion) and between 3 to 5 months full stereopsis suddenly develops (Worth grade 3 fusion).

The development of stereopsis does not parallel the development of visual acuity, which is poor at birth but steadily improves over the first few years. At birth, there is apparently no stereopsis, but this perception starts to develop at about 4 months. It then shows an abrupt improvement to near adult levels within a few weeks. This is illustrated by **Adler's Fig. 24-41A**.

Generally girl babies develop stereopsis about one month sooner than boys. Held speculated on the cause for this difference (in Regan, Ch. 9, p. 172).

> *Significant differences between the sexes in the ages of onset of both stereopsis and response to binocular rivalry were discovered. Females tend to show earlier onset than males. ... 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 the cortex. Held et al. (2084) 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.*

The sensitivity to crossed disparity (objects nearer than fixation) generally develops about 3 weeks earlier than uncrossed disparity stereopsis.

By **6 months** of age, the average infant has a stereoacuity threshold of **60 arc seconds**.

HELD'S TWO STAGE MODEL OF DEVELOPMENT

Histological studies of the visual cortex showed that early in life the afferent input from the LGN into the primary visual cortex (V1) are not clearly segregated into ocular dominance columns. Gradually over the first six months, the ocular dominance columns emerge, and this may be important to the development of binocular sensory fusion.

Recall that in the adult visual system (Lecture 22), the geniculate neurons that first synapse in V1 layers IVC α and β are monocular. That is, they receive input from either the right or left eye via the LGN. They are however organized into ocular dominance columns. This segregation into right/left ocular dominance columns is not present at birth.

As shown in Fig. 3, copied from Held (Regan, Ch. 9, p. 175) and in **Adler's Fig. 24-47**, prior to the emergence of ocular dominance columns, there is considerable overlap between the axons coming from the LGN, so that some of the first order neurons in layer IVC are initially binocular—they do have connections to both the right and left eye.
Quoting from Steinman (p. 279),

> *This overlap of information from the two eyes within layer 4C prevents the existence of binocularity and stereopsis, as cells outside layer 4C destined to become binocular cells then receive two inputs each with mixed information from both eyes, rather than two inputs with distinct left- and right-eye information.*

As the visual area matures in the first few months of life, the neurons specialize and segregate into ocular dominance columns. As such, each of the first order neurons (layer IVC α and β) receives input from either the right or left eye, but not both. At the next level up (layer IVB or layer II or III), right and left eye inputs are combined into truly binocular neurons in the mature visual cortex. Quoting from Held (Regan p. 175)

> *Another possible explanation for binocular development is derived from the observation that the ocular dominance columns of layer IVC are either not segregated or are incompletely segregated at birth. ... The model 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.*

Figure 3, from Held, "Development of Binocular Vision and Stereopsis", in Regan.