Visual Development in the Human Fetus, Infant, and Young Child

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The development of the visual system is the most studied of the sensory systems. The advances in technology have made it possible to study the neuroprocesses at the cellular and circuit level. The physical structure of the eye develops early in fetal life, whereas the neurocomponents and connections develop in later fetal and early neonatal life. The development of the visual system involves genetic coding, endogenous brain activity, exogenous visual stimulation after birth at term, and protected sleep cycles, particularly rapid eye movement sleep. Before birth at term, the fetus requires no outside visual stimulation or light. The critical element in development of the visual system before birth at term is protection of rapid eye movement sleep and sleep cycles. Sleep deprivation or disruption in utero and early months of neonatal life causes significant interference with visual development resulting in loss of the topographic relationships between the retina, the lateral geniculate nucleus, and the primary visual cortex in the infant.

Keywords: Visual development; Fetal development; Eye; Sleep deprivation, Fetus, Newborn infant; Retina; Endogenous stimulation

The recognition of retinopathy of prematurity (ROP) or retrolental fibroplasia has been the focus of research and changes in clinical care practice for more than 50 years. The early studies in visual development were focused on the diagnosis of ROP and factors associated with cause and frequency of occurrence. The existence of ROP led many investigators to study the development of the human eye and especially the early developmental process that could have an association with ROP.

The processes involved in visual development are the most studied and best understood of all of the sensory systems of the fetus and young infant. The advances in new technology have made it possible to study the processes involved in the building of the visual system at a cellular as well as individual circuit level of detail. The research in early development has been concentrated on four primary parts of the visual system: the retina,[1-4] the organization of the visual cortex,[5,6] the role of endogenous stimulation and exogenous visual experience in the development of the visual system,[7-9] and the role of sleep and sleep cycles.[10-13] So many scientists work with specific aspects of each area that there are more than 10 000 references on aspects of early visual development, the architecture of the visual system, and the function of the visual system.

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Components of the Visual System

The primary components of the visual system are shown in Fig 1.[14] They are listed below:

1. Eye
   (a) Cornea
   (b) Lens
   (c) Iris
   (d) Retina
2. Optic nerve and tract
3. Lateral geniculate nucleus
4. Optic radiations
5. Primary visual cortex
6. Superior colliculus (SC)
7. Connections to other parts of the cortex
8. Connections to the limbic system (emotional)
9. Connections to suprachiasmatic nucleus (circadian rhythms)

The basic structure of the eye is under genetic control and has characteristics that are unique to humans. The optics of the eye are made up of the cornea, lens, and iris. The eyelids and the iris function to limit the amount of light entering the eye.

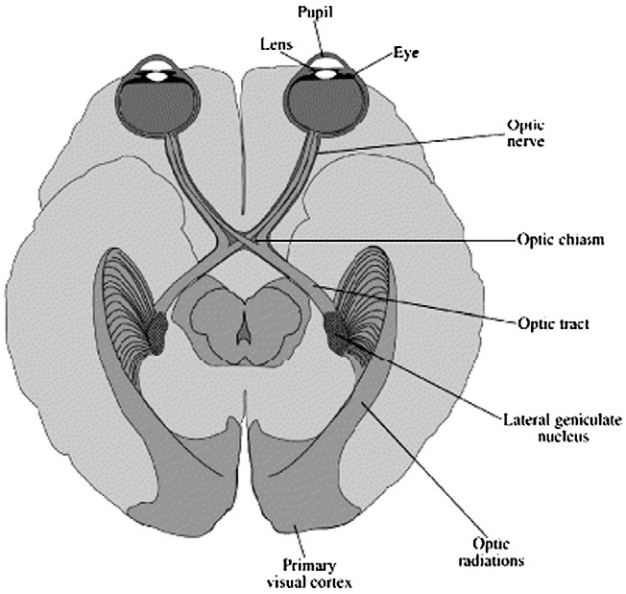

Fig 1. The human brain. The components of the visual system are highlighted and labeled. Reprinted with permission from David Hubel.[14]

The lens is for focus. Preterm infants at less than 32 weeks' gestation have little or no pupillary construction in response to light and have thin eyelids. Thus, they have little ability to limit light exposure to the retina. By term the infant would have consistent pupillary response to light and normal eyelids. The pupillary response to light is usually not consistent until 34 weeks' gestation, and the eyelid is thicker so that by 36 weeks' gestation and beyond, the infant can begin to limit light exposure. At 36 weeks' gestation, the photoreceptor to ganglion cell connections are not yet mature. The key role in the newborn intensive care unit (NICU) is to protect the eye from direct or intense light. Because the uterus is dark, light or visual experience is not needed until birth at term. Preterm birth does not accelerate the timing of the need for visual exposure.

The cellular structure of the retina is shown in Fig 2.[15] In addition to the pupillary construction, the human eye has a dual receptor system in the retina that allows it to adapt to changing light levels during active vision. The retina has two types of receptors for light[16]: rods and cones. The rods are designed to respond to low levels of light. The rods and rod bipolar cells transmit a wide range of light frequencies in low light levels but not color. They are for the scotopic visual system. The cones respond to higher light levels and specific wavelengths. The cones and cone bipolar cells form the photoptic visual system. The retina grows with the growth of the eye. As the eye grows, the rods migrate to the periphery; and the cones migrate to the central areas of the retina. The migration of rods to the periphery and cones centrally in the retina does not require light or visual stimulation. The concentration of cones in the central retina and their connections to bipolar and ganglion cells occur later in development than the bipolar rod connections. The scotopic, rod-based system is the primary system until 2 to 3 months of age. The maturation of the optics of the eye is designed to provide a clear image by term and continues to develop after birth. This allows the infant to accommodate and fixate on visual targets while maintaining clear vision. This is not operative in the preterm infant and matures in the early weeks after term birth.[17]

The staff of NICUs in the 1970s and 1980s, including this author, spent a great deal of energy working with preterm infants trying to encourage attention, focus, and visual tracking. It was believed to be needed for visual development. However, the research on visual development in humans has shown that the preterm infant needs no visual experience until near term and that direct light may be harmful. With preterm infants, the goal of nursing staff, parents, and physicians is to protect the eyes from direct light and provide care in dim light levels, especially when the infant is sleeping.

Knowledge of the structure of the visual system may seem far removed from the care of a preterm infant in the NICU. The timing of the processes involved determines the successful development of the visual system. Much of that development occurs between 24 and 40 weeks' gestation and in the absence of visual stimulation. Thus, environment and care practices in the NICU significantly impact the development of the visual system.

The Retina

The retina is the neurologic part of the eye. All of the neural cells of the retina derive from a single embryonic neuroblastic layer. These cells differentiate into one of five cell groups. Each of these cell groups then differentiate into very specific cell types within the group based on their function and role in the visual process. In addition to the five cell groups, there are three specific layers or eight layers in all. These are shown in Fig 3.[14]

Knowledge of the architecture and processes involved in early retinal development would not be as clinically important if all infants remained in utero until birth at term. Most of the critical processes in retinal development occur between 24 weeks' gestation and 3 to 4 months of age. Unfortunately, many of the processes that occur between 24 and 40 weeks' gestation can be adversely influenced by events in the environment and care of the infant. The environment and care practices usually do not alter the structure (except for ROP) but do affect the function. They impact function more than structure.[18]

Within the eye, there is a pigmented epithelial layer that is directly connected to the pigmented part of the photoreceptors (rods and cones)[10] (Fig 2). There are three basic types of rods and three types of cones. The rods outnumber cones by a ratio of 20:1. Rods connect to bipolar cells through three circuits or pathways that connect to ganglion cells. They are for different light levels. Two types of the rods are low light receptors. They connect to rod bipolar cells that connect directly to a ganglion cell. The third type of rod is for higher light levels. These rods synapse with a cone bipolar cell that connects to ganglion cells via a connection through an amacrine cell (Fig 2). This creates the scotopic visual system that operates in low light. It transmits a full light spectrum but does not transmit color. The scotopic visual system develops during the latter part of fetal life and is operative at term. This is the primary visual system at birth.