

## **Vision**

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## Introduction

In humans with healthy vision, sight provides a major source of information about the world. Newborns have some rudimentary visual abilities (e.g., they orient toward large, high-contrast stimuli), but most visual abilities develop significantly postnatally. Some aspects of vision continue to develop well into childhood and even adolescence. This development usually unfolds in a predictable sequence, but crucially depends on having normal visual experience.

A brief sketch of the anatomy of the human visual system will provide a context for understanding its development. Light focused by the cornea and lens falls on the retina, at the back of the eye, where light-sensitive cells (photoreceptors) convert patterns of light into neural signals. Three classes of cone photoreceptors sensitive to different wavelengths of light provide a basis for color vision and seeing fine detail, while rod photoreceptors are specialised for seeing in low light. After initial processing by retinal neurons, signals from the retina are relayed to the brain by the optic nerve. A major pathway is one to the primary visual cortex (V1) in the occipital lobe via the lateral geniculate nucleus in the thalamus (LGN). From V1 onward, visual information is processed by a complex hierarchy of cortical visual areas. Two major pathways are the 'ventral stream', subserving recognition of objects or faces, and the 'dorsal stream', providing information about spatial layouts to guide actions such as reaching and grasping. The function of this network largely develops postnatally.

Other, earlier-functioning visual pathways depend on sub-cortical rather than cortical processing. These networks include structures such as the superior colliculi and oculomotor nuclei. These pathways are involved in simpler, more reflexive visual functions, and underpin many early-developing visual responses such as the vestibulo-ocular reflex (which helps to

keep the eye's image steady when the head moves). Other important eye movements such as saccades are controlled by signals from both cortical and sub-cortical brain networks, as described below. Thus, developing a normal visual system involves setting up complex interactions between eyes and brain, and between brain structures.

Key components of the visual system develop prenatally, including the pathway from the retina to the LGN. In utero, before any visual experience, retinal ganglion cells fire spontaneously, generating 'waves' of activity across the retina. This spontaneous activity is thought to play a crucial role in organizing the synaptic connections between retina and LGN (Katz & Shatz, 1996). Following birth and the onset of vision, the neural circuits comprising the visual system continue to be sculpted by visual experience. This entry will first describe normal visual development in infancy and childhood, followed by disorders of visual development.

### **Visual development in infancy**

Human vision includes many different abilities from recognition of faces to guidance of accurate movements. A basic aspect of visual sensitivity is visual acuity: the ability to resolve fine detail, as tested (in adults) by an optician's letter chart. Limitations in the ability to see details would provide a bottleneck for any further visual analysis that depends on such details. A closely related function is contrast sensitivity: the ability to distinguish a pattern from its background based on differences in lightness. Good contrast sensitivity entails being able to see patterns based on subtle lightness differences. Behavioral and brain measures (EEG) show that newborns' visual acuity and contrast sensitivity are many times lower than those of adults, but that both normally improve rapidly during the early months of life, reaching adult-like levels by 3-4 years. A standard behavioral measure of infant visual acuity

is the Teller card procedure (Teller, McDonald, Preston, Sebris, & Dobson, 1986), which measures infants' preferences to look at increasingly fine patterns printed on cards as compared with uniform gray. Newer methods can measure acuity automatically using eye-tracking and on-screen stimuli (Jones, Kalwarowsky, Atkinson, Braddick, & Nardini, 2014). EEG measures of acuity include the 'sweep VEP' (visual evoked potential), in which brain responses to progressively finer spatial patterns are recorded.

The rapid, early development of acuity and contrast sensitivity is not well explained by optical changes in the eye (e.g., ability to maintain focus), but depends on changes in the retina, developing brain connectivity, and improvements in neural information transmission. At birth, cone photoreceptors are immature in their morphology, inefficient at capturing light, and not densely packed in the fovea (the central region of the retina that provides the highest visual acuity). Morphological maturity and spatial re-arrangement of cones in the first two years of life provide one basis for improving visual function. Other crucial factors are experience-dependent sculpting of the neural circuits between retina, LGN and V1, and improvements in the efficiency of these circuits via myelination.

As these brain changes depend crucially on having normal visual experience, when vision is limited during infancy, for example because of a congenital cataract, visual function is compromised, even once the original impairment (e.g., cataract) is removed. This condition, amblyopia, has its basis in the brain, as shown using animal models in the Nobel prize-winning work by David Hubel (1926-2013) and Torsten Wiesel (Wiesel, 1982). In absence of detailed visual input from one eye, neurons in visual cortex come to be strongly biased to process information only from the other eye. Animal models have shown in detail how the plasticity of these initial visual circuits is greatest during 'critical' or 'sensitive'

periods in early life. For more on amblyopia in humans, and human visual system plasticity in early and later life, see sub-section on Atypical visual development below.

### *The eye and eye movements*

Although humans have a wide visual field, only a very small region at its center provides very fine vision. For this reason, the eyes are constantly on the move, sampling the environment. These rapid, jerky eye movements are called ‘saccades’. Other kinds of eye movements provide stabilization to account for movement (e.g., continuous tracking of a moving target is termed ‘smooth pursuit’). Newborn control of eye movements is quite basic, and setting up precise eye movement control is a key challenge for the visual system. In the first months of life, normal visual development includes development of the abilities to converge both eyes to hold an object steadily in view, to track a moving object smoothly, and to shift the gaze flexibly from one target to another. These abilities depend on different but interrelated brain networks, including dedicated sub-cortical pathways and nuclei distinct from the main cortical visual pathway via LGN and V1. For example, the smooth pursuit network includes areas V1 and MT in the occipital lobe, the frontal eye fields in the frontal lobe, and sub-cortical structures including the pontine nuclei and the cerebellum. A hallmark of normal visual development is an increasing ability to drive eye movements not only by relatively inflexible sub-cortical mechanisms, but also by flexible cortical control based on more detailed image analysis. For example, infants aged below 3-4 months of age tend to get ‘stuck’ on a target and are unable to disengage from it even when another attractive target appears alongside (Atkinson, Hood, Wattam-Bell, & Braddick, 1992). The ability to disengage is an indicator of developing cortical control, and can be delayed in infants born prematurely or with perinatal brain injury. The assessment of this ability can therefore provide a useful indication of brain development in ‘at-risk’ groups.

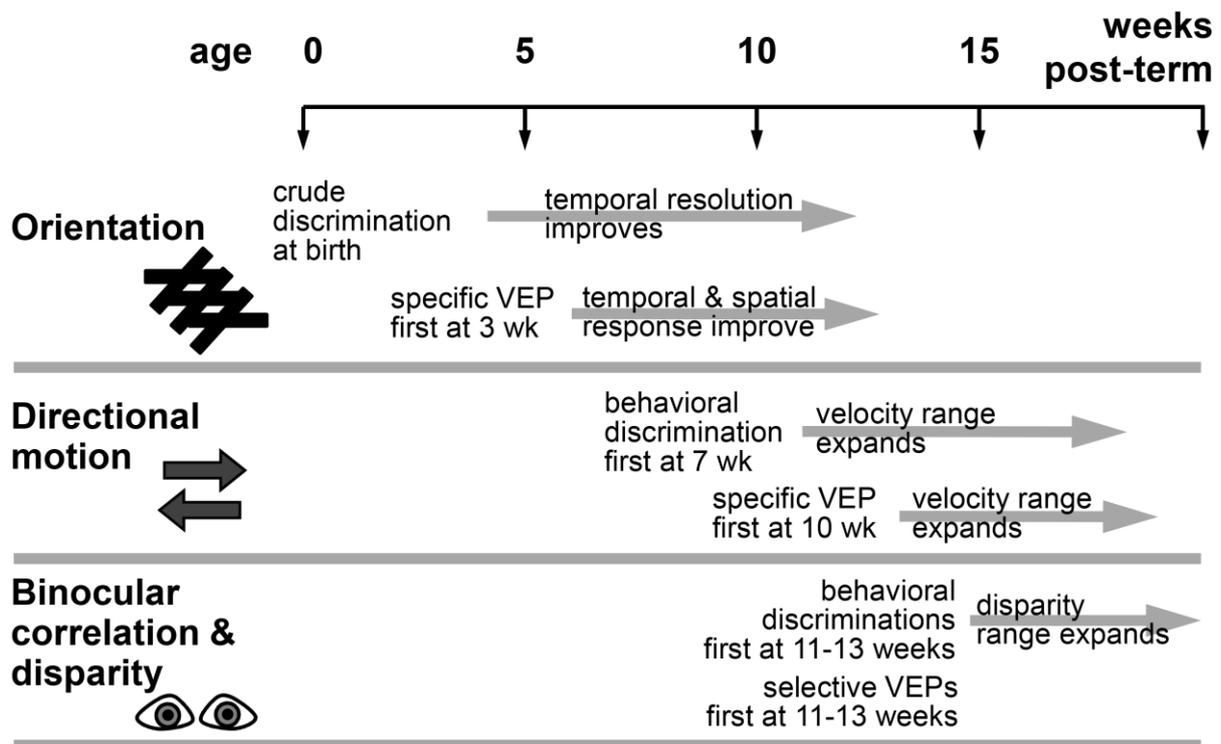
### *The visual brain*

Visual acuity and contrast sensitivity describe basic limits on spatial information available for the visual system to use. Related measures are chromatic sensitivity in the domain of color discrimination, and critical fusion frequency in the time domain (the latter describes how rapidly a pattern can flicker between two levels of lightness or color for the flicker still to be perceived, rather than ‘fused’ into one). Importantly, learning to see is not just a matter of overcoming these basic limitations, which one might liken intuitively to the progressive sharpening of a blurry image. There is still all the difficult work of visual analysis to be done, a process carried out by a complex network of cortical visual areas starting with V1 in the occipital lobe and taking up a large portion of the human brain. Neurons in visual areas at lower levels of this hierarchy are sensitive to simple, small, local image properties, such as edges or corners; those higher up to more extended properties such as contours stretching over the visual scene. At the highest levels, neurons are sensitive to complex stimuli including faces and objects. Are these kinds of cortical processing present at birth or do they develop postnatally? If so, how?

### *Form, motion, and disparity*

These questions were addressed in a series of landmark studies by Atkinson, Braddick and their collaborators beginning in the 1970s (Atkinson, 2000). They used both behavioral (preferential looking) and EEG measures to look for signatures of cortical visual processing related to key properties of V1 known from animal models: orientation, motion direction, and binocular disparity. Findings from these studies are summarized in Figure 1. Their results showed that all three kinds of cortical visual processing are almost entirely absent at birth,

and develop in the early months of life. Thus, for example, while newborns can detect relatively fast rates of flicker, signalling that something is changing or moving in the visual scene, they cannot resolve the direction of motion until age 2-3 months (Wattam-Bell, 1991). This shows that cortical mechanisms for interpreting the direction of motion normally develop in the early months of life. The same is true for orientation (direction of a static pattern), and binocular disparity (differences in the two eyes' images, which provide one basis for seeing in depth, see below). All these normally develop postnatally, at different ages (see Fig. 1). A different, and more basic kind of motion sensitivity based on sub-cortical pathways underlies the optokinetic nystagmus (OKN) reflex, in which the eyes follow large patterns moving horizontally from birth.

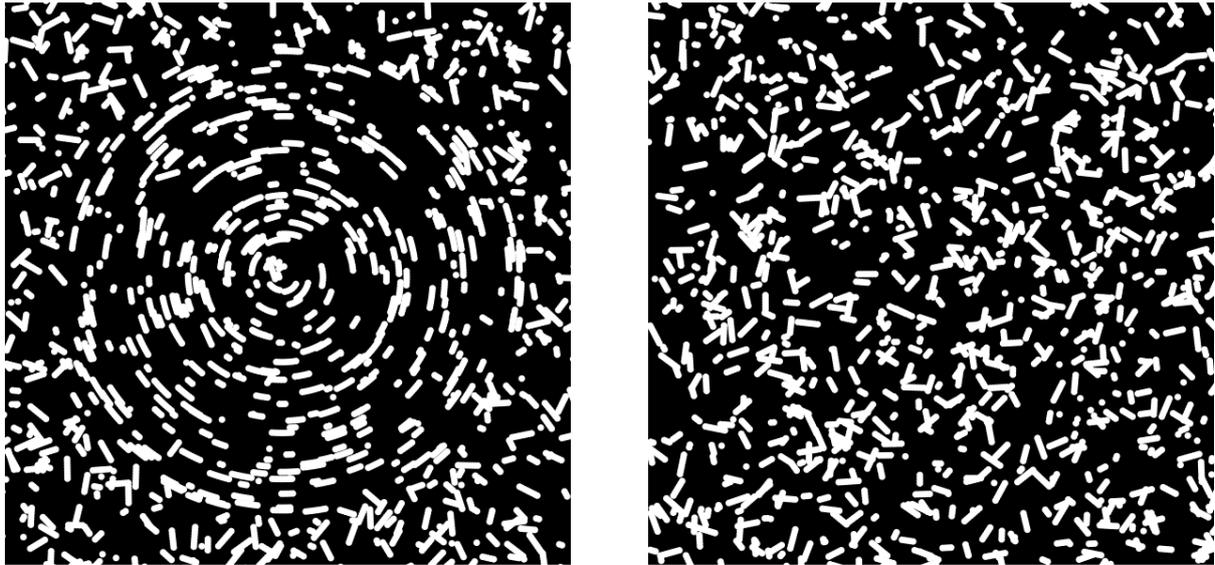


*Figure 1. Summary of behavioral and EEG results from studies by Atkinson, Braddick and colleagues. Redrawn from Atkinson (2000).*

### *Global form and motion*

These basic sensitivities to orientation, motion and disparity are linked to properties of V1 neurons, which carry out initial image analysis. Each V1 neuron only responds to simple image properties in a very small part of the visual field. Neurons higher up in the cortical hierarchy respond to more complex properties over larger parts of the visual field. Two aspects of this ‘mid-level’ visual processing are sensitivity to ‘global form’ and ‘global motion’ (as distinct from ‘local form’ or ‘local motion’). Determining the lines of extended edges is an example of global form processing, while segregating coherent parts of objects moving against a background is an example of global motion processing. Abilities to process global form or motion can be tested by comparing behavioral or brain responses to ‘coherent’ as compared with ‘incoherent’ patterns (see Fig. 2). In these patterns, the component local elements are the same so the patterns should be similar from the point-of-view of V1 neurons, but the global organization is different.

Global form and motion processing are expected to build on local processing. In line with this expectation, they are first seen in infancy, via behavioral and EEG recordings, a little later than local processing at around 4-6 months. Interestingly, while EEG responses to globally organized form and motion are evident at 5-months-of-age, the topography of these responses as recorded over the scalp are very different to those recorded in adults (Wattam-Bell *et al.*, 2010). This difference indicates that there is major reorganization of cortical visual processing between the first emergence of these kinds of sensitivity and their final adult state. The nature of this reorganization in both function and connectivity of cortical visual areas is not yet well understood and remains a topic of current research.



*Figure 2. Coherent (left) and incoherent (right) form patterns. The individual elements are distributed in the same way in both stimuli, but only in the coherent case do they follow a larger ('global') organisation.*

### *Color*

Normal color vision depends on three kinds of retinal photoreceptor, which respond to different wavelengths of light: 'L', 'M' and 'S' (long-, medium- and short-wavelength) cones, corresponding to colors seen as red, green and blue. Newborn color vision is limited in showing low sensitivity to chromatic contrast, but by two months there is evidence for discrimination for red-green contrasts, mediated by L- and M-cones. Discrimination for blue-yellow contrasts, mediated by S-cones, seems to develop later, after 4 months. This early development is likely to be driven by the maturation of cone photoreceptors, which change in shape to become more efficient at catching light, together with the development of cortical information processing (sensitivity to visual form or motion also depending on this change). Infants' earliest responses to color, however, may be based on a sub-cortical visual pathway via the superior colliculi which does not receive S-cone input.

## *Faces*

A class of visual stimuli with huge social importance is the human face. Very young infants, including newborns, already preferentially attend to and orient toward faces (Johnson, Dziurawiec, Ellis, & Morton, 1991), and infants only a few days old look longer at their mother's face than a stranger's face. Newborn face processing relies on the very basic visual information available given the low visual acuity and contrast sensitivity at this age, and seems to rely on different mechanisms to those used by older children and adults (Johnson, 2005). These early abilities have been proposed to depend on a specialized sub-cortical pathway including the superior colliculus, pulvinar and amygdala, which may be functional at birth and respond to faces using relatively simple image information present at low spatial frequencies (i.e. features evident even with low visual acuity)..Infants' face processing is initially quite general, before becoming 'fine tuned' by learning. Thus, at 6 months, infants are as good at discriminating two monkey faces from each other as they are at discriminating two human faces (Pascalis, de Haan, & Nelson, 2002). Likewise, EEG recordings at this age do not yet show specific responses to upright (as opposed to inverted) or human (as opposed to monkey) faces, as do those in adults (de Haan, Pascalis, & Johnson, 2002). The later-developing specific response to upright faces can be linked with an emerging specialization for face-processing, including that upright faces are recognised faster and more accurately, and in a distinctive 'configural' manner. Infant face processing therefore includes both precocious but imprecise discrimination abilities, and later-developing expertise with human faces via learning.

### *Objects and occlusion*

Everyday objects can temporarily disappear behind other objects (i.e., become occluded), but humans routinely keep track of them and expect them to re-appear. Although their abilities to follow moving objects using their eyes develops in the early months of life, infants seem at first to be poorly equipped to deal with occlusion. An example is the seminal finding of Jean Piaget (1896-1980) that infants aged below 8 months do not search for an object after it has been hidden from view. Measures of where infants look when an object is hidden (rather than whether and where they search for it) indicate earlier development of abilities to keep track of occluded objects, but this still depends on postnatal development. For example, in studies by von Hofsten and colleagues, infants were able to predict where a moving object would re-appear after temporary occlusion at 4 months (see von Hofsten, 2004). EEG measures have related infants' ability to maintain occluded objects in memory with activity in the temporal lobe (Kaufman, Csibra, & Johnson, 2003). When part of a moving object is occluded, one could interpret it either as a single object, or as two objects that happen to move together. There is evidence that the assumption of 'unity', that the parts all belong to one object, develops at 2-4 months (Johnson, 2004). The origins of infants' knowledge of objects and physics is a topic much debated in the cognitive development literature.

### *Depth*

Another crucial task for the visual system is to compute objects' positions in 3-D space. The task is not easy because retinal projections are two-dimensional, and do not directly provide depth information. A small object nearby can have a larger retinal projection than a large object far away. Differences between the two eyes provide one basis for judging depth,

known as stereopsis. As described in Figure 1, there is evidence for cortical processing of this disparity information at 12 weeks-of-age. Humans use many additional cues to depth, including patterns of motion produced by rotating objects, perspective, shading, and occlusion (see above). Work by Albert Yonas and his colleagues has documented the development of depth perception based on such cues in the first year-of-life. The pattern of motion generated by a rotating object can be used as a cue to the object's 3-D shape (the 'kinetic depth effect') as early as 8 weeks (Arterberry & Yonas, 2000). Use of 'pictorial' depth cues such as perspective, shading and occlusion is evident later, at between 5-7 months (e.g., Yonas, Cleaves, & Pettersen, 1978). Increasingly sophisticated depth judgments based on multiple visual cues emerge in the first year-of-life. This process is likely to depend on learning during infants' visual and motor interaction with the world.

#### *Visually guided reaching and grasping*

Human visual and motor systems are tightly coupled, and vision provides a basis both for selecting motor actions (e.g., deciding which object to pick up) and controlling them (e.g., adjusting the hand's hand orientation so that it can grasp the object). Infants first reach and grasp for objects at around 4-5 months, an ability dependent on the development of motor control of the limbs and of posture, but also on 'visual' factors reviewed above including developing perception of objects and of depth. Infants use vision to guide where they will reach as soon as they start reaching, but it is only during their second year of life that they also use vision of their own arm to better control and correct their reach trajectories. By the second or third year-of-life, reaches start to resemble those of adults in being relatively direct to their target and showing a smooth velocity profile. These are indicators of increasingly accurate use of vision for both initial planning and subsequent on-line correction of

movements. This early development is likely to depend on learning through experience, including learning to correctly calibrate visual distance to arm length.

### **Visual development in childhood**

The most dramatic changes in visual abilities take place in infancy, and infancy is also the period that is most critical for healthy visual development (see below). However, many visual abilities continue to develop through childhood and into adolescence. In general, more basic or ‘low-level’ aspects of image analysis, such as visual acuity and contrast sensitivity, mature early. More complex kinds of analysis, including object and face recognition and use of vision for action, continue to develop long into childhood. The brain’s abilities to make complex visual judgments continue to be fine-tuned by learning and experience throughout childhood.

#### *Global form and motion*

Studies of sensitivity to global form and motion have found extended development in childhood of abilities to follow contours, and to discriminate coherent movement or patterns embedded in random noise. For example, discrimination is not adult-like until 14 years for either simple up/down dot motion or more complex ‘biological motion’ (moving dots based on the movement patterns made by a human (*e.g.*, while running; Hadad, Maurer, & Lewis, 2011). These ‘mid-level’ visual abilities depend on integrating form and motion information encoded at lower levels of cortical processing (*e.g.*, combining the motions of multiple dots to extract an overall motion direction). Recent studies have related these developmental changes to improvements in the efficiency with which information is combined (Manning,

Dakin, Tibber, & Pellicano, 2014). The improvements in integration abilities are likely to reflect changes in cortical connectivity during childhood, as well as developing perceptual expertise.

### *Objects and faces*

At even higher levels of the cortical hierarchy associated with object and face recognition, there is similarly evidence for very long visual development through childhood. Young children may be very competent at recognizing common objects in everyday conditions. However, their abilities to recognize objects in unusual lighting or from unusual viewpoints, or to recognize newly learnt objects from new viewpoints, are still developing late into childhood (Nishimura, Scherf, & Behrmann, 2009). Abilities to tell faces apart based on subtle configural differences are likewise not mature until adolescence (Mondloch, Le Grand, & Maurer, 2002). In adults, these kinds of highly specialized visual processing rely on distinct cortical areas in the temporal lobe, along the ventral visual pathway, which neuroimaging (fMRI) studies have shown also emerge slowly over the course of development, particularly for face processing (Grill-Spector, Golarai, & Gabrieli, 2008).

### *Development and vision as inference*

An influential theoretical approach describes perception as probabilistic inference, in which perceptual evidence, which is often uncertain, is interpreted in light of internal models and prior knowledge. This approach goes back to Hermann von Helmholtz (1821-1894), one of the founders of visual psychophysics, and has now been formalized in mathematical models and related to cortical information processing (Clark, 2013). This account would suggest that children gradually acquire expertise at complex perceptual judgments by improving their

abilities to make correct inferences based on uncertain information. In line with this, when children's and adults' abilities to make inferences about 3-D shape based on two sources of evidence (texture and stereo disparity) were compared with model predictions, children made sub-optimal inferences until the age of 12 years. (Nardini, Bedford, & Mareschal, 2010). Likewise, children's propensity to interpret ambiguous 3-D shapes based on the prior assumption that the light is most likely to be coming from above is still developing at 10 years (Thomas, Nardini, & Mareschal, 2010). How the developing brain learns to deal with uncertain sensory information and so make 'optimal' perceptual inferences is a topic of current research. The perceptual inference contrasts with other influential theoretical frameworks, such as the 'ecological' approach pioneered by James Gibson (1904-1979) and Eleanor Gibson (1910-2002), which emphasises the rich sensory information available during naturalistic tasks.

### *Vision and action*

Another domain showing marked development throughout childhood is visually guided action, including manual tasks (pointing, reaching), balance, locomotion and navigation. The gradually developing expertise in visual recognition (e.g., of faces), supported by the ventral stream of visual processing, is paralleled by developing expertise in planning and executing visually guided actions, supported by the dorsal stream.

### **Atypical visual development**

As has been described, healthy visual development involves the acquisition of many different perceptual abilities. There are many points at which processing can be disrupted, from the eye (e.g., lens, retina), to the brain. Neonatal visual processing is very immature, and both the

brain's visual processing abilities, and the interactions between eye and brain for eye movements, have to develop postnatally. This development usually proceeds normally, but is vulnerable to disruption, especially in absence of normal visual experience.

### *The eye*

Clearly, disorders of the eye can impair visual function. Most common are refractive (focusing) errors, which can be corrected with glasses. Rarer conditions include congenital cataracts and genetic conditions such as nightblindness affecting cells in the retina. Babies born preterm are at risk of retinopathy of prematurity, in which abnormal development of blood vessels damages the retina. Other developmental eye conditions include congenital or infantile glaucoma (elevated intraocular pressure, which can lead to impaired vision and damage to the eye). When it is possible to correct vision at the level of the eye, it is crucial to do so early to ensure normal development of eye control and the visual brain, as described below.

### *Eye and brain: Strabismus, nystagmus, and amblyopia*

The control and feedback mechanisms between brain and eye can fail to develop correctly for guiding eye movements. In *strabismus* ('crossed eyes'), the directions of the two eyes are misaligned. Other primary vision problems (*e.g.*, congenital cataract, or much more commonly, far-sighted refractive errors) are risk factors, reflecting the developing system's need for a clear visual signal to calibrate itself correctly. In early-onset or congenital *nystagmus*, the ability to hold the gaze steady does not develop normally, and there is uncontrolled back-and-forth movement of the eyes. Reduced vision is also a risk factor for *nystagmus*, although it can also have a neurological cause in either genetic conditions or acquired injury affecting the developing eye-movement system.

In the above two conditions, the brain's control of the eye does not develop normally. In *amblyopia*, the brain's processing of the visual information provided by the eye does not develop normally. The great plasticity of the developing visual cortex means that if, early in life, cortical neurons receive much better information from one eye than the other, they develop to make use of the signal from the 'good' eye while discounting information from the other eye. Therefore, early visual problems at the level of the eye, such as cataracts, poor focus, or strabismus, can lead to amblyopia: abnormal development of visual cortex, leading to lasting vision impairment. Because there is much less cortical plasticity (potential for reorganization) in later life, amblyopia typically remains even if the problem is subsequently dealt with at the level of the eye. For this reason, where possible early interventions are used to improve vision from a weaker eye (*e.g.*, focal correction, cataract surgery), and to encourage the brain to use the signal from both eyes (*e.g.*, patching treatment to promote use of the weaker eye). However, new research suggests that there may be more scope for lifelong cortical plasticity allowing treatment of amblyopia than was previously recognised (Bavelier, Levi, Li, Dan, & Hensch, 2010).

### *Deprivation and brain plasticity*

Well-known, clinically recognized visual problems associated with early visual deprivation (*e.g.*, congenital cataract) include lasting impairments in visual acuity and contrast sensitivity. These are associated with an under-representation of the signal from the affected eye at the initial levels of cortical visual processing. However, visual deprivation is also associated with impairments in higher-level functions such as coherent motion processing, shape and face recognition. These functions, too, need normal early visual input to develop, and patients who had bilateral cataracts removed only in late childhood or adulthood show marked deficits in them. Interestingly, infants who had cataracts removed at an age younger than those at which

these functions are normally acquired still show some of these deficits later on; these ‘sleeper effects’ show a role for early vision on development of functions that do not normally emerge until later (Maurer, Mondloch, & Lewis, 2007). Profound and lasting visual deprivation can also lead to a major reorganization of the brain’s processing of sensory information, including involvement of the visual cortex in braille reading and echolocation (orientation by sound echoes) in blind people.

### *Atypical visual processing in developmental disorders*

Some developmental disorders with atypical brain organization are associated with specific deficits of visual function. For example, there is evidence for specific impairments in the dorsal stream of visual processing ,related to coherent motion perception and visual control of movement, in a range of neurodevelopmental disorders including Williams syndrome, fragile X syndrome and autism (‘dorsal stream vulnerability’; Braddick, Atkinson, & Wattam-Bell, 2003). These findings show how visual brain areas vary in their vulnerability to atypical development, and have led to new insights such as mapping of visuo-spatial deficits with object-rotation tasks in Williams syndrome to structural and functional brain abnormalities in the dorsal stream (Meyer-Lindenberg *et al.*, 2004). Assessment of visual functions can therefore provide a way into understanding the processes underlying normal and atypical brain development.

### *Cerebral visual impairment*

As much of the brain deals with visual information, acquired brain injury can have major effects on visual function. The nature of the deficit can range from parts of the visual field ‘missing’, associated with damage to sites of early visual processing such as the optic nerve and primary visual cortex, to more specific difficulties with object recognition or visual

movement planning, associated with injuries to brain areas carrying out higher-level visual processing. Although like adults, children can suffer brain injury from traumatic accidents, they are also at risk of congenital injury, including perinatal brain injury. Because of the remarkable plasticity of the developing brain, there is more scope for brain reorganization and recovery of normal function with injuries acquired early in life than at older ages.

Research by Joan Stiles and her colleagues has documented difficulties associated with visual tasks following early brain injury, and the scope for later re-organization (Stiles *et al.*,2012).

## **Conclusions**

Vision is a crucial sense that largely develops postnatally. During this development the visual brain learns to interpret and attach meaning to the information it receives from the eye. The major development of basic aspects of vision such as acuity and contrast sensitivity normally takes place in infancy. From both animal and infant studies, we have a reasonable model for the neurodevelopmental processes underlying basic visual abilities dependent on the primary visual cortex. However, the development of more complex abilities such as coherent form and motion perception, and face and object recognition, continues long into childhood. The reorganization of function in higher cortical visual areas supporting these abilities remains an important topic for current research. It is thought to include changes in the overall architecture (pattern of ‘wiring’ between brain areas) as well as ‘fine-tuning’ of connections, changes that can be driven by both age-related maturation and experience-dependent learning.

Because of the crucial need for normal visual experience, visual development is vulnerable to early deficits such as high optical defocus or congenital cataracts, and for these reasons treatment is generally provided as early as possible. However, new research shows

that there can be scope for recovery of visual function via training even in later life. The factors governing brain plasticity and learning in these situations are another important topic of current research.

**See also:**

**Constructivist theories; Learning theories; Eye tracking; Magnetic Resonance Imaging (MRI); Connectionist modeling; The status of the human newborn; Attention; Biological motion perception; Cognitive development during infancy; Cognitive development beyond infancy; Multisensory perception; Face perception and recognition; Perception and action; Locomotion; Prehension; Brain and behavior development; Cognitive neuroscience; Autism; Fragile X syndrome; Prematurity and low-birthweight; Visual impairments; Williams syndrome; Future of cognitive developmental research**

**Further readings**

Atkinson, J. & Braddick, O. (2013). Visual Development. In Zelazo, P. D. (Ed), *The Oxford Handbook of Developmental Psychology*. NY: Oxford University Press.

Bavelier, D., Green, C. S., Pouget, A., & Schrater, P. (2012). Brain plasticity through the life span: Learning to learn and action video games. *Annual. Review of Neuroscience*, 35, 391-416.

**Relevant scientific organisations**

The Association for Research in Vision and Ophthalmology. <http://www.arvo.org/>

Vision Sciences Society. <http://www.visionosciences.org/>

## References

- Arterberry, M. E. & Yonas, A. (2000). Perception of Three-Dimensional Shape Specified by Optic Flow by 8-Week-Old Infants. *Percept. Psychophys.*, 62, 550-556.
- Atkinson, J. (2000). *The Developing Visual Brain*. Oxford: OUP
- Atkinson, J., Hood, B., Wattam-Bell, J., & Braddick, O. (1992). Changes in Infants' Ability to Switch Visual Attention in the First Three Months of Life. *Perception*, 21, 643-653.
- Bavelier, D., Levi, D. M., Li, R. W., Dan, Y., & Hensch, T. K. (2010). Removing Brakes on Adult Brain Plasticity: From Molecular to Behavioral Interventions. *J Neurosci.*, 30, 14964-14971.
- Braddick, O., Atkinson, J., & Wattam-Bell, J. (2003). Normal and Anomalous Development of Visual Motion Processing: Motion Coherence and 'Dorsal-Stream Vulnerability'. *Neuropsychologia.*, 41, 1769-1784.
- Clark, A. (2013). Whatever Next? Predictive Brains, Situated Agents, and the Future of Cognitive Science. *Behav. Brain Sci.*, 36, 181-204.
- de Haan, M., Pascalis, O., & Johnson, M. H. (2002). Specialization of Neural Mechanisms Underlying Face Recognition in Human Infants. *J. Cogn Neurosci.*, 14, 199-209.
- Grill-Spector, K., Golarai, G., & Gabrieli, J. (2008). Developmental Neuroimaging of the Human Ventral Visual Cortex. *Trends Cogn Sci.*, 12, 152-162.
- Hadad, B. S., Maurer, D., & Lewis, T. L. (2011). Long Trajectory for the Development of Sensitivity to Global and Biological Motion. *Dev. Sci.*, 14, 1330-1339.
- Johnson, M. H., Dziurawiec, S., Ellis, H., & Morton, J. (1991). Newborns' Preferential Tracking of Face-Like Stimuli and Its Subsequent Decline. *Cognition*, 40, 1-19.
- Johnson, S. P. (2004). Development of Perceptual Completion in Infancy. *Psychol. Sci.*, 15, 769-775.
- Jones, P. R., Kalwarowsky, S., Atkinson, J., Braddick, O. J., & Nardini, M. (2014). Automated Measurement of Resolution Acuity in Infants Using Remote Eye-Tracking. *Invest Ophthalmol. Vis. Sci.*,

- Katz, L. C. & Shatz, C. J. (1996). Synaptic Activity and the Construction of Cortical Circuits. *Science*, 274, 1133-1138.
- Kaufman, J., Csibra, G., & Johnson, M. H. (2003). Representing Occluded Objects in the Human Infant Brain. *Proc. Biol. Sci.*, 270 Suppl 2, S140-S143.
- Manning, C., Dakin, S. C., Tibber, M. S., & Pellicano, E. (2014). Averaging, Not Internal Noise, Limits the Development of Coherent Motion Processing. *Dev. Cogn Neurosci.*, 10, 44-56.
- Maurer, D., Mondloch, C. J., & Lewis, T. L. (2007). Sleeper Effects. *Dev. Sci.*, 10, 40-47.
- Meyer-Lindenberg, A., Kohn, P., Mervis, C. B., Kippenhan, S., Olsen, R. K., Morris, C. A., & Berman, K. F. (2004). Neural Basis of Genetically Determined Visuospatial Construction Deficit in Williams Syndrome. *Neuron*, 43, 623-631.
- Mondloch, C. J., Le Grand, R., & Maurer, D. (2002). Configural Face Processing Develops More Slowly Than Featural Face Processing. *Perception*, 31, 553-566.
- Nardini, M., Bedford, R., & Mareschal, D. (2010). Fusion of Visual Cues Is Not Mandatory in Children. *Proc. Natl. Acad. Sci. U. S. A*, 107, 17041-17046.
- Nishimura, M., Scherf, S., & Behrmann, M. (2009). Development of Object Recognition in Humans. *F1000. Biol. Rep.*, 1, 56.
- Pascalis, O., de Haan, M., & Nelson, C. A. (2002). Is Face Processing Species-Specific During the First Year of Life? *Science*, 296, 1321-1323.
- Teller, D. Y., McDonald, M. A., Preston, K., Sebris, S. L., & Dobson, V. (1986). Assessment of Visual Acuity in Infants and Children: the Acuity Card Procedure. *Dev. Med. Child Neurol.*, 28, 779-789.
- Thomas, R., Nardini, M., & Mareschal, D. (2010). Interactions Between "Light-From-Above" and Convexity Priors in Visual Development. *J. Vis.*, 10, 6.
- von Hofsten, C. (2004). An Action Perspective on Motor Development. *Trends Cogn Sci.*, 8, 266-272.
- Wattam-Bell, J. (1991). Development of Motion-Specific Cortical Responses in Infancy. *Vision Res.*, 31, 287-297.
- Wattam-Bell, J., Birtles, D., Nystrom, P., von, H. C., Rosander, K., Anker, S., Atkinson, J., & Braddick, O. (2010). Reorganization of Global Form and Motion Processing During Human Visual Development. *Curr. Biol.*, 20, 411-415.
- Wiesel, T. N. (1982). Postnatal Development of the Visual Cortex and the Influence of Environment. *Nature*, 299, 583-591.
- Yonas, A., Cleaves, W. T., & Pettersen, L. (1978). Development of Sensitivity to Pictorial Depth. *Science*, 200, 77-79.