Child's Nervous System
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REVIEW ARTICLE

The development of vision between nature and nurture: clinical implications from visual neuroscience

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Abstract

Background Vision is an adaptive function and should be considered a prerequisite for neurodevelopment because it permits the organization and the comprehension of the sensory data collected by the visual system during daily life. For this reason, the influence of visual functions on neuromotor, cognitive, and emotional development has been investigated by several studies that have highlighted how visual functions can drive the organization and maturation of human behavior. Recent studies on animals and human models have indicated that visual functions mature gradually during post-natal life, and its development is closely linked to environment and experience.

Discussion The role of vision in early brain development and some of the neuroplasticity mechanisms that have been described in the presence of cerebral damage during childhood are analyzed in this review, according to a neurorehabilitation prospective.

Keywords Neurodevelopment · Visual functions · Cerebral visual impairment · Visual behavior

Introduction

Vision can be considered as the individual's ability to organize and give meaning to the sensory data collected by the visual system, but it includes several aspects with different onset and maturation times, and for this reason, the term "visual function" is often used in the plural "visual functions" [1, 2]. Commonly, visual functions are considered a set of basic and higher properties which are indispensable for our normal daily life but closely interlinked for a global vision of reality and for guiding our behavior: ocular motility and accommodation, visual acuity, visual field, contrast sensitivity, stereopsis, color vision, visual attention, visuo-motor control, recognition of objects and forms, spatial and visual orientation recognition, motion perception, and numerosity judgements are only some of the most important. From this perspective, adult visual behavior is the result of a complex and long-term interplay of genetic and environmental influences that starts in utero before eye opening, continues during postnatal life, and requires appropriate sensory experiences in order to stimulate the development of visual functions [3, 4].

At birth, the visual pathways have just been developed but the visual cortex (V1) is already able to receive signals from the retina [5, 6]. However, newborn's visual functions are very different from adult's visual functions, because of differences in visual receptive fields (RFs), that constitute regions in the visual field where a visual cell responds to visual stimuli [7, 8]. In fact, maturation of the visual system and particularly of V1 is very long and strongly influenced by visual experience during the early stages of life, thanks to brain plasticity [3, 9], that refers to the brain's ability to undergo functional and structural alterations in response to internal and external environmental changes [10].

During "critical period" of a specific function, brain plasticity is at its highest level [11]. Nowadays, most researchers agree that there are multiple critical periods associated with various brain functions, and that they are shorter and earlier for early sensory processing than that for higher complex functions or cognitive/executive functions [12]. Hence, every visual function shows a different developmental trajectory with multiple visual critical periods in anatomical, physiological, and behavioral development and different levels of V1 vulnerability [13]. For example, in humans, visual acuity develops to adult levels during the first 5 years after birth, while stereoacuity starts to develop at 4–6 months, quickly reaches a

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plateau, but then is followed by a longer slower period of development to adult levels that continues well into school age [14].

Although most of the knowledge about visual system plasticity derives from the paradigm of sensory deprivation [15–18], a recent series of experiments used environmental enrichment as a strategy to investigate the influence of sensory experience on brain development, and to provide evidence, both in animal and human models, that mechanisms of cross-modal plasticity are likely to underlie the beneficial effects of enhancing visual activity [16, 19–21]. For example, Guzzetta et al. [21] showed that body massage affects brain development and in particular visual system maturation in both preterm human infants and in rat pups and suggested that the environment acts by modulating the level of endogenous factors such as IGF-1, which regulate brain growth and the development of visual cortex. Similar results were obtained also by Purpura and colleagues [22] in presence of genetic disorders such as Down syndrome.

According to these findings, the remarkable plasticity of the visual system is the basis for understanding the profound behavioral differences between visual disorders with onset at an early age and those acquired later in life. This high plasticity permits the restoration of competences, but it can also be translated into an increased vulnerability during the first stages of the neurodevelopment. For these reasons, it is necessary to consider that the visual system is a particularly suitable model for examining the neurodevelopment and for studying experience-dependent plasticity, because it is paradigmatic of brain maturation. Although the maturation of the visual system starts in utero by genetic programs or spontaneous activity, a total absence of sensory input in this stage leads to a delay in the functional and anatomical maturation of V1, while it is known that a proper development of the visual system requires long and complex sensory experience in the extra-utero environment [3, 23, 24].

In the present brief review, we will summarize current knowledge on the role of the visual functions in neurodevelopment and the possible outcomes after brain damage.

The role of visual functions in neurodevelopment

Vision is an adaptive function and should be considered a prerequisite for neurodevelopment as a whole, for the evolution of motor abilities and learning, for a child's neuropsychological and psychic development, and for his emotional and affective growth. Vision is necessary from the beginning of life to create a relationship with caregivers through eye-contact, to develop preverbal communication, to structure cognitive, motor, affective, and social intentionality and reciprocity. The perception of human faces from birth [25, 26], for example, is essential for the global development of the individual because the human face is the vehicle for a large amount of information, identifies the species and indicates identity and group membership, and expresses emotional as well as linguistic signals. From birth, babies demonstrate a clear and precise visual preference for faces [27]; this preference is favored by the degree of contrast and by the organization of the face and has a high biological and adaptive value for the development of human perception. Fraiberg's definition of vision as the central agency of sensorimotor adaptation, a sort of "synthesizer of experience" [28], highlights the visual system's capacity to coordinate all the other perceptual-sensory systems and to give a significance to the environment. Visual functions facilitate social initiative towards the surrounding world; therefore, they guide the execution of proper action, the action coding of others, and permit the knowledge of the object and the adaptation. In this sense, vision is characterized by "tonic" functioning, which allows continuous monitoring of the external world and integrates the various perceptual experiences into a mental representation. So, without vision, the organization and maturation of these processes can be complex, and the opportunities of social learning can be very restricted and disorganized (Fig. 1).

In fact, different kinds of daily activities have different requirements for visual information, and during the learning of a new activity, the eye-movements first provide feedback on the motor performance, but as this is perfected, they provide feed-forward direction, seeking out the next object to be acted upon [29]. For its crucial role in neurodevelopment, the influence of visual functions on neuromotor, cognitive, and emotional development has been investigated by several studies [5, 30, 31] that have highlighted how visual functions can drive the organization and maturation of human behavior.

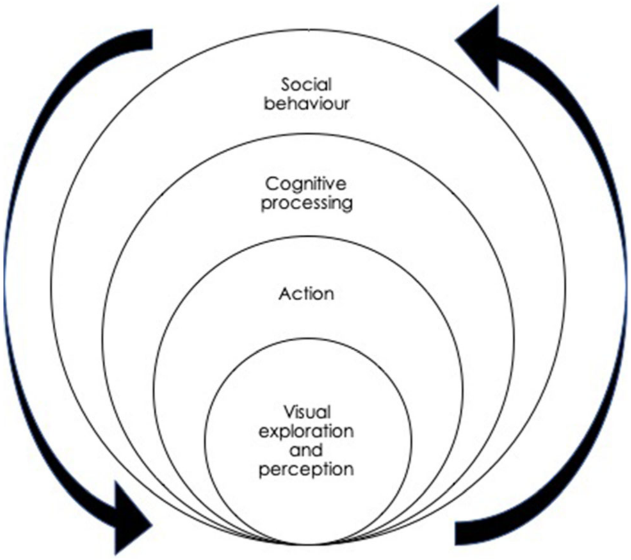

Fig. 1 Role of visual function on human development

As regards the interlink between vision and motor abilities, Prechtl and colleagues [32] suggested that during motor development, vision provides important feedback to the vestibular and proprioceptive systems. They found significant differences in early spontaneous motor patterns in peripheral blind children. In these subjects, "fidgety movements" (that occur around 9-week post-term age until 20–22 weeks) were widely disturbed in a specific way (exaggerated in amplitude and jerky in character), and their presence lasted longer than in sighted infants (until 8–10-month post-term age). The authors hypothesized that exaggerated fidgety movements may indicate an effort to compensate for the lack of integration between vision and proprioceptive stimuli, that typically happens during earlier stages of life. In fact, in the same study, they analyzed fidgety movements in normal infants filmed in the dark and they found that their movement pattern did not change in character. These results support the idea that early visual experience and its integration with vestibular and proprioceptive stimuli are necessary for motor and postural control development. Other insights into the role of vision in motor development derive from Braddick and Atkinson's studies [33, 34] that focused the development of manual abilities in terms of distinct visuo-motor modules. They measured the kinematics of hand movement in 6- to 9- month-old infants, in two conditions: with one eye covered or in binocular condition. In monocular compared with binocular viewing, infants' reaches were poorly controlled, and showed more segments, with higher peak velocity, suggesting as binocular information plays a critical role in controlling hand action [33]. Similarly, the reaching behaviors of young infants appear uncontrolled, leading frequently to failures to contact the toy or requiring large corrective movements to grasp it, if children reach in darkness for a small, previously illuminated toy [34]. For these reasons, it is possible to think that visual-perceptual abilities guide the maturation and completion of motor control from the first periods of life. Moreover, also in the characteristics of walking, the visual functions seem to have a crucial role. Hallemans and collaborators [35] highlight the analogue developmental trend of independent walking in blind or low vision children, due to congenital disorders of the peripheral visual system, in comparison to children with normal vision, although with significant differences in the spatial gait parameters (slower walking speed, shorter stride length, prolonged duration of stance and of double support in the individuals with severe visual impairments).

As regards the influence of visual function on cognitive development, Dale and collaborators [36] indicate how at 1 year of age, a lower visual acuity, in children with peripheral visual disorders, is correlated with a lower sensorimotor developmental quotient, suggesting that the lack of vision is associated with a delayed early-object manipulative abilities and concepts.

In fact, also when the visual disorders are due to cerebral lesions, there is an association between the results on the visual tests performed at 5 months of age and the neurological and neurodevelopmental outcomes at the age of 2 years. In fact, children with more abnormalities in visual function tests tend to have an abnormal outcome on both neurological examination and developmental scales [37].

The predictive role of the quality of visual information processing for the neurodevelopmental outcome in high-risk preterm infants was explored also by Guzzetta and colleagues [38]. They prospectively investigated early development by means of the Fagan Test of Infant Intelligence and an ad-hoc battery for the early assessment of visual functions. The performances were then correlated to the Griffiths Mental Developmental Scales scores at 2 years. The authors point out that the visual findings at 9-month post-term age are a good indicator of neurodevelopmental outcomes and underline the importance of visual experiences for a normal maturation of cognitive and neuropsychological functions.

The presence of cognitive and communication difficulties in young children with severe visual impairment was investigated by Cass et al. [39]. They underlined the risk of a developmental setback, often accompanied by impaired social communication, stereotypies, and behavioral disorders in children with peripheral visual impairment with no additional disabilities at the first early neurologic evaluation. Similarly, Dale and Sonksen [40] stated that developmental setback is strongly associated with more profound visual impairment and that the presence of perception of form and motion appears to exert a protective effect on early cognitive and language development. Furthermore, although the risk of a social and communication disorder similar to autism spectrum disorder is very high in children with visual impairment [41, 42], the factors of coexistence of this type of disturbs are not very clear. It seems that the comorbidity of behavior problems in blind children is more frequent consequently to the greater severity of visual impairment, brain damage, and mental retardation [43].

So, what we can assume from literature is that visual impairment is often correlated to several neurodevelopment dysfunctions, probably for its key-role in early interaction with the reality. Vision permits the adaptation and learning of the child, because through visual information we can progressively learn to detect, decode, process, and respond to the information coming from the surrounding environment. Therefore, a visual deficit during childhood, if not considered in a life-span perspective, can lead to cascading consequences on other functional areas and on the entire neurodevelopment, and successively on the adaptive behavior and on the quality of life [44].

Therefore, early identification of visual impairment through appropriate tools for infants and children, might help to evaluate the compensation's mechanisms and eventually make it possible to optimize early rehabilitation programs, which could improve infant's visual, neuromotor, cognitive, and social outcome [45, 46].

Cerebral visual impairment: difference between congenital and acquired visual disorders

Among visual disorders, "Cerebral Visual Impairment" (CVI) is the leading cause of visual impairment in children in developed countries and it has many causes and manifestations. The term "Cerebral Visual Impairment" defines a type of visual disorder caused by brain damage in the absence of ophthalmological disability. It is observed in children with congenital or acquired brain lesions that involve central visual pathways, and its clinical manifestation is different from that in adults. It is likely that such differences depend on brain plasticity mechanisms, whereby environmental stimuli are more powerful and effective during the early stages of development; so during adult age, the visual system shows lower re-organization capabilities, and the patients show more effort in re-adapting to their environment [47].

The timing, the location, and the extent of the pathology determine the severity and typology of CVI; for example, the extent of impairment of visual acuity and visual field is often correlated with the extent of damage to the central nervous system (CNS). Many children with CVI have additional visual dysfunctions, including abnormalities in contrast sensitivity, impairment in visual processing (of form, faces, and movement), and ocular motility disorders [48].

CVI is very common also in patients (adults and children) with unilateral brain lesion with involvement of the occipital cortex giving as principal manifestation a visual field disorder [49]. Visual field defects can be very extended and involve the entire hemifield, such as homonymous hemianopia or only a part of the hemifield (inferior or superior visual field deficits, known as quadrantanopia). Adult patients with hemianopia typically have visual spatial disorientation in the blind hemifield, and they show unsystematic scanning, with important difficulties in daily life such as reading and driving [50]. Nevertheless, residual visual abilities in the blind field (in particular the capacity to detect visual information) without a conscious perception of the stimuli were described in a small percentage of patients: this visual phenomenon was called "blindsight" [51–54]. Exactly the same behavior is found in children with brain lesions acquired later in childhood: they often exhibit behavioral impairments similar to those found in adult patients with hemianopia, like difficulties in detecting stimuli and finding objects in the impaired visual space, often complaining about having a limited overview, bumping into obstacles or people in busy places, and missing or misreading words [55]. On the contrary, evidence coming from recent literature demonstrates that, in nearly all cases, children with congenital brain lesions and hemianopia have residual unconscious visual perception—"blindsight"—in their blind hemifield [18, 56, 57].

Descriptions of cortically blind animals and humans with residual visual functions without a conscious perception of stimuli date back to the beginning of the last century. In the literature, it is possible to find a distinction between blindsight without visual awareness (type I) [58, 59] and blindsight associated with awareness of the presence of the stimulus, without perceiving it (type II) [59].

The presence of blindsight phenomenon in some patients, but not in others, is may be explained by the possible strategies adopted by the immature brain to solve the problem of the interruption of visual pathways, that are unavailable at a later stage of life. In a recent review, Bourne and Morrone [60] suggest that, taken together, the data from several neuropsychological laboratories and evidence from monkey and cat lesion studies [61–63] indicate that Superior Colliculus (SC) and thalamus (Lateral Geniculate Nucleus -LGN- and pulvinar) may be the key neuronal structures subserving blindsight [64, 65] and that thalamic projections can be relatively plastic during development. Recently, Ajina and Bridge [66] identified a specific functional connection between LGN and hMT+ area in 8 adult patients with blindsight, that was absent in patients without blindsight, despite a retained functional connection with ventral pulvinar and SC. These data support a critical functional role for the LGN in human blindsight, and in particular its connection with hMT+, reinforced by recent evidence for an intact anatomical connection between these structures [67]. These results also revealed that hMT+ area does not require intact V1 for a normal speed response, but LGN may support motion-selective input to hMT+ in the absence of V1. The important role of LGN was also recently demonstrated by Mikellidou et al. [68], who described the visual reorganization of a child with near normal central field vision despite a massive unilateral lesion to the optic radiations acquired early in life. The patient underwent surgical removal of a right hemisphere parieto-temporal-occipital atypical choroid plexus papilloma of the right lateral ventricle at 4 months of age. Both the tumor and surgery severely compromised the optic radiations, and probabilistic tractography revealed that optic radiations between LGN and V1 were very sparse in the lesioned hemisphere consistent with the post-surgery cerebral resection, while they were normal in the intact hemisphere. Strong structural connections between hMT+ and LGN were found in the lesioned hemisphere, while the equivalent tract in the spared hemisphere showed minimal structural connectivity. These results suggest that during development of the pathological brain, abnormal thalamic projections can lead to functional cortical changes, which may mediate functional recovery of vision [60, 69].

Furthermore, it is possible that the infant's brain develops new cortico-thalamic connections capable of bypassing the lesion or re-organize the ability to differentiate functional tissue within a larger impaired cortex. The lesion can activate neuroplastic processes during any stage of development, but in the early period of life, this ability is more pronounced and efficient. This probably applies to the pathways bypassing V1 and directly reaching the extrastriatal visual structures, most of which are normally present in the older brain, but less predisposed to the great expansion observed after early damage [47]. This idea could explain why the blindsight phenomenon occurs in a large percentage of patients with congenital brain damage, while it occurs only in 2–3% of subjects in which the brain injury was acquired late in childhood or in adulthood.

Children with congenital (but not with acquired) brain lesions show spared visual perception (although unconscious) in the affected hemifield, clear evidence for blindsight, thanks to a massive reorganization of their visual system. In these children, V1 of the intact hemisphere also responds to stimuli in the ipsilateral "blind" hemifield [57]. These patients with congenital lesions performed correctly in three different tasks (alignment task, contrast sensitivity for orientation discrimination, contrast sensitivity for motion-direction discrimination) compared with patients with acquired lesions who performed worse. Given the profound lesion, the BOLD response in the lesioned hemisphere cortex did not respond to any visual stimulus, including all the dorsal area, and hMT+ in particular. However, the visual cortex in the normal hemisphere did respond abnormally to both the contralateral and the ipsilateral visual field. This effect was observed already at the level of V1. Since these children had unilateral lesions of the optic radiation and large cortical and subcortical lesions, it is very difficult to imagine a crossed hemispheric pathway that can relay the signal from the ipsilateral visual field to the primary cortex. A possibility is the strong pulvinar-MT projection, observed in the marmoset. The ipsilateral visual signals could reach the pulvinar through several routes, including via SC. From pulvinar, the signal would be first relayed to hMT and then back to occipital cortex. Mikellidou et al. [68] suggested that the level of brain plasticity and reorganization potential at the time of lesion is an important property for the effective presence of blindsight, consistent with the animal brain-lesion literature. This difference in the reorganization mechanisms of the CNS seems to be evident on visual exploration and visual search too [55].

Perspective on early neurorehabilitation

The study of visual processes and their close connection with brain plasticity, from the earliest stages of development to adulthood, suggests the possibility for new non-invasive therapeutic approaches. In order to further understand the development of the brain and the organization of sensory processes in typical and atypical conditions, the analyzing neuroplasticity with a multifaceted approach appears to be increasingly pursued in the rehabilitation of neurological patients. According to this idea, it is very important to better define the clinical and functional characteristics of child's vision, that requires long periods of observation not only by pediatric neurologists and ophthalmologists, but also by therapists and psychologists, in order to plan the appropriate intervention and reduce the possible negative impact of the visual impairment on the global neuropsychomotor functioning. The findings of the several studies presented in this review are closely interconnected and confirm the importance of using a multidisciplinary investigative approach for improving clinical care and treatment [12, 47].

Clinical research, aimed at considering possible new therapeutic models, is fundamental for guiding physicians and therapists in their clinical practice and for ensuring patients receive the best interventions for their specific disabilities [70–72]. As a matter of fact, home-based and family-centered early intervention in infants and young children with visual impairment was associated with enhanced developmental outcomes [73] although further studies are required to better investigate the benefits and limitations of a neurorehabilitative approach in early childhood.

This line of research offers important contributions for clinical practices within educational and psychomotor settings, indicating the benefits of developmental facilitation for children with sensory disorders. Currently, research in the field of evidence-based pediatric rehabilitation is limited by the heterogeneity of the interventions used and, thus, by a lack of consistent and reliable data. For this reason, further well-designed and larger experimental studies are needed to strengthen the generalizability of the findings and their use in early interventions for children with neurodevelopmental disability.

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Compliance with ethical standards

Conflict of interest The authors have no present or potential conflict of interest to disclose.

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