The Effects of Preterm Birth on Visual Development

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Abstract:

Children born very preterm are at a greater risk of abnormal visual and neurological development when compared to children born at full term. Preterm birth is associated with retinopathy of prematurity (a proliferative retinal vascular disease) and can also affect the development of brain structures associated with post-retinal processing of visual information. Visual deficits common in children born preterm such as reduced visual acuity, strabismus, abnormal stereopsis and refractive error are likely to be detected through childhood vision screening programmes, ophthalmological follow-up or optometric care. However routine screening may not detect other vision problems

such as reduced visual fields, impaired contrast sensitivity and deficits in cortical visual processing that may occur in children born preterm. For example, visual functions associated with the dorsal visual processing stream, such as global motion perception and visuomotor integration, may be impaired by preterm birth. These impairments can continue into adolescence and adulthood and may contribute to the difficulties in learning (particularly reading and mathematics), attention, behaviour and cognition that some children born preterm experience. Improvements in understanding the mechanisms by which preterm birth affects vision will inform future screening and interventions for children born preterm.

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Preterm birth is common worldwide, with approximately 15 million babies born before 37 weeks' gestational age (GA) annually; 15% of these babies are born very preterm (GA<32 weeks).[1] Visual function in children born very preterm has been studied extensively as this population is at greater risk of abnormal visual and neurological development than children born at full term. In 2010, the global estimate of severe impairment or blindness in preterm birth survivors associated with retinopathy of prematurity (ROP) was 20,000 while a further 12,300 individuals had mild to moderate visual impairment.[2] Of those with visual impairment, an estimated 55% also had a neurodevelopmental impairment.[2]

Visual deficits associated with very preterm birth include reduced visual acuity;[3] higher rates of strabismus (prevalence estimates range from 5-25%);[4–6] presence of high refractive errors, particularly myopia (3-20%);[7–9] lowered stereoacuity,[10] and loss of peripheral vision.[10,11] Visual deficits are measured and defined in various ways so the exact prevalence is unknown. Damage to the retina from ROP is a common effect of very preterm birth.[12,13] In addition, preterm birth can affect the development of brain structures that are involved in post-retinal processing of visual information such as the optic nerves, optic radiations, primary visual cortex, extrastriate visual cortex and visuomotor integration areas.[14–16] Brain injury is common in babies born very preterm or with a very low birth weight (<1500 grams), with up to 40% having MRI findings of white matter injury and up to 20% experiencing extensive white matter injury from conditions such as periventricular haemorrhage (PVL) and intraventricular haemorrhage (IVH).[17–19]

In this review, the impact of very preterm birth (GA<32 weeks) on development of the eye and visual system will be examined. In addition, the effects of very preterm birth and associated conditions (including ROP and PVL) on form perception, motion

perception, and visuomotor integration will be explored. This is of particular interest in the context of the dorsal stream vulnerability hypothesis, which suggests that preterm birth has a more profound effect on the dorsal visual stream (specialised for motion perception and visuomotor control) than the ventral visual stream (specialised for form perception).[20] The implications of visual deficits associated with preterm birth on subsequent educational development are also discussed.

Retinopathy of Prematurity

An example of retinal damage commonly found in babies born preterm is retinopathy of prematurity (ROP), a proliferative retinal vascular disease.[12,13,21] Since the 1940s, ROP has been identified as a major cause of visual impairment in children born very preterm,[22] and oxygen supplementation has been recognised as an important risk factor in the ROP development.[23] Up to 65% of babies born with a birth weight ≤1250 grams develop ROP.[12,13] The disorder is characterised by abnormal growth of peripheral retinal blood vessels in response to altered retinal oxygen concentrations when a baby is born very preterm.[23] The peripheral retina is only fully vascularised near full term; therefore, when an infant is born preterm, areas of the peripheral retina remain avascular.[23,24] After birth, the baby is exposed to a relatively hyperoxic environment compared to *in utero* and this downregulates vascular endothelial growth factor (VGF) production and halts the growth of the blood vessels in the peripheral retina.[23] As the retina becomes more metabolically active (after approximately 31 weeks' GA), the existing blood vessels cannot adequately meet the oxygen demands, which upregulates VGF production in the retina, resulting in uncontrolled proliferation of blood vessels.[12,23] These new blood vessels extend from the retina into the vitreous as extraretinal fibrovascular proliferations, which, in turn, can lead to retinal detachment and subsequent vision loss.[25] This process of ROP has been categorised using a

system of zones (locations on the retina), stages (severity) and extent (angular extent of retinal area affected in clock hours) according to the International Classification of Retinopathy of Prematurity (ICROP)[24] (Figure I).

Two large multi-center studies, the Cryotherapy for ROP (CRYO-ROP) study[26] and the Early Treatment ROP (ETROP) study,[27] investigated the efficacy of avascular retina ablation for preventing blindness in severe ROP by reducing uncontrolled neovascularisation and ensuing retinal detachment. In the CRYO-ROP study, patients with threshold ROP (defined as five or more contiguous or eight cumulative clock hours of stage 3 ROP in zone 1 or 2 in the presence of 'plus' disease) were randomised to transscleral cryotherapy applied to the avascular retina or no treatment.[26] In the 15 year follow-up study of the babies who had threshold ROP, significantly fewer eyes in the treatment group had severe visual impairment (visual acuity of 6/60 or worse) or partial/full retinal detachment compared to the untreated group.[28] In some children from the CRYO-ROP study, even when ROP regressed without treatment, visual acuity was still severely reduced at 5 ½ years of age; this may indicate poor vision due to preterm-birth-related factors other than retinal damage.[29]

Following the CRYO-ROP study, the ETROP study initiated treatment at a prethreshold stage of active ROP.[27] The result was a revised indication to treat high-risk prethreshold ROP, or Type 1 ROP (defined as any stage of ROP in zone 1 or zone 2 with plus disease; or stage 3 in zone 1 without plus disease) before it became threshold ROP, as this significantly reduced the rate of visual acuity impairment and retinal detachment at 9 months corrected age.[30,31] During this period, ablation treatment was changed from cryotherapy to laser photocoagulation, which may also have contributed to the improvement in ocular structural and functional visual

outcomes of children with severe ROP in the ETROP study.[32] Since the implementation of guidelines and techniques from these studies and subsequent development of stringent ROP screening programmes, and improvements in neonatal care, incidence of severe visual impairment in babies born preterm has reduced greatly.[3,21,28,30] However, as neonatal care has improved, survival rates have increased and subsequently, the absolute numbers of babies with ROP have also been rising.[21] In this context, it is important not only to prevent blindness, but also to maximise visual outcomes for children born preterm. More recently, the use of intravitreal injection of anti-VGF to treat ROP has been investgated.[33,34] Preliminary results show promise; however, further long term investigation into visual outcomes and safety in children are needed.[34]

Cortical processing of visual information

Despite reductions in blindness and severe visual impairment in children who previously had ROP, preterm birth continues to be associated with a number of visual deficits that may be due to abnormal cortical development or cerebral injury.[14–16] Mild visual impairment (reduced best-corrected visual acuity),[3] strabismus,[4,5] abnormal stereopsis,[10] and refractive error[7,8] associated with preterm birth are likely to be detected through childhood vision screening programmes, ophthalmological follow-up or optometric care.[35,36] However, other vision problems such as reduced visual fields,[14,33] impaired contrast sensitivity[37] and cortical processing deficits [38–48] that have been linked to preterm birth are not routinely screened for due to time constraints and the need for challenging and/or non-standardised tests.[36,49] Such deficits may contribute to the difficulties in learning, attention, behaviour and cognition that some children born preterm experience despite having normal or near-normal visual acuity.[48,50–54]

Dorsal and Ventral Processing Streams

Late last century, Mishkin and Underleider identified two cortical pathways for visual processing.[55,56] One pathway involves the inferior temporal cortex and supports object recognition while the other involves the posterior parietal cortex and supports object localisation.[55,56] The resulting dual pathway theory of visual processing was further developed by Goodale and Milner.[57] They described a ventral cortical stream receiving input from the parvocellular layers of the lateral geniculate nucleus and projecting through the ventral regions of the visual cortex to the temporal lobe and a dorsal stream with magnocellular input projecting through dorsal areas of the visual cortex and area V5 to the parietal lobe (Goodale et al[58] Figure I).[57] The ventral stream is concerned with form perception (what an object is), and the dorsal stream supports motion perception, object localisation and visuomotor control (how to interact with an object).[57] Although these cortical streams differ in their functional specialisations, they are interconnected and rely on a number of common cortical areas.[59]

Motion integration is sequential and begins with the detection of motion signals within small, local regions of the visual field.[60] Motion within these small regions is termed local motion and these signals can be generated by changes in luminance (first-order motion) or changes in components of the visual scene other than luminance such as contrast, depth or texture (second order motion) (see Figure II for a stimulus example).[39,60] Detection of first order motion primarily involves processing at the level of the primary visual cortex (V1) whereas second order motion may involve both the primary and extrastriate visual cortices.[60] Subsequent processing in extrastriate dorsal stream areas such as V3 accessory cortical area (V3A),[61] and V5 (also called the middle temporal area (MT))[62] enable integration of local signals into a coherent, global perception of motion.[59] Similarly, global form perception is hypothesized to begin as

local feature processing at the level of the primary visual cortex, followed by feature integration within ventral areas of the extrastriate visual cortex and the inferior temporal cortex.[63]

The assessment of global motion perception has been of particular interest as impaired performance of global motion tasks in early childhood has been proposed to be reflect atypical brain development and associated neurodevelopmental disorders.[64]

Psychophysical tests of global motion and form perception

Psychophysical coherence threshold testing is frequently used to assess global motion and form perception (see Figure III for a stimulus example).[65–67] The measurement of global motion perception typically involves a stimulus known as a random dot kinematogram (RDK).[66] The stimulus is constructed from a field of moving dots. A certain proportion of the dots move in the same direction (signal dots) and the remaining dots move in random directions (noise dots) (Figure III). The observer's task is to indicate the direction of the signal dots. By varying the proportion of signal to noise (coherence) within the stimulus, it is possible to measure a motion coherence threshold which provides an estimate of the signal to noise ratio required for a particular level of task performance (Figure III). Lower motion coherence thresholds (the ability to detect fewer signal dots amongst more noise dots) indicate a higher sensitivity to global motion.[66] The underlying concept is that areas such as V5 are required to integrate the local motion signals generated by each dot into a global percept of coherent motion.

Other types of motion perception that involve local motion integration include motion-defined form and biological motion (see Figure IV for a stimulus example). Motion-defined form tasks often involve asking participants to name a shape or a letter that is defined by target dots (signal) moving with a different speed or direction relative to

background dots (Figure IV).[40] Biological motion perception is typically tested using a "point light display" whereby the human body is represented by a group of moving dots with each dot corresponding to a specific anatomical location (typically the major joints and the head).[68] This stimulus can be placed within a background of randomly moving dots or scrambled point light displays (Figure IV). The subject is asked to identify the action or direction of movement being represented by the point light display.[68]

The measurement of global form perception follows the same principles as global motion assessment, except that the stimuli are constructed from oriented elements such as stationary pairs of dots (dipoles), Gabor patches or short lines, each of which can be arranged to form shapes (see Figure III for stimulus examples).[69,70] The task requires the observer to detect a common orientation of elements or a shape embedded in randomly oriented elements.[70] [69] By varying the signal to noise ratio in the stimulus, a coherence threshold can be measured (Figure III). Other form perception tasks include finding a shape within a stimulus array of varying luminance, texture or contrast.[65] As with motion coherence thresholds, lower form coherence thresholds indicate a higher global form perception sensitivity (less signal is required to perform the task).

In all of these psychophysical tests, the task is to assess the ability of the observer to distinguish the signal from the noise. Task difficulty can be altered by varying the signal to noise ratio in the stimulus, stimulus size, density of stimulus elements, presentation time, contrast, and, in motion perception tasks, speed.[43,70–72] This is of importance as the studies reviewed here have used different stimulus parameters, which constrains direct comparisons between studies.

Dorsal and Ventral Processing in Children Born Preterm

Motion integration impairments in children born preterm have been revealed through psychophysical testing when compared to children born at full term.[20,39–41,67] Yet, form perception is relatively spared in children born preterm.[10,39,67]Consequently, the dorsal stream has been hypothesized to be particularly vulnerable to the effects of prematurity on brain development.[38,67]

Several studies have compared motion perception and form perception in children born preterm and children born at full term. Children who had significant neurosensory impairment such as blindness or deafness were excluded. All children were screened to have adequate visual acuity in at least one eye (better than 6/6 to 6/30) for the psychophysical tasks.[39–41,67] Studies of global motion and form perception in 4-11 year old children born at GA 25-32 weeks and controls found that 60% of children born preterm had reduced stereoacuity (to pass the titmus test of stereoacuity: at least 100 seconds of arc for 5 years of age and younger; 40 seconds of arc for 6 years of age and older), while all of their full term controls passed the stereoacuity screening.[39,67] The preterm groups had significantly higher coherence thresholds for global motion than control groups.[39,67] MacKay et al also found that their preterm group exhibited lower sensitivity to both first order and second order local motion tasks compared to the control group, and only one child in the preterm group performed at the same level as the term born controls for local and global motion perception.[39]

Studies of motion-defined form in cohorts of children born at GA≤30 weeks found that approximately 50% of children born preterm were unable to detect motion-defined form correctly 75% of the time, whereas, all term born controls were able to complete the task.[40,41] Sensitivity to biological motion was similarly impaired in children who were very preterm.[16,67] As well as tests of different types of motion perception, these studies

also investigated form perception and found no difference in form perception sensitivity between children born preterm and those born at full term.[39,41,67] This suggests a relative sparing of global form perception (ventral steam) compared to global motion (dorsal stream) in preterm birth, which supports the theory of dorsal stream vulnerability.[39,41,67]

As well as considering the effects of preterm birth on motion-defined form perception; effects of periventricular brain injury (PVBI), which was defined as germinal matrix/intraventricular haemorrhage or hypoxic/ischaemic injury has been investigated. PVL/PVBI and ROP have been associated with alterations in the optic radiations; however, it is unclear whether these alterations play a role in the development of motion perception deficits noted in children born preterm.[15,73] In a group of children born preterm at GA≤30 weeks' and term born controls with no brain injury, Downie et al found that while children born preterm performed significantly worse in the motion-defined form task than children born at full term, PVBI *per se* did not significantly affect performance.[40] This study included children who had ROP and severity of ROP was evenly distributed across the preterm group. Conversely, Jakobson et al found that the children who were born preterm and had no PVBI or ROP had motion-defined form perception comparable to term born controls while children with mild PVBI, ROP or both had impaired motion-defined form perception.[41]

Similarly contradictory results have been reported for biological motion perception. Adolescents who were born preterm (GA 27-33 weeks) and previously had periventricular leukomalacia (PVL) were found to have poorer biological motion perception than term born controls and children born preterm without PVL.[16] Conversely, a later study reported significantly poorer biological motion perception in children born preterm compared to term born controls but no statistically significant

difference in performance between children born preterm with detected abnormalities on neonatal cranial ultrasounds and children born preterm without abnormalities.[43]

Few studies have measured motion perception specifically in children who previously had ROP[39,41,67] and the majority of experiments have involved the central visual field which is less likely to be affected by appropriately treated ROP. As past studies have included small numbers of subjects, particularly those who had PVBI or ROP, and children who are born preterm are subjected to many inter-related conditions and treatments near birth; the relative contributions of preterm birth *per se*, brain injury and/or ROP to motion-defined form or biological motion perception impairments remain unclear.

At present, we can only speculate on the real world implications of the dorsal stream deficits that have been associated with preterm birth. It is of importance to note that no statistical significance is not the same as no clinical significance and as many of these tests of visual perception are exploratory in nature, clinical significance of these findings are currently unknown. Estimates of the normal developmental trajectories for form and motion perception differ between studies,[67,74–76] and it is currently unknown whether the effects of preterm birth on global motion perception reflect a delay in maturation or an absolute deficit. Motion coherence thresholds measured using RDKs are correlated with reading rate in school aged children;[77,78] nevertheless, the evidence between impaired motion perception and poorer reading performance is controversial.[79] Impaired biological motion perception has also been linked to social cognition.[43,80,81] Williamson et al found that children born preterm performed worse on biological motion tasks and displayed more autistic-like traits when compared to their peers in the term control group.[43] Despite the complexity of these relationships, the combined effect of global motion and biological motion deficits may be associated with

the lower educational achievement[50,82] and poorer social relations[83] that have been reported in long term follow-up studies of preterm birth. More data are needed that test this possibility.

Motion processing can be improved through intensive training; a process known as perceptual learning.[84,85] It is possible that perceptual learning could be used to improve global and biological motion perception in children born preterm. However, it is unknown whether training using specific motion tasks to improve certain aspects of motion perception will also translate to improvement in tasks involving more complex cortical processing such improving visuomotor integration or reading.[86,87]

In summary, current open questions include whether reduced motion perception in children born preterm affects their ability to perform daily activities, whether PVL has an independent effect on visual development, and whether early motion perception screening with potential early training would be beneficial for these children.

Neuropsychological Tests

Tests of neuropsychological function and visuomotor integration also involve measures of dorsal stream function.[45,55] Such tests include psychophysical tests,[44–46] differentiating between different pictures by naming or pointing,[20,88] reaction times and processing speeds,[44] and standardised test batteries.[48,50,51,89–93] Through the use of these tests, there is a general consensus that children born preterm perform poorly in tasks involving motor skills,[48,51,94] aspects of visual perception such as discriminating line orientations, naming shapes or matching block patterns,[44,51] and visuomotor integration[48,90] when compared to children of the same age who were born at full term. These deficits continue into later childhood[45,95] and are even noted in adulthood.[46]

Furthermore, the incidence of the deficits has not changed with advances in neonatal care.[96]

Using standardised test batteries of neuropsychological tests, studies have found that children born very preterm were more likely to have poorer visual perception and motor skills than children born at full term,[48,51,90,97] especially in those who have had PVL[100] or cerebral palsy.[101] Marlow et al found that six year old children born preterm (GA<26 weeks) had a lower visuospatial score by 1.6 standard deviations than the term born controls.[51] These differences were apparent even after adjustments for intelligence were made.[48,51,90] Performance of motor, visual perception and visuomotor integration tasks appears to be correlated with gestational age and birthweight, where children born at lower gestational ages and lower birthweights have poorer performance.[48] Although most of the reviewed studies did not report the incidence of strabismus or stereopsis performance in their samples, poor depth perception has been associated with reduced fine motor skills, which can have implications on visuomotor function.[98] Therefore, abnormal stereopsis may be one of the contributors towards the lowered performance in motor skills and visuomotor integration in children born preterm, particularly as the incidence of strabismus and reduced stereopsis is elevated in this group.[6,41,99] Reduced visual acuity[102] and severe ROP[102,103] have also been associated with poorer visuomotor skills, particularly fine motor skills. Despite the advances in neonatal care and treatments, the proportion of children born preterm with minor motor skill deficits has remained higher than children born at full term.[48,104,105] Insights into the underlying factors associated with reduced visuomotor skills are required to tailor management for these frequent and ongoing deficits.

Chaminade et al suggested that adults who were born preterm (mean GA 30 weeks) were unable to effectively use higher-order processing to perform action recognition

tasks and thereby, compensate by relying heavily on low-level visual information.[46] The evidence for this theory came from functional MRI measurements of brain activity. During a task where term born control adults had to distinguish whether two successive pictures had the same grasping motion of a hand or drinking vessel, there was activation in an anterior cluster at the junction of the anterior intraparietal and postcentral sulci. This cluster has been associated with the representation of higher-order dorsal stream processing. However, in subjects born preterm, there was more activity in a region of the lingual gyrus that is involved in the detection of simple stimulus features like contours.[46] This abnormal pattern of activation in subjects born preterm may partially explain the dorsal stream-related visual and motor deficits noted in preterm birth.

Young adults born preterm with birth weight ≤1500g who had lowered visuomotor integration scores also had associated structural changes to the brain. These cortical changes included thinning in the lateral areas of the temporal and parietal lobes along with thickening of the frontal lobe; reduced cortical surface area primarily in the frontal, temporal and parietal lobes; and reduced white matter integrity within association tracts.[106] Ventricular dilatation, corpus callosum thinning and reduced white matter integrity have also been associated with impaired visuomotor and visual perceptual performance in adolescents born very preterm with birth weight <1250 grams.[107] These findings highlight the complexity of preterm birth effects on brain development. Understanding how brain abnormalities influence visuomotor control and visual perception will advance the prevention and management of neuropsychological deficits associated with preterm birth.

Few studies have investigated the possible association between ROP severity and visual-motor integration.[102,103,108] Goyen et al studied visual-motor integration and motor

skills in 45 children with stage 1-3 ROP at 3 years of age without congenital abnormalities and who were not born small for gestational age.[103] Visual-motor integration ability was not found to vary significantly as a function of ROP severity. However, O'Connor et al found a statistically lower score on fine motor skills tasks in children with zone 1 ROP compared to those with zone 2 ROP (zone 1 is closer to the macula, the centre of vision, and likely to indicate more severe ROP).[102] Of the 61 children in the study, mean Teller acuity was 0.42 ± 0.71 logMAR, with 6 children who were classified as having light perception or no light perception; this would have affected the number of children who would be able to complete all the tasks. Children with severe ROP are more likely to have reduced vision, strabismus/amblyopia or refractive error, which can all affect visuomotor integration; consequently, there is an uncertainty of whether ROP *per se* affects visuomotor development, particularly as there is a paucity of longitudinal data.[103] However, all children born preterm with or without ROP and/or brain injury are at higher risk of deficits in these domains compared to children born at full term and may benefit from early screening.[90,103]

Implications of deficits in visual perception and visuomotor integration

From preschool to adolescence, visual perception, motor skills and visuomotor integration have been associated with educational outcomes, learning, behaviour and attention.[50,82,109] Children born very preterm experience less favourable academic outcomes, particularly in mathematics.[52,54] In a cohort study of 204 children born extremely preterm (GA<26 weeks) who were assessed at 6 years of age, 180 did not have any significant neurologic abnormality and were taught at a mainstream school.[51] However, visuospatial perception, visuomotor co-ordination, attention-executive function and gross motor performance of the children born preterm were poorer than

their classmates born at full term.[51] After adjusting for cognitive function, the academic performance of the children born preterm remained poorer than their classmates. This effect continued to be evident at 11 years of age, particularly in mathematics and reading.[50] The authors suggest that cognitive and visuomotor scores explained approximately 54% of the variance in academic performance for the children born preterm.[51] It has been proposed that the reduced mathematical ability of children born preterm is associated with visuospatial working memory, visual processing and executive function. Adjustments for working memory and visual perception in regression models appear to minimise the difference in mathematical ability between preterm and term born children indicating that visual development may be involved in the mathematical deficits.[54] Although visual perception has been shown to be impaired in many children who are born preterm, including those who are deemed “healthy” (absence of congenital malformations or major neurological/sensory problems); there is a lack of routine screening protocols in place to detect vision problems in children born preterm.[10,47]

Conclusion

Mild visual impairments are common in children born very preterm, particularly children with previous ROP. However, children born preterm are at risk of reduced performance on tasks targeting higher-level visual function, even when they have normal visual acuity. These difficulties may be related to the conditions associated with preterm birth such as intraventricular haemorrhage, PVL and ROP and treatments in the perinatal period. However, the research in this area has been limited to case studies and small cohort studies and the results are often contradictory. The relationship between local retinal processing and higher visual processing in the dorsal stream function remains unclear. Another outstanding issue is whether deficits in visual perception apparent in

children born preterm are due to maturational delay or reflect an absolute deficit. Studies of adolescents and adults who were born preterm show impaired performance on vision and visuomotor tasks compared to individuals born at term; this suggests that these deficits may be absolute.

Although visual perception and visual processing have been associated with learning difficulties, particularly in mathematics, it is unknown whether there is a causative relationship. The wide range of participant ages and tests used in the current literature has added to the difficulty in determining the associations between preterm birth, motion perception and visual processing. It is important to clarify these associations as they may contribute in part to the individual's wellbeing, academic achievement, employment and social relations in adolescence and adulthood. Improvement in understanding of underlying issues will inform future screening and interventions for deficits in these areas.

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Figures

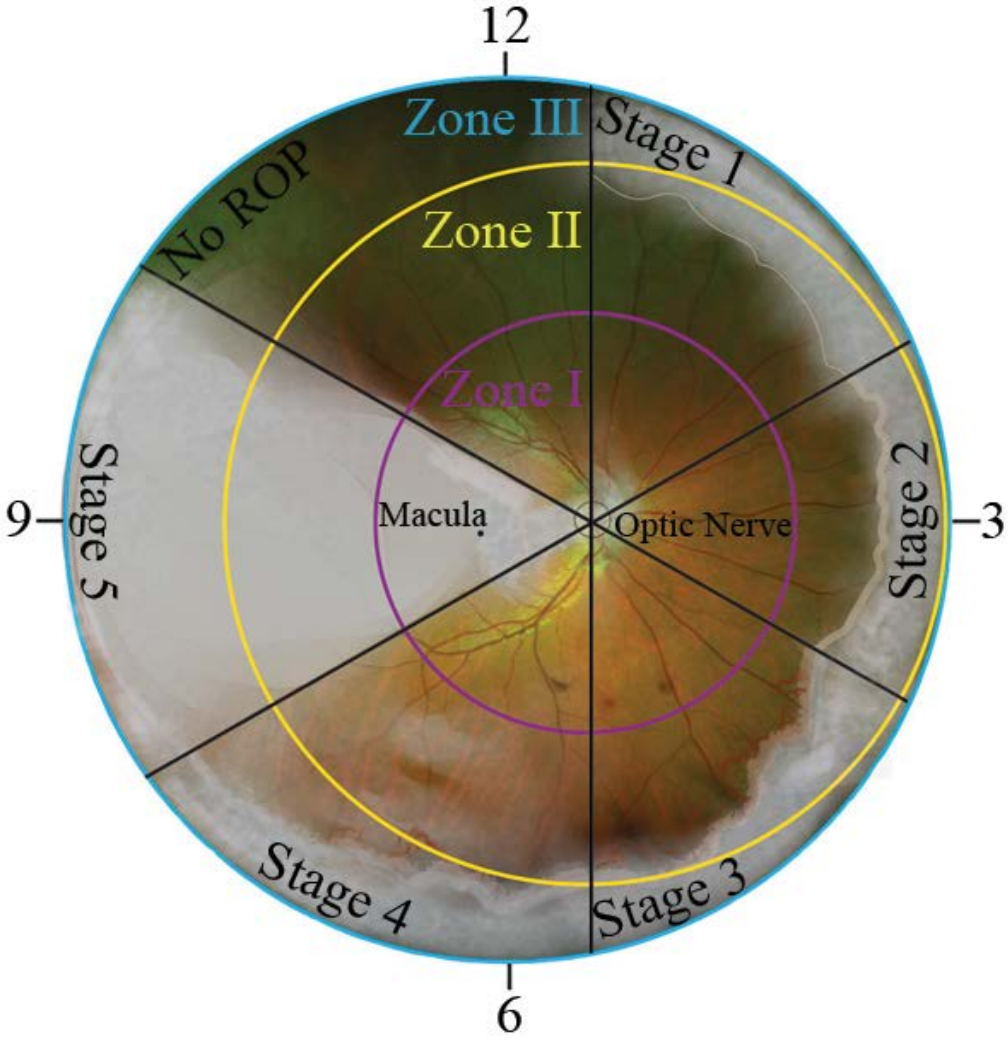

Figure I Classification of Acute ROP

The stages of ROP represent:
stage 1: demarcation line between vascular and avascular retina, stage 2: ridge, stage 3: extraretinal fibrovascular proliferation, stage 4: partial retinal detachment, stage 5: total retinal detachment

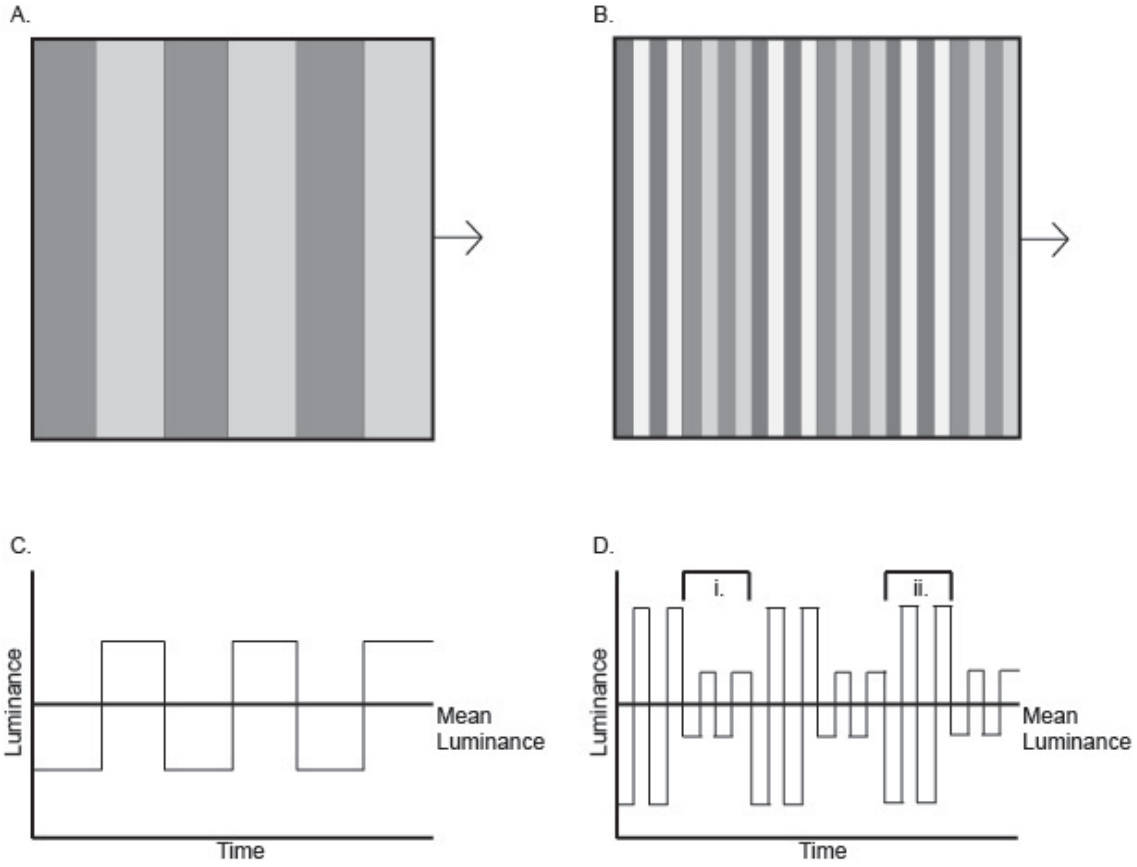

Figure II First Order and Second Order Local Motion

A1. First order local motion task. As the gratings move, the change in luminance allows perception of the direction of movement as depicted in C.

B1. Second order local motion task. The contrast changes across time (Di. and Dii.) while maintaining the same mean luminance. This change in contrast allows perception of the direction of movement as depicted in D.

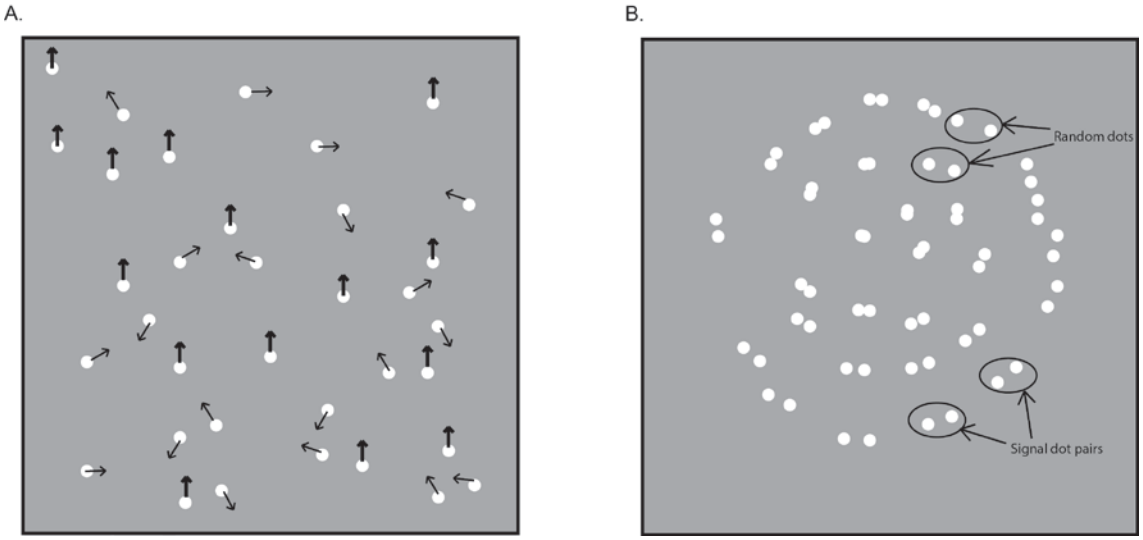

Figure III Global Motion and Global Form

A. Global motion task. The dots with arrows pointing upwards depict the signal moving upwards while the dots with arrows in different directions depict the noise moving in various directions. The coherence level is the proportion of signal versus signal and noise, where lower coherence indicates higher sensitivity to global motion.

B. Global form task. The signal dot pairs (dipoles) produce the perception of concentric circles. The task difficulty is varied by adjusting the number of dot pairs or by replacing a proportion of signal pairs with randomly oriented pairs (noise).

Note: the arrows in A are not present during testing.

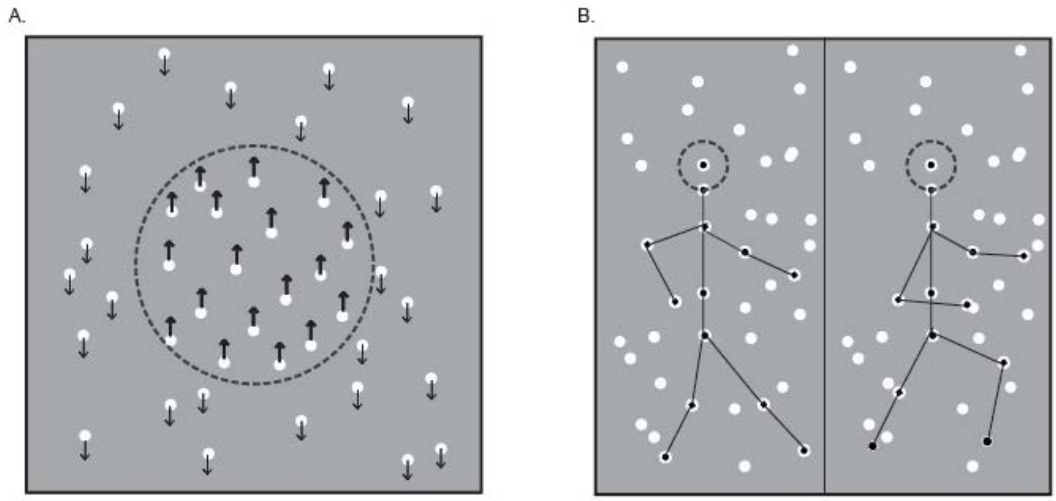

Figure IV Motion-defined Form and Biological Motion

A. Motion-defined form task. The circle shaped (dashed lines) defined by target dots (signal) moving with a different direction relative to background dots. The shape can also be produced by different speed of movement between signal and background. The coherence of the signal dots or the strength of the motion contrast in the stimulus can be manipulated to vary the difficulty of the task.

B. Biological motion. Specific anatomical locations such as the major joints and head are represented by a group of dots; these are marked in black with a white outline for ease of visualisation. These dots move in a co-ordinated way to produce a biological movement. This stimulus can be placed within a background of randomly moving dots or scrambled point light displays.

Note: the dotted circle is not present during testing for A; for F, the black lines denoting the figure are not present during testing and the black dots with the white outline are the same colour as the noise dots.