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Multifactorial determinants of visual outcome in very and extremely preterm infants: A systematic literature review of risk factors for visual and oculomotor dysfunctions

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ABSTRACT

Preterm birth is often associated with neurological, neurodevelopmental and visual impairment arising from the complex interplay of ocular, visual pathway, and cerebral vulnerability in the immature infant. Visual dysfunction in premature infants may reflect ocular, anterior visual pathways, retrogeniculate pathways and visual associative areas abnormalities, as seen in Cerebral Visual Impairment.

This systematic review synthesized evidence on the association between pre-, peri-, i and postnatal factors on basic visual (visual acuity, contrast sensitivity, visual field) and oculomotor (fixation, smooth pursuit and saccades) functions in very and extremely preterm infants. MEDLINE/PubMed, Scopus, Web of Science, and the Cochrane Library were searched for studies published between January 2010 and 6 June 2025. Twenty-five studies were included. Across the included studies, VA was the most frequently assessed outcome, whereas contrast sensitivity, visual field, visual fixation, and smooth pursuit were less extensively examined. Retinopathy of prematurity, neuroimaging abnormalities, lower gestational age, and lower birth weight were the most frequently investigated risk factors; associations with visual outcomes were reported for each factor, although the associations varied across studies. Evidence concerning systemic, metabolic, and prenatal factors was more limited and heterogeneous.

This review highlights the multifactorial nature of visual dysfunction in very and extremely preterm infants, further emphasizing the complex relationship between preterm birth, visual outcomes, and neurological vulnerability.

1. Introduction

The evolving clinical and epidemiological landscape of prematurity is characterized by significant shifts in prematurity-related sequelae [1–3]. Among these sequelae, visual and neurodevelopmental abnormalities remain particularly common, especially in children born very or extremely preterm [4,5].

Visual dysfunction in this clinical population ranges from lower-order deficits, such as refractive errors, strabismus, reduced visual acuity and stereoacuity, and visual field loss [6], to higher-order visual impairment (VI) affecting visuo-perceptual processing, visuomotor integration, attention and/or navigation [7–13]. These lower order deficits may result from abnormalities affecting the anterior visual system but may also occur in the context of post-geniculate visual pathway involvement. Higher-order deficits have usually been associated with Cerebral Visual Impairment (CVI), a brain-based disorder encompassing both lower-order (e.g., reduced acuity, impaired contrast sensitivity, restricted fields and oculomotor abnormalities) and higher-order

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impairments [8–13].

From a neurobiological perspective, the potential contribution of cerebral factors to visual dysfunction in preterm infants is closely related to cerebral immaturity between 20 and 40 weeks' gestation [14]. Preterm infants are inherently vulnerable to cerebral damage driven by germinal matrix haemorrhage, white-matter injury, periventricular parenchymal involvement, and cerebellar haemorrhage [1,15,16]. Both hypoxic-ischemic and hemorrhagic injuries damage subplate neurons, disrupting brain connectivity and causing dysmaturation of white and grey matter structures [1]. This underlying brain pathology contributes significantly to the broad long-term adverse outcomes in preterm infants [1], among which visual pathway disruption plays a prominent role. In this context, thorough consideration and early evaluation of prematurity-related VI risk factors carry paramount clinical importance [17].

The visual system is one of the most widely utilized models for investigating the mechanisms of central nervous system recovery and plasticity following early brain injury [18–22]. This is due to its high accessibility for experimental procedures, as it represents a well-defined and isolated pathway within the brain. Furthermore, it encompasses all stages of cerebral maturation and allows for precise measurement of visual acuity from the earliest days of life. The development of the visual pathways is strongly influenced by visual experience during short postnatal periods of heightened plasticity, known as “critical periods” [23–25]. Visual functions are often described as a “window to the brain”, providing essential insights into early neurological maturation, particularly in preterm infants [26–29]. However, established international screening protocols for preterm infants focus primarily on ocular structures and anterior visual pathways through red reflex and fundoscopy [30]. Visual dysfunction after preterm birth may result from ocular abnormalities and involvement of the anterior visual pathways, as well as from damage to post-geniculate networks and cerebral pathways. For these reasons expanding functional visual evaluations beyond peripheral screening during the first months of life may be critical for characterizing visual dysfunction and identifying infants who may warrant further neurological and visual assessment [17,31–33]. In this context, the systematic evaluation of prematurity-related risk factors becomes clinically crucial: identifying clinical, perinatal, and postnatal risk factors provides clinicians with a fundamental tool to stratify individual risk, guide targeted visual screening, and, where appropriate, prompt further assessment and tailored habilitative protocols as soon as possible [17]. Nevertheless, despite numerous risk factors being recognized in literature, their specific contributions to VI remain incompletely defined, and a systematic synthesis of findings is lacking.

To address this knowledge gap, this systematic literature review aims to explore the associations of pre-, *peri-* and postnatal risk factors with basic visual and oculomotor outcomes in very and extremely preterm infants (born before 32 weeks of gestation), with the aim of synthesizing the available evidence on prenatal, perinatal and postnatal determinants of visual and oculomotor outcomes, identifying consistently reported associations and highlighting emerging factors that may warrant further investigation.

2. Methods

This review was registered in the International Prospective Register of Systematic Reviews (PROSPERO; registration number CRD420251114937) and followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [34]. An evidence review team was constituted prior to study initiation, including experts in systematic review methodology and in the assessment of visual and oculomotor functions in preterm populations.

A comprehensive literature search was conducted in the following electronic databases: MEDLINE/PubMed, Scopus, Web of Science, and The Cochrane Library. The search strategies for each database are detailed in the Supplementary File (Section 1). The search covered published records from 1 January 2010 to 6 June 2025.

The cutoff of 2010 was selected to ensure that the synthesis reflects contemporary practices in neonatal care, advanced neuroimaging (e.g., widespread implementation of high-resolution neonatal MRI), and modern management of retinopathy of prematurity, all of which significantly changed the neurodevelopmental and visual outcomes of very and extremely preterm infants compared to earlier historical cohorts.

No language restrictions were applied during the electronic database searches. Studies were eligible for inclusion if they adopted gestational age (GA) <32 weeks' as inclusion criteria, involved very preterm (<32 weeks' gestation) or extremely preterm (<28 weeks' gestation) infants and examined at least one pre-, peri-, or postnatal risk factor potentially associated with basic visual or oculomotor dysfunction, including, but not limited to GA and Birth Weight (BW), Retinopathy of prematurity (ROP), neuroimaging abnormalities (e.g. intraventricular haemorrhage, periventricular leukomalacia), and neonatal morbidities (e.g. hyperglycemia). Eligible studies were required to report measures of basic visual function and oculomotor function, including visual acuity (VA), contrast sensitivity (CS), visual field (VF), visual fixation, saccadic eye movements, and smooth pursuit. Studies were included when visual outcomes were reported according to the presence, absence, or severity of one or more risk factors, or when statistical analyses examining associations between risk factors and visual outcomes were provided. Studies were excluded if they included individuals born at ≥32 weeks'' gestation, unless data for the eligible subgroup were described separately; if they did not report visual outcomes or did not provide stratified visual data or statistical analyses of associations between risk factors and visual outcomes; if they focused exclusively on structural ocular abnormalities (e.g., isolated retinal or macular lesions) without assessing functional visual outcomes.

All records identified through the database searches were imported into the Systematic Review web app Rayyan QCRI [35], and duplicates were removed through a semi-automatic process. Study selection was conducted in two stages: first, titles and abstracts were screened by at least two reviewers to assess potential eligibility; second, the full texts of relevant articles were retrieved and evaluated against the inclusion and exclusion criteria. Before title and abstract screening, two reviewers independently assessed a 20% sample of records as a calibration exercise using the predefined eligibility criteria. Inter-reviewer agreement was high (Cohen's $\kappa = 0.96$). Any disagreements between reviewers during study selection were resolved through discussion. If necessary, a third reviewer was consulted to reach a final decision. The flowchart detailing the study selection process is shown in Fig. 1.

Data were independently extracted by at least two reviewers using a piloted data extraction form developed by the evidence review team. Extracted information included study and participant characteristics, exposure variables (pre-, peri-, and postnatal risk factors), visual and oculomotor outcomes assessed, age at outcome assessment, statistical methods and main findings. In cases of disagreement, data were rechecked against the original publication and resolved by consensus. Given heterogeneity across studies in populations, exposure definitions, outcome measures, description of confounder management, analytical approaches and assessment timing, a narrative synthesis was planned as the primary data synthesis method. Methodological quality and risk of bias were assessed using the appropriate Joanna Briggs Institute (JBI) Critical Appraisal Tools [36], selected according to each study design.

3. Results

3.1. General results

The search strategy provided 3403 studies; 1245 duplicates were removed. A total of 2158 records were screened for inclusion and exclusion criteria. Based on title and abstract screening, 1925 non-pertinent works were excluded. The remaining 233 records were

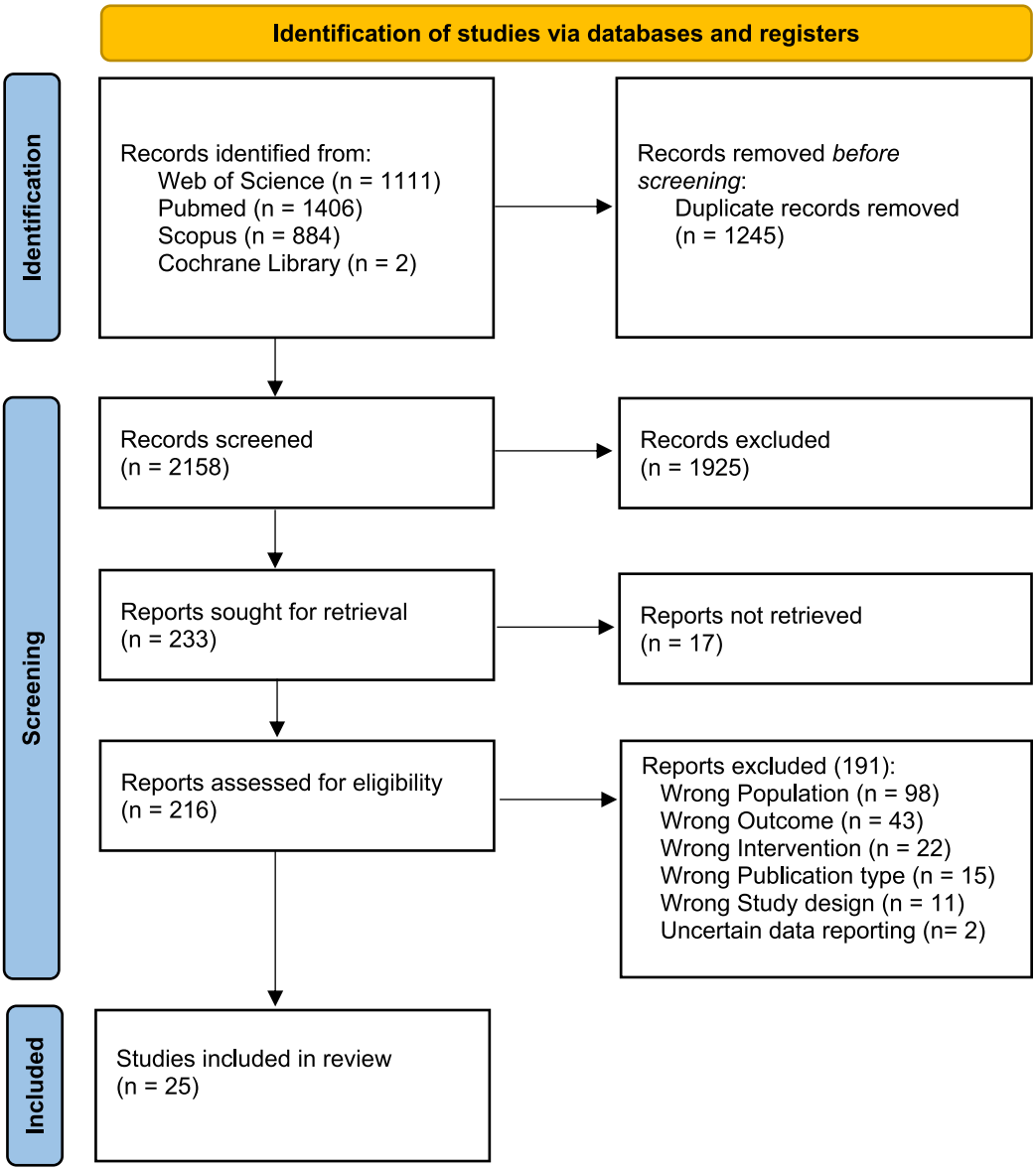


Fig. 1. Flow chart of the literature selection process following the PRISMA guidelines [34].

sought for retrieval; 17 could not be retrieved. Therefore, 216 full-text reports were assessed for eligibility. Studies classified as having the wrong population ($n = 98$), wrong outcome ($n = 43$), wrong intervention ($n = 22$), wrong publication type ($n = 15$), wrong study design ($n = 11$), or uncertain data reporting ($n = 2$) were excluded. The list of references included and excluded after full-text review, along with the reasons for exclusion, are reported in the Supplementary File (Section 2). A total of 25 studies were included in the review.

Included studies were conducted in Europe ($n = 17$), United Kingdom ($n = 2$), United States ($n = 3$), Canada ($n = 1$), Australia ($n = 1$), and Japan ($n = 1$). Details on the geographical distribution of the included studies are provided in the Supplementary File (Section 3). Funding sources were reported in most studies (68%), and 96% of the studies declared no conflicts of interest. Sample sizes and follow-up durations varied widely, ranging from assessments in early infancy (term equivalent age or 6–12 months) to adolescence and young adulthood. Fig. 2 illustrates the age distribution of visual function assessments across the included studies.

The included studies differed in their primary aims and analytical approaches, which ranged from descriptive and exploratory analyses to confounder-controlled association models with varying covariate sets. Table 1 summarizes the characteristics of the included studies, and Table 2 summarizes the distribution of prematurity-related risk factors across the included studies. Additional characteristics extracted from the studies are reported in the Supplementary File (Section 4). JBI results are summarized in the Supplementary File (Section 5).

3.2. *Visual outcome across risk factors*

VA was the most frequently assessed outcome, reported in 18 studies. CS was examined in 5 studies, VF and visual fixation in 3 each, and smooth pursuit in 1. A limited number of studies adopted an instrument-based approach, such as eye tracking, to explore early markers of higher-order visual functions, using fixation and saccade metrics to characterize visual search and visual orienting. To facilitate interpretation of the available evidence across visual domains, Table 3 provides a cross-domain synthesis by risk factor and visual outcome. To complement the table, the narrative results are organized by visual outcome and focus on the main patterns.

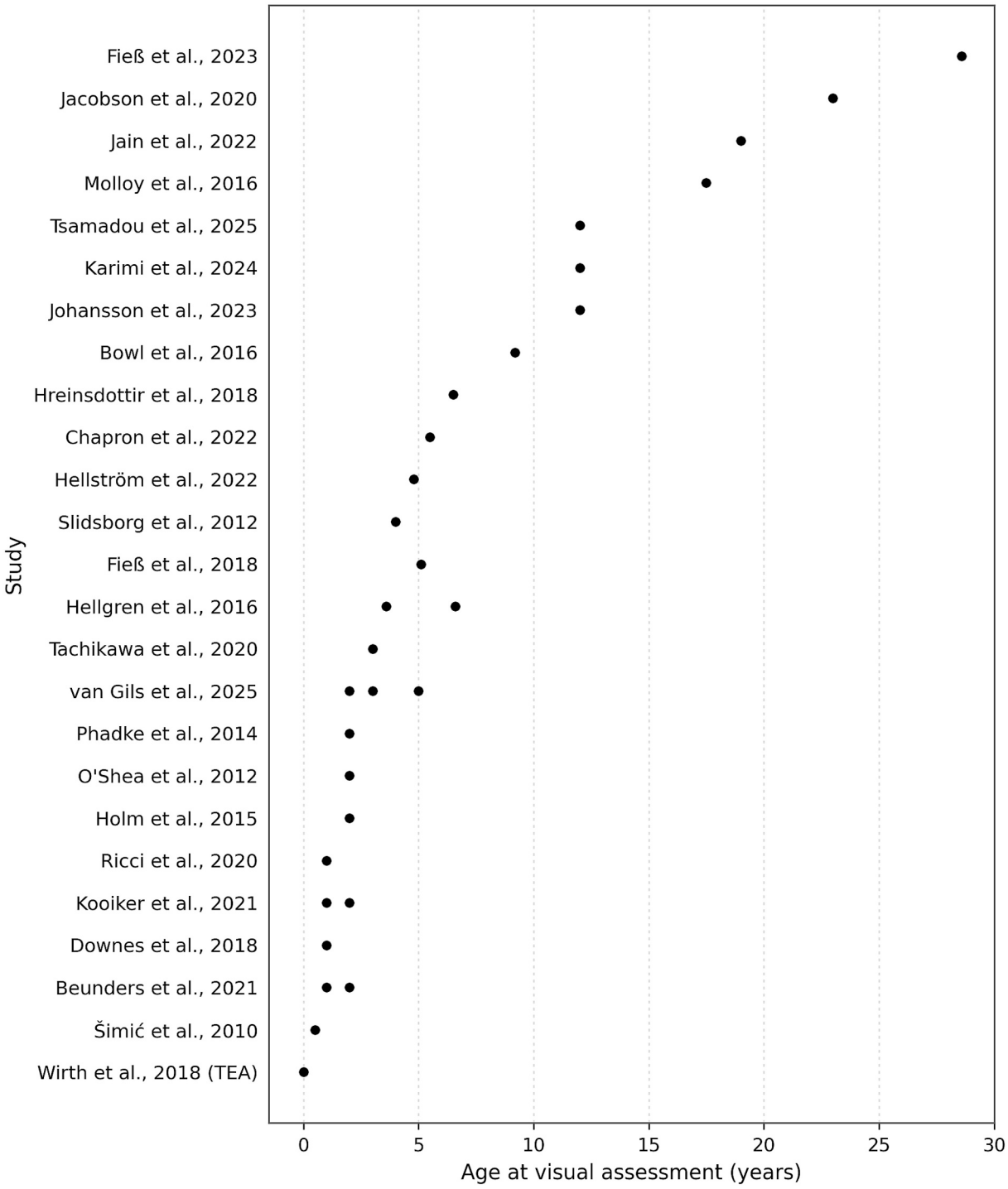


Fig. 2. Fig. 2. Age of visual assessement: each point represents the age at the time of visual evaluation for each study.

3.2.1. Visual acuity

A total of 18 studies provided data on the impact of pre-, peri-, and postnatal risk factors on VA development in extremely and very preterm infants. VA assessment demonstrated substantial heterogeneity in acuity parameters, testing modality, and instruments employed, with behavioural preferential-looking or electrophysiological methods predominantly used in infancy and recognition-based tests in older children. Because both assessment methods and the relative contribution of investigated risk factors varied with age, findings are summarized across three developmental periods.

3.2.1.1. Age-related visual acuity in infancy. Three studies assessed VA in the first years of life [52,53,57]. Neuroimaging related findings were among the factors most reported to be associated with suboptimal VA. Wirth et al. [57] showed that neuroimaging abnormalities including supra-tentorial injuries (Germinal Matrix Haemorrhage/Intraventricular haemorrhage - IVH, periventricular leukomalacia -PVL and posterior fossa lesions) were the only variable retained in multivariable models. Evidence regarding the association between ROP and early VA was limited, with descriptively poorer VA outcomes reported in infants with severe ROP (Stages 3–5) [52], whereas ROP and other perinatal variables were not retained in the final multivariable model once

Table 1
Characteristics of the included studies.

Study	Study design	Primary aim	Main analytical strategy
Beunders, 2021 [9]	Combined cohort study with retrospective and prospective data collection	Association and predictive value of visuospatial attention for neurodevelopmental outcome	Linear regression analyses assessing associations between reaction time to fixation and neurodevelopmental outcomes; hierarchical multiple linear regression assessing added predictive value beyond neonatal risk factors. Non parametric independent – group tests by GA, ROP and brain injury. Restricted sample excluding severe congenital/ chromosomal abnormalities, perinatal asphyxia, IVH grade III, TORCHES infections, treated PHVD and treated ROP grade III.
Bowl, 2016 [37]	Multicentre cohort study with cross sectional visual assessment	Visual function related to ROP, GA and BW	One-way ANOVA; Holm–Sidak or Dunn multiple-comparison tests across strata by ROP, GA and BW strata; Pearson correlation between VA and central light increment sensitivity. Restricted sample excluding psychological or neuronal disorders, hypoglycemia, IVH or severe birth asphyxia related HIE
Chapron., 2022 [38]	Population-based prospective cohort study with cross-sectional visual assessment	Ophthalmological and visual impairments according to GA and neonatal morbidity	χ^2 tests across GA groups; GEE logistic regression models for associations with CP and ROP, adjusted for GA and severe neonatal morbidity and accounting for multiple births.
Downes, 2018 [39]	Cross Sectional comparative study	Early attention control development	Multivariate and univariate ANOVA for eye-tracking group differences; bivariate correlations for GA and eye-tracking outcomes.
Fieß, 2018 [40]	Cross Sectional study	Ophthalmic parameters and neurological development	χ^2, Mann–Whitney U and Kruskal–Wallis tests across three groups jointly defined by GA and ROP status. Univariable and multivariable linear regression models assessed ophthalmic and neonatal factors in relation to PDI, MDI and head circumference. No multivariable model used VA as the dependent outcome. Exclusion criteria: congenital chromosomal disorders, congenital heart diseases, neural tube defects. Restricted sample excluding severe congenital anomalies.
Fieß, 2023 [41]	Retrospective cohort study with prospective data collection	Long-term visual outcomes according to prematurity and ROP/treatment	Descriptive statistics were reported across groups defined by GA, ROP occurrence and ROP treatment. Spearman correlations between DCVA and GA, BW, ROP, ROP treatment, and a binary composite indicator of severe perinatal adverse events- conducted in the entire cohort. Simple and multivariable logistic regression analyses were conducted for amblyopia.
Hellgren, 2016 [42]	Prospective population -based cohort study and cross sectional assessment	Ophthalmologic outcome in extremely preterm	Group comparisons using independent *t*-tests, Mann–Whitney tests and Fisher exact. Logistic regression models examined visual impairment, strabismus, refractive errors and a composite ophthalmological outcome in relation to GA, with adjustment for treatment-requiring ROP.
Hellström, 2022 [43]	Retrospective population-based cohort study	Ophthalmological and neurological outcomes	Univariable logistic regression assessed GA, birth weight, birthweight SDS, sex, BPD, NEC, any ROP and ROP treatment as predictors of composite visual impairment. A multivariable logistic regression model including GA, sex, BPD and ROP treatment assessed independent associations with visual impairment. Pearson χ^2 tests compared neurological disorders between children with and without VI
Holm, 2015 [44]	Prospective cohort follow-up study	Antecedents and correlates of visual field deficits	Time-oriented multivariable logistic regression evaluating maternal, placental and neonatal predictors of visual field deficits (including gestational age, placental inflammation, ventriculomegaly, echolucent white matter lesions, prethreshold ROP, severe BPD and NEC). Variables entered according to their temporal occurrence and retained through a step-down procedure
Hreinsdottir, 2018 [5]	Prospective population-based cohort study	Predictive factors for visual problems	Separate univariable logistic regression analyses assessed GA, BW, IVH grade 3–4/PVL, ROP, sex, early visual-tracking measures, CP, cognitive disability and block-test performance as predictors of VA and CS; variables with univariable $p < 0.10$ were entered into outcome-specific stepwise multivariable logistic regression models. Similar models were performed for refractive error, strabismus and composite ophthalmological outcomes
Jacobson, 2021 [45]	Prospective population-based cohort study	Association of severe treatment-requiring ROP with visual, cognitive and functional outcomes	VA was compared descriptively between participants grouped according to ROP. Multiple regression analyses and Mann–Whitney tests were used for cognitive outcomes.
Jain, 2022 [46]	Prospective cohort study	Long-term visual function and ocular morbidity after extreme prematurity and according to neonatal ROP status	Kruskal–Wallis analyses compared subgroups according to ROP. Mann–Whitney tests and mixed-effects models with a random participant effect compared VA and CS between extremely preterm and term-born groups.
Johansson, 2023 [47]	Prospective population-based cohort study	Visual perception and social functioning	Descriptive comparison. Student's t-test and χ^2 test; univariate linear regression explored associations among perceptual, social, neonatal, ophthalmological and clinical variables followed by multivariable and hierarchical multivariable linear regression.
Karimi, 2024 [15]	Cross-sectional analysis within a prospective population-based cohort	Association between structural brain MRI findings and ophthalmological outcomes	Independent-samples *t*-tests, Mann–Whitney *U* tests and Pearson χ^2/ Fisher exact tests were used for group comparisons. Generalized linear models examined associations between MRI and VA and CS. Generalized linear models also assessed associations between perinatal factors and MRI findings.
Kooiker, 2021 [48]	Prospective longitudinal screening and follow-up study	Visual processing dysfunction and neurological risk signs	Outcomes were classified against age-related term-born normative trajectories. Wilcoxon signed-rank tests examined visual findings within referred children, and Mann–Whitney U tests compared changes

(*continued on next page*)

Table 1 (*continued*)

Study	Study design	Primary aim	Main analytical strategy
			between children classified with and without risk at baseline. Restricted sample excluding ROP ≥ grade 3
Molloy, 2016 [49]	Prospective longitudinal cohort	Long-term outcome with and without severe ROP	Continuous logMAR VA was compared between severe and no/mild ROP groups using t-tests and ANCOVA adjusted for postnatal corticosteroids, severe cranial ultrasound abnormality and neonatal surgery. Dichotomous VA impairment was analyzed using χ^2 and logistic regression
O'Shea, 2012 [50]	Prospective multicentre cohort study	IVH and developmental outcomes	Adjusted logistic models examined impaired clinical fixation and confrontation visual-field deficit in relation to IVH only, sonographic white-matter damage only and combined IVH/WML, controlling for GA, sex and public insurance.
Phadke, 2014 [51]	Prospective multicentre birth-cohort study	Antecedents of impaired visual fixation	Time-oriented logistic regression models assessed antenatal, early postnatal and concurrent correlates of impaired clinical fixation, entering variables sequentially by epoch and using a step-down retention criterion
Ricci, 2020 [52]	Prospective single-centre cohort	Visual and developmental outcomes according to ROP severity	ANOVA and χ^2 analyses according to ROP severity. Mixed-effects analysis evaluating nystagmus, visual-function score and neurodevelopment. Restricted sample excluding: major brain lesions and major congenital, genetic, metabolic or infectious conditions.
Šimić, 2010 [53]	Prospective longitudinal cohort study	Thyroid hormone deficiency, neonatal morbidity and visual development	GA-stratified group comparisons using MANOVA and post hoc tests; within preterm infants, demographic factors, neonatal morbidities and thyroid hormone levels were examined in bivariate analyses, and significant correlates were subsequently entered into outcome-specific multiple linear regression models for visual outcomes that differed from term-born controls. Restricted sample excluding: positive congenital hypothyroidism screening; congenital or chromosomal abnormality; child or maternal thyroid disease; maternal exposure to organic solvents, alcohol or other substances of abuse; maternal use of anticonvulsant or antiarrhythmic medication
Slidsborg, 2012 [54]	Cohort study	Cerebral damage and visual outcome	Kruskal–Wallis/χ^2 group comparisons and stepwise multiple logistic regression for visual impairment, evaluating global developmental deficit, moderate-to-severe foveal sequelae and ROP treatment.
Tachikawa, 2020 [55]	Retrospective single-centre cohort study	Low birth weight, ROP severity and visual outcome	ROP severity/treatment group comparisons (Kruskal–Wallis, Fisher exact and Steel–Dwass tests) and univariable–stepwise multivariable logistic regression for poor VA, evaluating BW, GA, ROP severity, refraction, anisometropia, strabismus and dragged disc. ROP severity and GA were not retained, and their adjusted estimates were not reported.
Tsamadou, 2026 [56]	Prospective longitudinal cohort study	Risk factors for visual outcome after extreme prematurity	Mann–Whitney U and linear mixed-effects models for longitudinal VA comparisons; Within the EPT cohort, Fisher–Freeman–Halton exact tests examined unadjusted associations of GA, IVH grade, ROP stage, ROP treatment, CP, cognitive disability
van Gils, 2025 [7]	Cohort study with repeated cross-sectional analyses	Developmental trajectories of visual orienting functions	Perinatal factors were compared across four longitudinal cartoon-RTF trajectory groups, while adjusted linear regression examined neonatal MRI scores as predictors of stimulus-specific RTF at 5 years. Restricted sample excluding ROP ≥ grade 3 and VA < 0.05
Wirth, 2018 [57]	Prospective observational study with cross-sectional assessment	Visual maturation and neonatal/MRI predictors	Perinatal, ophthalmological and MRI factors were first assessed using bivariate tests and simple linear regression; variables meeting a $p < 0.20$ entry criterion were considered in stepwise multivariable linear regression, with $p < 0.05$ required for retention. Restricted sample excluding facial malformation, craniosynostosis, genetic syndrome and ocular abnormalities

Abbreviations: ANCOVA: Analysis of Covariance; BPD: bronchopulmonary dysplasia; BW: birth weight; CB: cerebellar bleeding; CLD: chronic lung disease; CNS: central nervous system; CP: cerebral palsy; CRIB(-II): Clinical Risk Index for Babies (version II); CVI: cerebral visual impairment; GA: gestational age; GEE: Generalized Estimating Equations; HA: hospital admission; HIE: hypoxic ischemic encephalopathy; IH: intracranial haemorrhage; IQR: interquartile range; IVH: intraventricular haemorrhage; MRI: Magnetic Resonance Imaging; MV: mechanical ventilation; NEC: necrotizing enterocolitis; NR: not reported; PC: photocoagulation; PDA: patent ductus arteriosus; PI: placental insufficiency; PS: postnatal steroids; PVL: periventricular leukomalacia; RD: respiratory distress; ROP: retinopathy of prematurity; RTF: reaction time to fixation; SD: standard deviation; SF: supplementary file; SGA: small for gestational age; SNAP-II: Score for Neonatal Acute Physiology II; VLBW: very low birth weight; VO: visual outcome; VOF: visual orienting functions; VSA: volume slice area; CSI: cortex skull index; *Z*-score: standard score; ZI: zone I; ZII: zone II; Vit: lens-sparing vitrectomy.

neuroimaging abnormalities were considered [57]. GA and other systemic/perinatal factors showed no consistent association with early VA across these studies [53,57].

3.2.1.2. Age-related visual acuity in toddlerhood and childhood. Six studies evaluated VA in children aged 4 to 10 years [38,40,42,43,54,55]. Cooperative children were assessed with standardized optotypes (Lea Symbols, HOTV, Landolt C, and the Sander–Zanlonghi scale) whereas infants and non-cooperative children were evaluated using preferential looking techniques (Teller and Cardiff Acuity Cards). GA and ROP were the most consistently investigated variables although their independent contribution to VA was not always distinguished.

Lower GA was frequently associated with poorer VA in some univariate analyses [42,43,55], but was not consistently retained after adjustment [42,55]. Treatment-requiring or advanced ROP was associated with poorer VA in some analyses [42,43,54], particularly following treatment for Zone I ROP [55], whereas other studies did not confirm adjusted associations between ROP stage and VA; Chapron et al. [38] did not find an adjusted association between ROP and VA, but the analysis included the entire 24–34-week cohort and estimates restricted to children born before 32 weeks' GA were not provided [38]. Studies jointly stratifying children by GA and ROP status similarly suggested

Table 2
Distribution of prematurity-related risk factors across the included studies.

	Sample		GA wks	BW gr	IVH/IH	PVL	ROP	BPD
Author	Group	(N)	Mean ± SD	Mean ± SD	%	%	%	%
Beunders 2021 [9]		209	27,7[§]	1020[§]	IVH: 25 (Sg 1:11; Sg 2:15); CB: 2	4	Sg 1: 25; Sg 2: 5; Sg 3: 2	Mild: 21; Severe: 9
Bowl 2016 [37]	≤28 wks, no ROP	11	27,2 ± 0,6	1061 ± 244				
	>28 – <32 wks, no ROP	56	30,0 ± 0,7	1441 ± 257	NR	NR	NR	NR
	≤28 wks, sr-ROP	35	26,3 ± 0,9	931 ± 93	NR	NR	NR	NR
	>28 – <32 wks, sr-ROP	15	29,8 ± 1,5	1292 ± 128	NR	NR	NR	NR
Chapron 2022 [38]		1943[#]	24 to 31	NR	See SF	See SF	See SF	See SF
Downes 2018 [39]		16	25,8 ± 2,2	796 ± 27	25	25	69	93
Fieß 2018 [40]	29–32 wks no ROP	51	29,9 ± 0,7	1405 ± 297	12	0	0	NR
	≤28 wks noROP	31	26,4 ± 1,1	930 ± 210	13	0	0	NR
	≤32 wks ROP	24	25,6 ± 1,8	780 ± 233	25	4	Sg 1:50, Sg2:29, Sg3:21	NR
Fieß 2023 [41]	29–32 wks no ROP	92	30,6 ± 1,2	1559 ± 330	1	1	0	4
	≤28 wks no ROP	18	26,6 ± 1,5	918 ± 197	0	6	0	6
	≤32 wks ROP no treatment	48	27,8 ± 2,1	1057 ± 387	4	8	Sg:1 36; Sg 2:54; Sg 3: 7; Sg 4: 0; Sg 5: 2*	27
	≤32 wks ROP with treatment	15	26,7 ± 2,3	807 ± 244	7	7	Sg:1 0; Sg 2:20; Sg 3: 73; Sg 4: 6; Sg 5: 0*	47
Hellgren 2016 [42]	6-year group	406	22–26	348–1315	NR	NR	No: 28; Sg 1–2: 36,6; Sg 3–5: 35,4; treated:19,8	NR
Hellstrom 2022 [43]	Total sample	355	23 + 2[§]	565[§]	–	–	Any ROP: 92; treated: 47	NR
	Visually impaired	–	–	–	Any: 44; Sg 3–4: 20	14		NR
	Not visually impaired	–	–	–	Any: 52; Sg 3–4: 17	8,8		NR
Holm 2015 [44]		1023	<28	NR	Ventriculomegaly; echolucent lesions	Present	Present	Present
Hreinsdottir 2018 [5]		84	28,6	1205	IVH or PVL:10,7		Sg 1–2: 23; Sg 3–4: 6; Severe treated: 5	NR
Jacobson 2021 [45]	Severe, treated ROP	19	25	<1500	IVH g 3–4 and/or PVL: 3		19	CLD: 15
	No or mild ROP	20	26		IVH g 3–4 and/or PVL: 3		20	CLD: 30
Jain 2022 [46]		128	<25	NR	NR	NR	No:48; not treated:39; Treated:13*	NR
Johansson 2023 [47]	28–31 wks	53	29,9 ± 1	1365 ± 259	Sg 3–4: 21	13	0	NR
	<28 wks	25	25,7 ± 1,5	858 ± 217	Sg 3–4: 8	0	16	NR
Karimi 2024 [15]		47	29	1226	25,5 (Sg 1)	4,3	Any:19; > o = 3:2; treated: 0	21,3
Kooiker 2021 [48]		48	27,9 ± 1,5	1088	Sg 2–3:16	NR	NR	NR
	IVH	13	29 + 2	1063 + 71	Sg 1–2	NR	Any < Sg 2 and no plus: 38,5	NR
Molloy 2016 [49]		180	25,8 ± 1,1	885,4 ± 174	Sg 3 o 4: 8,9	4,4	Sg 1:8,3; Sg 2:20,6; Sg 3:12,8; Sg 4 or 5: 2,2	44,1
O'Shea 2012 [50]		939	<28	NR	19	WML:11	NR	NR
Phadke 2014 [51]		1057	23 to 26	≤1000	See SF	See SF	Sg 4–5:0,1; Sg 3:26	See SF
Ricci 2020 [52]		105	27,5	891	NR	NR	No 40; Sg 1 zone 2:6; Type 1:18; Type 2:35	NR
Simic 2010 [53]	23–26 wks	10	25 ± 6/7	739 ± 129	See SF	See SF	40	11.1
	27–29 wks	23	28 ± 1	1213 ± 267	See SF	See SF	40	4,5
	30–32 wks	19	31 ± 4/7	1502 ± 267	See SF	See SF	20	0
Slidsborg 2012 [54]		178	<28	900	20,2	3,9	36,5	NR
Tachikawa 2020 [55]		161	25[§]	738[§]	NR	NR	See SF	NR

(*continued on next page*)

Table 2 (*continued*)

	Sample		GA wks	BW gr	IVH/IH	PVL	ROP	BPD
Author	Group	(N)	Mean ± SD	Mean ± SD	%	%	%	%
Tsamadou 2026 [56]		332	22 to 26	NR	Sg 0:61; Sg 1–2:29; Sg 3–4: 10	NR	Sg 0:27; Sg 1–2:37 Sg 3–4:36; Treatment: 19	NR
van Gils 2025 [7]	Total	263	27,6 ± 1,7	1044 ± 283	See SF	NR	NR	NR
	Follow-up	49	27,6 ± 1,5	1051 ± 257	See SF	NR	NR	NR
Wirth 2018 [57]		54	29,5 ± 1,7	1194 ± 288	14,8	0	25	Mild:43; Moderate:46; Severe:11ç

Wks: weeks; CB: Cerebellar bleeding; CLD: chronic lung disease; SF: supplementary file; NR: not reported; Sg: stage; g: grade; ANCOVA: Analysis of Covariance; BPD: bronchopulmonary dysplasia; BW: birth weight; CLD: chronic lung disease; CNS: central nervous system; CP: cerebral palsy; GA: gestational age; HIE: hypoxic ischemic encephalopathy; IH: intracranial haemorrhage; IVH: intraventricular haemorrhage; #with complete binocular VA data (308 born at 24–26 wks and 1635 at 27–31 wks); *refers to eyes; § median value; ç percentage on BPD cases (28 cases, 52% of the sample).
Data for participants ≤32 wks were reported.

poorer VA among children with lower GA and ROP, but the individual contribution of each factor could not always be separated [40].

Evidence for other perinatal factors was less consistent. BPD and NEC were not associated with VA [43], while BW, refraction, and dragged disc remained independently associated with visual outcome [55]. Global developmental deficits, used as a proxy for cerebral damage or developmental abnormalities have been reported to be associated with poorer VA [54], suggesting that both retinal/perinatal and neurological factors may contribute to visual outcomes in this age range.

3.2.1.3. Age-related visual acuity in childhood up to adulthood. Nine studies evaluated long-term VA outcomes. ROP severity, GA, and BW were frequently investigated [5,37,41,45,47,49,56]. Poorer VA was associated with ROP severity or treatment-requiring ROP and extreme prematurity [37,46,47,49,56]. However, the independence of these associations varied across analytical approaches and the association with ROP was sensitive to how VA was analyzed [5,49]. Other studies reported univariable, descriptive, or association-based findings [45–47,56]. One study reported significantly poorer VA in children with stage 3 ROP than in those with stage 1–2 ROP [37]. Beyond ocular and perinatal factors, neuroimaging abnormalities, including increased posterior ventricular index and reduced peritrigonal white matter thickness, were associated with poorer VA, although this was reported without adjustment for neonatal confounders [15].

3.2.2. Contrast sensitivity

Five papers provide data on associations between CS outcomes and pre-, peri-, and postnatal risk factors [5,15,46,47,53]. CS was assessed using sweep visual evoked potentials within the first year of life, whereas behavioural methods, including the Lea Hyvärinen and Pelli-Robson charts, were used in older children.

Significant differences in CS were reported in preterms (24–32 weeks) versus term-born controls, while within the 23–32 week preterm cohort PDA remained independently associated with reduced CS in multivariable analysis [53]. In older children (>6 years of age), findings appeared heterogeneous. Reduced CS was observed in very and extremely preterms [5,47]; GA was not reported to be associated with atypical CS in univariable analysis and ROP was significantly associated with reduced CS in stepwise multivariable models, together with other clinical variables [5]. Further, ROP treatment status was associated with differences in visual measures [46]. MRI-derived abnormalities were also associated with reduced CS [15], although these analyses did not include comprehensive adjustment for neonatal confounders. At 12 years, reduced CS was reported in 25% of children born preterm [47].

3.2.3. Smooth pursuit

One study [52] examined ROP in relation to smooth pursuit, which was qualitatively assessed by observing the infant's ability to track a colored target. 12-month-old infants with moderate ROP (stage 3) showed largely preserved visual outcomes, suggesting that infants with spontaneously regressed stage 3 ROP often achieve visual outcomes, including normal smooth pursuit, like those without ROP. In contrast, all 13 infants with ROP stages 4 and 5 exhibited abnormal smooth pursuit.

3.2.4. Visual field

Three studies reported the visual field (VF) measurements at 12 months and 24 months of age [44,50,52]. VF was assessed using behavioural techniques adapted for infancy or kinetic perimetry. Neuroimaging abnormalities were associated with VF deficits in 2 studies. White matter lesions, with or without IVH, were independently associated with VF deficits after adjustment for GA, sex, and public insurance, whereas isolated IVH was not [50]. Similarly, ventriculomegaly remained independently associated with VF deficits after adjustment for postnatal variables, while GA was no longer significant after including postnatal factors into the time-oriented model [44]. In that analysis, several neonatal and systemic factors were associated with VF deficits, with ventriculomegaly, prethreshold ROP, prolonged respiratory morbidity, recurrent/persistent acidemia, and maternal aspirin use remaining significant in the final model [44]. One study descriptively reported severe ROP with abnormal VF [52], although ROP severity was not formally tested as an independent predictor.

3.2.5. Visual fixation

Three studies qualitatively evaluated visual fixation in children aged 12–24 months [50–52], assessed by observing the infant's ability to fixate on a colored target [52], to fixate the examiner's hand or objects [50], and by evaluating the inability to briefly fixate or sustain eye contact [51]. Findings focused on ROP, neuroimaging abnormalities (e.g., IVH), and prenatal aspirin exposure, but variables were not analyzed uniformly across studies.

Descriptively, visual fixation was generally preserved in children without ROP or with mild ROP (stages 1–2), whereas impairments were more frequent in severe ROP (stage ≥3) [52]. In multivariable modeling, impaired fixation (present in 7% of infants and showing marked co-occurrence with neurodevelopmental deficits) remained independently associated with prethreshold ROP, whereas the initial association with lower GA lost significance after adjusting for postnatal variables [51]. Finally, neuroimaging abnormalities were associated with fixation impairment, with both IVH and white matter lesions conferring increased adjusted risk, particularly when co-occurring [50].

3.3. Oculomotor metrics in the assessment of visual orienting and attention

A small group of studies employed eye-tracking to quantify reaction time to fixation, utilized across various stimuli (Cartoon, Motion, Form,

Table 3
Cross-domain synthesis of evidence section outcomes.

	Multivariable model-based analysis					Descriptive, unadjusted analysis				
Risk factor	VA	CS	VF	SP	Fixation	VA	CS	VF	SP	Fixation
GA	**[5]**, [42][1], [55][†]		[44][2]		[51][3]	**[5]**, [37][σ], [38][4], **[40]**[5], [41][6], **[42]**[1], **[43]**[7], [47][8], [53][°], [55–57]	[5,47][8], [53][°]	[44][9]		[51][9]
BW	[5][†], **[55]**				[51][†]	[5,37][σ], [41][6], [43,55]; [57]	[5]	[44][9]		[51][9]
IVH / IH	[57][†]		[50]		**[50]**	[5]; [41][6,10]; [43]; [56,57]	[5]			
PVL / WML			[44][†], **[50]**		**[50]**	[5,43]	[5]	[44][9]		[51][9]
Neuroimaging abnormalities	**[57]**[11]		**[44]**		[51][†]	**[15]**[12], [57]	**[15]**[12]	[44][9]		
ROP	[5][†], [38][13], **[43]**, **[49]**[#], **[54]**[14], [55][†]	**[5]**	**[44]**		**[51]**	**[5]**, **[37]**, **[40]**[5], **[41]**[6], **[42]**, **[43]**, [45][15], **[46]**, **[49]**, [52][16], [54–57]	**[5]**, **[46]**	[44][9]; [52][16]	[52][16]	[51][9], [52][16]
BPD / CLD			**[44]**		[51][†]	[41][6,10], [43,57]		[44][9]		
NEC			[44][†]		[51][†]	[41][6,10], [43,57]		[44][9]		
PDA		[53][~]				[57]	**[53]**[~]	[44][9]		[51][9]
Sepsis	[57][†]	[53][~]			[51][†]	[57]	**[53]**[~]			[51][9]
Metabolic / endocrine		[53][~]	**[44]**		[51][†]		**[53]**[~]	[44][9]		

Studies are represented when the corresponding neonatal risk factor was evaluated in relation to the specific visual outcome, through descriptive data/comparisons or association analyses. Stratification or sample restriction may address selected potential confounders but studies in which a variable was excluded or controlled a priori by study design or included solely as an adjustment covariate are not represented. Relevant sample restrictions are reported in Table 1. Studies assessing visual orienting were not included in this table because fixation latency or reaction time was used as an operational measure of visual orienting and processing speed, rather than as a direct measure of fixation ability. Within each cell, **bold type** indicates a statistically significant association factor-outcome at the conventional $p < 0.05$ level. Regular type indicates either a non-significant association or a descriptive result for which factor-specific statistical significance is not determined or reported or an association reported as statistically significant only in a broader cohort that included participants outside the review eligibility range (details in footnotes).

[†] Candidate predictor in a confounder-controlled stepwise/time-oriented model but not retained.

[σ] Significant differences were observed for the ≤28-week and <1000-g groups compared with term-born controls; significant differences between eligible preterm GA or BW strata were not reported.

[#] The adjusted association remained significant for continuous logMAR VA whereas the adjusted association with dichotomous VA impairment was not significant

[°] Data were reported across GA-defined groups, the significant data according to Gestational-Age Group included participants born at 33–35 weeks and term-born controls.

[~] Analyses conducted across the entire cohort.

[1] Significant in univariable analysis, but no longer significant after adjustment for treatment-requiring ROP.

[2] Significant when entered into the time-oriented model, but no longer significant after inclusion of postnatal factors.

[3] Significant in the antenatal model but attenuated after inclusion of postnatal and concurrent developmental variables.

[4] Data were reported separately for children born at 24–26 and 27–31 weeks, but the test included the 32–34-week group; no <32-week-specific test was reported.

[5] Significant differences across groups jointly defined by GA and ROP status; separate effects of GA and ROP and pairwise inferential results were not reported.

[6] Correlations with GA, BW, ROP, and ROP treatment were statistically significant in the entire cohort, which also included term-born participants and individuals born at 33–36 weeks. For participants born at <32 weeks, outcome data were reported descriptively by study group.

[7] Included as a covariate in the multivariable model.

[8] Data were descriptively reported.

[9] Descriptive data.

[10] Perinatal adverse events, composite.

[11] Neuroimaging abnormalities were defined as a composite MRI measure including supratentorial lesions, sequelae of germinal matrix or subependymal haemorrhage, diffuse or cystic periventricular leukomalacia, and infratentorial or posterior fossa lesions.

[12] Treatment-requiring ROP was absent from the analyzed preterm sample. Associations were estimated using generalized linear models without multivariable adjustment for other neonatal or demographic confounders.

[13] The adjusted analysis was conducted in the entire 24–34-week cohort, including participants born at 32–34 weeks.

[14] Findings differed between better- and worse-eye models.

[15] Outcome was reported descriptively.

[16] Descriptive data were reported. Significant overall association between ROP stage and global visual function was reported, but outcome-specific results were not separately provided.

and Contrast) to assess processing speed [7,9,48]; fixation dynamics, gaze fixation area and fixation duration on target stimuli [39,48] and visual salience responses [7]. In these studies, reaction time to fixation was not the ultimate objective, but rather the means through which visual-orienting functions were investigated. For this reason, these studies are reported separately and are not included in Table 3. Despite the methodological similarities, the impact of pre-, peri-, and postnatal risk factors on visual-orienting outcomes shows significant heterogeneity. The evidence suggests a general improvement of visual attention over time expressed in terms of reaction times to fixation; however, the longitudinal changes in visual orienting functions appear to show limited and still inconsistent associations with neonatal risk status across studies so far [7,9,39,48].

4. Discussion

This review synthesizes evidence on the association between established or potential risk factors and visual outcomes in very and extremely preterms in a life-long perspective. Heterogeneity across study designs, outcome definitions, and analytical approaches warrants caution in inferring causal relationships. Nevertheless, despite this heterogeneity, the available evidence consistently indicates that very and extremely preterm infants are at increased risk of visual dysfunction across multiple functional domains, although the strength of the associations varies according to the outcome assessed and the methodological characteristics of the included studies. The narrative results were organized by visual outcome, whereas the following discussion provides a complementary cross-domain synthesis by risk factor.

VA emerged as the most extensively studied visual function in relation to various risk factors. This predominance likely reflects the clinical feasibility of assessment methods, particularly those based on preferential looking, which allow standardized, albeit indirect, evaluation of visual function even in pre-verbal infants [58]. Furthermore, VA addresses the need for a universally recognized parameter to define visual impairment and blindness, according to International Classification of Diseases/ World Health Organization criteria. Consequently, VA represents the most widely used indicator to ensure comparability across studies, and its greater availability likely reflects its longstanding clinical role as a marker of both ophthalmological and neurological integrity. In the context of prematurity, where damage is often retrogeniculate, VA is frequently used as a proxy for the evaluation of both anterior and posterior visual pathways. By contrast, other visual aspects, such as contrast sensitivity, visual field, visual fixation, and smooth pursuit, have been less frequently and less systematically investigated for methodological issues.

4.1. Cross-domain synthesis by risk factor

A range of risk factors was identified across studies. Among the most frequently investigated risk factors, ROP, neuroimaging abnormalities, lower GA, and lower BW appear to contribute differentially across developmental stages and outcome domains.

ROP is among the most extensively studied risk factors for VA deficits [59], with effects varying by disease severity, age assessment, and interaction with other risk factors. Evidence on ROP derives from studies employing heterogeneous analytical approaches, including both comparative and regression-based analyses, with differences in confounder adjustment across studies.

In some analyses, the association between ROP and visual outcomes was reduced after adjustment for GA, neuroimaging abnormalities or other neonatal morbidities, suggesting the interdependence among these risk factors. Moreover, estimates should be also interpreted in light of eligibility criteria applied in the selected studies that excluded infants with severe neurological injury or advanced ROP, potentially limiting representation of the full spectrum of clinical severity. Within this review, associations between ROP and poorer VA were more often reported from toddlerhood onward and at later ages, particularly for severe or treatment-requiring ROP. The greater impact observed in severe or treated ROP is biologically plausible, as advanced retinal disease reflects more profound disruption of retinal vascular and neuroretinal development during a critical period of visual maturation [60]. Such alterations may compromise not only retinal integrity but also the subsequent maturation of the visual pathways, potentially explaining the persistence of visual deficits into later childhood and adulthood [61]. In a recent review Porteny et al. [59] concluded that visual deficits are more pronounced in severe ROP but may also be detectable, although to a lesser extent, in preterm individuals without ROP, suggesting that prematurity itself may contribute to visual vulnerability. Compared with VA, evidence for other visual domains remains considerably more limited. The available studies suggest that ROP severity may also influence contrast sensitivity, visual fixation and smooth pursuit, whereas evidence regarding visual fields is less consistent. However, these conclusions remain tentative because of the small number of available studies, heterogeneous outcome measures and differences in analytical approaches.

From a developmental perspective, lower GA reflects earlier interruption of intrauterine maturation together with prolonged exposure of the immature visual system to the extrauterine environment during a critical period of neurodevelopment [62]. Lower GA was generally accompanied by poorer VA [5,41,47], although this association was not consistently retained in multivariable analyses and it was partly explained by coexisting factors such as treated ROP and lower BW [43,55]. In one study, the GA was not identified as an associated factor, while neuroimaging abnormalities emerged as significant predictors [57]. A similar pattern is observed for CS, for which GA may play a non-primary role [53], whereas ROP was independently associated with reduced CS [5]. GA may act as a background vulnerability factor for visual field limitation [44,53], and it has been reported as an initial risk factor for visual fixation [51]. Conversely, its influence on visual orienting functions appears to be limited to group-level differences, with studies reporting heterogeneous developmental trajectories from infancy to 5 years of age [7,39].

While visual dysfunctions in preterm infants have often been primarily attributed to severe ROP, the leading cause of VI in children in high-income countries is increasingly recognized as cerebral in origin, the well-known CVI [63,64]. Across the included studies, associations between neuroimaging abnormalities and adverse basic visual or oculomotor outcomes were reported, although the type of lesion, imaging modality and degree of confounder adjustment varied substantially. These findings may support the concept that visual dysfunction in preterm infants may also reflect altered brain development rather than an isolated ophthalmological condition [28,65]. However, the available evidence does not support considering neonatal brain injury as a single entity, because different lesions involve distinct anatomical substrates of the developing visual system, such as PVL, IVH, ventriculomegaly and broader abnormalities of brain maturation.

Periventricular white matter injury, including cystic PVL and diffuse white matter abnormalities, is well described as a determinant of VI because the optic radiations course through the periventricular white matter during a period of high developmental vulnerability [1,66]. Injury to these pathways may contribute to abnormalities in basic visual and oculomotor functions via visual signal transmission and impair the maturation of dorsal and ventral visual networks [11,12,67]. Severe IVH frequently coexists with periventricular white matter injury or post-haemorrhagic ventricular dilatation, making it difficult to disentangle the contribution of haemorrhage itself from secondary white matter disruption [50]. Ventriculomegaly may in turn represent either a marker of diffuse white matter loss or post-haemorrhagic ventricular dilatation, both of which may further distort neighbouring optic radiations and long associative pathways involved in visual processing [44]. Recent MRI-based studies further investigated variability in visual outcomes according to quantitative abnormalities of brain maturation, including reduced optic chiasm thickness and alterations in white matter, cerebellar and deep grey matter development [7,15]. The association reported across the included studies between neuroimaging abnormalities and adverse visual outcomes may suggest that alterations in developing cerebral networks are associated with visual dysfunction following very and extremely preterm birth, with a broad spectrum of visual deficits, involving both higher-order and lower-order visual components [10,11,20,68]. A previous study [17] showed that the neonatal evaluation of basic visual and oculomotor functions may distinguish subjects with and without neurological impairment, as defined by brain lesion assessment. In this review, across the assessed parameters of VA, contrast sensitivity, visual field and visual fixation, brain abnormalities were frequently associated with adverse visual outcomes from infancy through adulthood. However, direct comparison across studies remains challenging because neuroimaging abnormalities were defined using different imaging modalities and classification systems, ranging from cranial ultrasound-defined lesions to conventional and quantitative MRI measures.

Across studies, lower BW tended to accompany poorer VA [37,41], but the available evidence does not allow its specific contribution to be clearly separated from GA, ROP, and other markers of prematurity severity. Overall, BW may therefore be interpreted as a marker of prematurity-related vulnerability of visual dysfunction. Further, compared with ROP and neuroimaging findings, evidence regarding systemic and prenatal factors remains considerably weaker because available studies investigated heterogeneous exposures, used different outcome measures and frequently lacked adjustment for important neonatal confounders. For example, systemic and respiratory

complications, including neonatal sepsis and bronchopulmonary dysplasia, have been reported to be associated with specific visual deficits, such as reduced CS and restricted visual field, but reported in only a few numbers of studies. The influence of metabolic and endocrine alterations was limited to a small number of studies, reporting contrasting results. Finally, specific prenatal exposures were implicated in isolated visual dysfunctions; for instance, maternal aspirin use was identified as a possible predictor of impaired visual fixation and visual field loss, although the underlying maternal conditions prompting its use were not accounted for as potential confounders. In contrast, prenatal alcohol exposure showed no significant association with early visual development. Ultimately, across all these studies, the evidence supporting an association between these secondary factors and deficits in basic visual or oculomotor functions remains preliminary and warrants further confirmatory research.

Overall, the interpretation of these findings should also consider the methodological quality of the included studies. Although most studies met most of the JBI quality criteria, important differences remained in study design, confounder adjustment, and analytical approaches. The findings should therefore be interpreted collectively, taking into account their consistency across studies, the consideration of potential confounding, and the methodological context in which they were obtained. These differences limited direct comparison and precluded quantitative synthesis. Because no formal grading of the certainty or strength of evidence was performed, patterns described should therefore be interpreted as findings of a narrative synthesis rather than as a hierarchy of established determinants.

4.2. A combined interpretation

The findings of this review suggest that visual dysfunctions in very and extremely preterm infants should be considered part of the broad spectrum of sequelae of prematurity. Rather than representing an additional, distinct outcome alongside the well-established motor, cognitive, and socio-communicative impairments observed in preterm populations, it can be intrinsically embedded in the nature of the underlying brain injury and may be interpreted within a "prematurity-with-complications" framework. In the context of visual dysfunctions, GA and BW may reflect the underlying biological immaturity rather than acting as isolated determinants. Instead, they appear to establish a baseline of marked biological vulnerability that predisposes infants to a range of complications, particularly ROP and brain abnormalities, which may represent proximal correlates of visual system dysfunction [54,69]. This interpretation emphasizes the relevance of a clinical stratification approach that accounts for retinal, neurological, and systemic complications as downstream consequences of prematurity-related vulnerability. Accordingly, visual, cognitive and motor deficits frequently converge into a characteristic spectrum of neurodevelopmental phenotype associated with preterm birth [70,71].

These findings further support the need for a "trajectory-based model" of visual surveillance in preterm populations. However, variability in outcome assessment across methods, ages and study designs limits the ability to distinguish transient developmental variation from persistent dysfunction and may obscure the characterization of visual developmental trajectories. As a result, the timing and persistence of visual deficits may vary across individuals, highlighting the need for longitudinal assessment of basic visual and oculomotor functions across development. The review also highlights that oculomotor functions, such as fixation, smooth pursuit, and saccades, remain underrepresented compared with VA. The issue is also related to methodological challenges in assessment, and emerging eye-tracking studies may provide a more objective approach for monitoring these important parameters. The evaluation of oculomotor function, however, may be particularly informative in early life, as subtle dysfunctions may be associated with alterations in cerebral development and in the complex oculomotor networks, which also involve subcortical centers that are particularly vulnerable, as demonstrated by neuroimaging studies in preterm infants [1]. Fixation instability, impaired smooth pursuit, or atypical orienting responses may therefore represent sensitive indicators of early basic visual and oculomotor dysfunctions, potentially reflecting cerebral vulnerability alongside VA, particularly in infants and toddlers [17,74]. Their relative absence in the literature therefore represents a relevant gap in both research and clinical practice and highlights the need for broader assessment frameworks that extend beyond acuity-based outcomes.

4.3. Limitations

This review presents limitations. First, data analysis revealed substantial heterogeneity across studies in population characteristics, outcome definitions, and assessment methods. In addition, in a limited number of studies, some analyses were conducted across broader GA ranges, limiting the attribution of those findings to the target population. Moreover, definitions of VI and neonatal brain injury were not fully standardized across the included studies since we adopted the definitions provided by the original authors, which may have contributed to between-study heterogeneity and should be considered when interpreting the results. Taken together, these methodological differences precluded meaningful quantitative synthesis. This is particularly evident in the evaluation of VA, which was assessed in various forms across studies. The range of visual functions known to be potentially affected by preterm birth is extremely broad and encompasses not only functions related to the integrity of the anterior visual pathways but also those associated with the retrogeniculate and associative visual pathways, which are characteristic of CVI at both lower- and higher-order levels of dysfunction. The decision to focus exclusively on lower order visual dysfunctions, such as basic visual (visual acuity, contrast sensitivity, visual field) and oculomotor (visual fixation, smooth pursuit and saccades) functions, was made to reduce the degree of functional variability considered and to open the analysis also to those studies involving infants not able to access the evaluation of higher order visual functions. Furthermore, although the search strategy covered the major international biomedical databases without language restrictions, grey literature was not included. Consequently, publication bias cannot be entirely excluded, and potentially relevant unpublished studies may have been missed. The restriction to studies published from 2010 onwards may have also resulted in the omission of relevant earlier evidence. Accordingly, the findings should be interpreted as a synthesis of contemporary rather than historical literature.

This review adopted an inclusive approach by considering all quantitative studies that contributed to understanding the relationship between prematurity-related risk factors and basic visual and oculomotor functions, regardless of study design or analytical strategy. As a result, the included studies varied substantially, ranging from descriptive reports and unadjusted group comparisons to multivariable regression models. Even among studies using regression analyses, covariate selection was not standardized across studies. Overall, these methodological limitations highlight the need for future studies using standardized visual assessments and comprehensive multivariable models to better delineate the independent contributions of neonatal risk factors to visual outcomes in preterm populations.

4.4. Implications for the clinical perspective and for policy makers

Findings from this review suggest that the complex clinical vulnerability associated with very and extremely preterm birth extends beyond the well-known neurological sequelae and can be associated with an increased risk of a broad range of basic visual and oculomotor dysfunctions. These findings support the importance of identifying visual dysfunctions as early as possible and considering the neonatal and neurological context in which it occurs. Early identification and interpretation in the neonatal and neurological context may be particularly

relevant for infants presenting neuroimaging abnormalities and severe ROP. For this reason, visual assessment should be considered a key component of structured, multidisciplinary, multidimensional follow-up of very and extremely preterm infants. Assessment should be extended beyond ophthalmological examination alone and include, where feasible, a comprehensive evaluation of visual acuity, contrast sensitivity, visual field, and oculomotor functions [17,31–33,72,73]. Although the available evidence does not yet support identifying specific combinations of risk factors with sufficient predictive accuracy, the coexistence of multiple neonatal morbidities may justify comprehensive longitudinal visual assessment and increase clinical awareness of possible cerebral involvement of the visual system. This would strengthen epidemiological surveillance and contribute to a more accurate estimate of the long-term burden and clinical heterogeneity of prematurity-related visual dysfunction.

Current policies should move towards a model of functional visual surveillance that considers both anterior/peripheral and cerebral components of visual dysfunction. Basic visual and oculomotor functions should be regarded in the context of prematurity, as they may constitute clinically relevant indicators of both neural and visual system dysfunction [75]. In this context, initiatives such as VIPPSTAR, a European Commission Horizon Europe–funded project (https://vippstar.eu/), to which the present review was developed to support the clinical data collection protocol may offer a useful model for building structured surveillance frameworks and harmonized approaches to visual and neurodevelopmental monitoring.

CRediT authorship contribution statement

Serena Micheletti: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Francesca Fulceri:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Data curation. **Erika Loi:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Martina Micai:** Writing – review & editing, Visualization, Methodology, Investigation, Data curation. **Stefania Agostini:** Writing – review & editing, Visualization, Methodology, Investigation, Data curation. **Letizia Gila:** Writing – review & editing, Visualization, Methodology, Investigation, Data curation. **Giulia Paderni:** Writing – review & editing, Visualization, Methodology, Investigation, Data curation. **Angela Caruso:** Writing – review & editing, Visualization, Methodology, Investigation, Data curation. **Jessica Galli:** Writing – review & editing. **Mara Sabbioni:** Writing – review & editing, Visualization, Methodology, Investigation, Data curation. **Elisa Fazzi:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Maria Luisa Scattoni:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Ethics declaration

The author(s) declare(s) that the study does not involve humans nor animal subjects.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used AI-assisted technologies to perform internal consistency check, and to perform basic checks of grammar, spelling, and punctuation. AI-assisted technologies were also used to improve the presentation of Fig. 2. After using AI-assisted technologies, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Declaration of competing interest

The authors declare no conflicts of interest.

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Appendix A. Supplementary data

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References

[1] T.E. Inder, J.J. Volpe, P.J. Anderson, Defining the neurologic consequences of preterm birth, N. Engl. J. Med. 389 (5) (2023 Aug 3) 441–453, https://doi.org/10.1056/NEJMra2303347.

[2] A. Pascal, P. Govaert, A. Oostra, G. Naulaers, E. Ortibus, C. Van den Broeck, Neurodevelopmental outcome in very preterm and very-low-birthweight infants born over the past decade: a meta-analytic review, Dev. Med. Child Neurol. 60 (4) (2018 Apr) 342–355, https://doi.org/10.1111/dmcn.13675.

[3] S.P. Sarda, G. Sarri, C. Siffel, Global prevalence of long-term neurodevelopmental impairment following extremely preterm birth: a systematic literature review, J. Int. Med. Res. 49 (7) (2021 Jul) 3000605211028026, https://doi.org/10.1177/03000605211028026.

[4] E. Fazzi, J. Galli, S. Micheletti, Visual impairment: a common sequela of preterm birth, NeoReviews 13 (9) (2012) e542–e550, https://doi.org/10.1542/neo.13-9-e542.

[5] J. Hreinsdottir, Y. Fredriksson Kaul, L. Hellström-Westas, K. Rosander, C. von Hofsten, G. Holmström, Impaired cognitive ability at 2.5 years predicts later visual and ophthalmological problems in children born very preterm, Acta Paediatr. 107 (5) (2018 May) 822–830, https://doi.org/10.1111/apa.14209.

[6] M.P. Leung, B. Thompson, J. Black, S. Dai, J.M. Alsweiler, The effects of preterm birth on visual development, Clin. Exp. Optom. 101 (1) (2018 Jan) 4–12, https://doi.org/10.1111/cxo.12578.

[7] M.M. van Gils, A. Bijlsma, M.J. Vermeulen, I.K.M. Reiss, K.F.M. Joosten, M.J. G. Kooiker, et al., Developmental trajectories of visual orienting functions in children born very or extremely preterm, Early Hum. Dev. 201 (2025 Feb) 106191, https://doi.org/10.1016/j.earlhumdev.2025.106191.

[8] M.Y. Chang, L.B. Merabet, CVI Working Group, Cerebral/cortical visual impairment (CVI) working definition: a report from the National Institutes of Health (NIH) CVI workshop, Ophthalmology 131 (12) (2024 Dec) 1359–1365, https://doi.org/10.1016/j.ophtha.2024.07.013.

[9] V.A. Beunders, M.J. Vermeulen, J.A. Roelants, N. Rietema, R.M. Swarte, I.K. Reiss, et al., Early visuospatial attention and processing and related neurodevelopmental outcome at 2 years in children born very preterm, Pediatr. Res. 90 (3) (2021 Sep) 608–616, https://doi.org/10.1038/s41390-020-01314-2.

[10] F. Tinelli, S. Bulgheroni, S. Mazzotti, C. Vago, M. Groppo, R.T. Scaramuzzo, et al., Ventral stream sensitivity in "healthy" preterm-born adolescents: psychophysical and neuropsychological evaluation, Early Hum. Dev. 90 (1) (2014 Jan) 45–49, https://doi.org/10.1016/j.earlhumdev.2013.11.008.

[11] E. Fazzi, S. Bova, A. Giovenzana, S. Signorini, C. Uggetti, P. Bianchi, Cognitive visual dysfunctions in preterm children with periventricular leukomalacia, Dev. Med. Child Neurol. 51 (12) (2009 Dec) 974–981, https://doi.org/10.1111/j.1469-8749.2009.03272.x.

[12] E. Pagliano, E. Fedrizzi, A. Erbetta, S. Bulgheroni, A. Solari, R. Bono, et al., Cognitive profiles and visuoperceptual abilities in preterm and term spastic diplegic children with periventricular leukomalacia, J. Child Neurol. 22 (3) (2007 Mar) 282–288, https://doi.org/10.1177/0883073807300529.

[13] G. Lanzi, E. Fazzi, C. Uggetti, A. Cavallini, S. Danova, M. Egitto, et al., Cerebral visual impairment in periventricular leukomalacia, Neuropediatrics 29 (3) (1998 Jun) 145–150, https://doi.org/10.1055/s-2007-973551.
[14] S. Johnson, N. Marlow, Early and long-term outcome of infants born extremely preterm, Arch. Dis. Child. 102 (1) (2017 Jan) 97–102, https://doi.org/10.1136/archdischild-2015-309581.
[15] A. Karimi, S. Setänen, E. Larsson, G. Holmström, Y. Fredriksson Kaul, O. Kochukhova, et al., Brain MRI findings and their association with visual impairment in young adolescents born very preterm, Neuroradiology 66 (1) (2024 Jan) 145–154, https://doi.org/10.1007/s00234-023-03235-5.
[16] S. Bano, V. Chaudhary, U.C. Garga, Neonatal hypoxic-ischemic encephalopathy: a radiological review, J. Pediatr. Neurosci. 12 (1) (2017) 1–6, https://doi.org/10.4103/1817-1745.205646.
[17] A. Rossi, M. Gnesi, C. Montomoli, G. Chirico, L. Malerba, L.B. Merabet, et al., Neonatal Assessment Visual European Grid (NAVEG): unveiling neurological risk, Infant Behav. Dev. 49 (2017 Nov) 21–30, https://doi.org/10.1016/j.infbeh.2017.06.002.
[18] O. Braddick, J. Atkinson, Development of human visual function, Vision Res. 51 (13) (2011 Jul 1) 1588–1609, https://doi.org/10.1016/j.visres.2011.02.018.
[19] S.M. Bova, A. Giovenzana, S. Signorini, R. La Piana, C. Uggetti, P.E. Bianchi, et al., Recovery of visual functions after early acquired occipital damage, Dev. Med. Child Neurol. 50 (4) (2008 Apr) 311–315, https://doi.org/10.1111/j.1469-8749.2008.02044.x.
[20] E. Fazzi, S.M. Bova, C. Uggetti, S.G. Signorini, P.E. Bianchi, I. Maraucci, et al., Visual–perceptual impairment in children with periventricular leukomalacia, Brain Dev. 26 (8) (2004 Dec) 506–512, https://doi.org/10.1016/j.braindev.2004.02.004.
[21] C.A. Matsuba, Assessment of autism in children with visual impairment, Dev. Med. Child Neurol. 56 (1) (2014 Jan) 8–9, https://doi.org/10.1111/dmcn.12320.
[22] C. Uggetti, M.G. Egitto, E. Fazzi, P.E. Bianchi, R. Bergamaschi, F. Zappoli, et al., Cerebral visual impairment in periventricular leukomalacia: MR correlation, AJNR Am. J. Neuroradiol. 17 (5) (1996 May) 979–985.
[23] N. Berardi, T. Pizzorusso, G.M. Ratto, L. Maffei, Molecular basis of plasticity in the visual cortex, Trends Neurosci. 26 (7) (2003 Jul) 369–378, https://doi.org/10.1016/S0166-2236(03)00168-1.
[24] A. Bartoletti, P. Medini, N. Berardi, L. Maffei, Environmental enrichment prevents effects of dark-rearing in the rat visual cortex, Nat. Neurosci. 7 (3) (2004 Mar) 215–216, https://doi.org/10.1038/nn1188.
[25] A. Sale, E. Putignano, L. Cancedda, S. Landi, F. Cirulli, N. Berardi, et al., Enriched environment and acceleration of visual system development, Neuropharmacology 47 (5) (2004 Oct) 649–660, https://doi.org/10.1016/j.neuropharm.2004.07.009.
[26] G. Ayoub, A window to the brain—the enduring impact of vision research, Brain Sci. 15 (5) (2025) 453, https://doi.org/10.3390/brainsci15050453.
[27] A. London, I. Benhar, M. Schwartz, The retina as a window to the brain—from eye research to CNS disorders, Nat. Rev. Neurol. 9 (1) (2013 Jan) 44–53, https://doi.org/10.1038/nrneurol.2012.227.
[28] V. Chau, M.J. Taylor, S.P. Miller, Visual function in preterm infants: visualizing the brain to improve prognosis, Doc. Ophthalmol. 127 (1) (2013 Aug) 41–55, https://doi.org/10.1007/s10633-013-9397-7.
[29] A. Madan, J.E. Jan, W.V. Good, Visual development in preterm infants, Dev. Med. Child Neurol. 47 (4) (2005 Apr) 276–280, https://doi.org/10.1017/S0012162205000517.
[30] S.P. Donahue, C.N. Baker, Committee on Practice and Ambulatory Medicine, Section on Ophthalmology, American Academy of Pediatrics, et al., Procedures for the evaluation of the visual system by pediatricians, Pediatrics 137 (1) (2016 Jan) e20153597, https://doi.org/10.1542/peds.2015-3597.
[31] H.C. Leonard, M. Bernardi, E.L. Hill, L.A. Henry, Executive functioning, motor difficulties, and developmental coordination disorder, Dev. Neuropsychol. 40 (4) (2015) 201–215, https://doi.org/10.1080/87565641.2014.997933.
[32] H. Grönqvist, K.S. Brodd, K. Rosander, Development of smooth pursuit eye movements in very prematurely born infants: 2. The low-risk subgroup, Acta Paediatr. 100 (7) (2011 Jul) e5–11, https://doi.org/10.1111/j.1651-2227.2011.02247.x.
[33] D. Ricci, L. Cesarini, M. Groppo, A. De Carli, F. Gallini, F. Serrao, et al., Early assessment of visual function in full term newborns, Early Hum. Dev. 84 (2) (2008 Feb) 107–113, https://doi.org/10.1016/j.earlhumdev.2007.03.010.
[34] M.J. Page, J.E. McKenzie, P.M. Bossuyt, I. Boutron, T.C. Hoffmann, C.D. Mulrow, et al., The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, BMJ 372 (2021 Mar 29) n71, https://doi.org/10.1136/bmj.n71.
[35] M. Ouzzani, H. Hammady, Z. Fedorowicz, A. Elmagarmid, Rayyan—a web and mobile app for systematic reviews, Syst. Rev. 5 (1) (2016 Dec) 210, https://doi.org/10.1186/s13643-016-0384-4.
[36] M. Hilton, JBI critical appraisal checklist for systematic reviews and research syntheses, J. Can. Health Libr. Assoc. 45 (3) (2024) 141–143, https://doi.org/10.29173/jchla29725.
[37] W. Bowl, B. Lorenz, K. Stieger, S. Schweinfurth, K. Holve, C. Friedburg, M. Andrassi-Darida, Correlation of central visual function and ROP risk factors in prematures with and without acute ROP at the age of 6–13 years: the Giessen long-term ROP study, Br. J. Ophthalmol. 100 (2016) 1238–1244, https://doi.org/10.1136/bjophthalmol-2015-307855.
[38] T. Chapron, V. Pierrat, G. Caputo, M. Letouzey, E. Kermorvant-Duchemin, Y. Abdelmassih, et al., Ophthalmological impairments at five and a half years after preterm birth: EPIPAGE-2 cohort study, J. Clin. Med. 11 (8) (2022 Apr 11) 2139, https://doi.org/10.3390/jcm11082139.
[39] M. Downes, D. Kelly, K. Day, N. Marlow, M. de Haan, Visual attention control differences in 12-month-old preterm infants, Infant Behav. Dev. 50 (2018 Feb) 180–188, https://doi.org/10.1016/j.infbeh.2018.01.002.
[40] A. Fieß, R. Kölb-Keerl, A.K. Schuster, M. Knuf, B. Kirchhof, P.S. Muether, et al., Correlation of morphological parameters and visual acuity with neurological development in former preterm children aged 4–10 years, Acta Ophthalmol. 96 (8) (2018 Dec) e1010–e1017, https://doi.org/10.1111/aos.13755.
[41] A. Fieß, K. Greven, E. Mildenberger, M.S. Urschitz, H.M. Elflein, F. Zepp, et al., Visual acuity, amblyopia, and vision-related quality of life in preterm adults with and without ROP: results from the Gutenberg prematurity eye study, Eye (Lond.) 37 (9) (2023 Jun) 1794–1801, https://doi.org/10.1038/s41433-022-02207-y.
[42] K.M. Hellgren, K. Tornqvist, P.G. Jakobsson, P. Lundgren, B. Carlsson, K. Källén, et al., Ophthalmologic outcome of extremely preterm infants at 6.5 years of age: Extremely Preterm Infants in Sweden Study (EXPRESS), JAMA Ophthalmol. 134 (5) (2016 May 1) 555–562, https://doi.org/10.1001/jamaophthalmol.2016.0391.
[43] A. Hellström, L. Jacobson, A. Al-Hawasi, L. Hellström-Westas, A. Rakow, M. Johnson, et al., Retrospective evaluation of ophthalmological and neurological outcomes for infants born before 24 weeks gestational age in a Swedish cohort, BMJ Open 12 (8) (2022 Aug 3) e055567, https://doi.org/10.1136/bmjopen-2021-055567.
[44] M. Holm, M.E. Msall, J. Skranes, O. Dammann, E. Allred, A. Leviton, Antecedents and correlates of visual field deficits in children born extremely preterm, Eur. J. Paediatr. Neurol. 19 (1) (2015 Jan) 56–63, https://doi.org/10.1016/j.ejpn.2014.10.002.
[45] L. Jacobson, B. Vollmer, A. Kistner, B. Böhm, Severity of retinopathy of prematurity was associated with a higher risk of cerebral dysfunction in young adults born extremely preterm, Acta Paediatr. 110 (2) (2021 Feb) 528–536, https://doi.org/10.1111/apa.15461.
[46] S. Jain, P.Y. Sim, J. Beckmann, Y. Ni, N. Uddin, B. Unwin, et al., Functional ophthalmic factors associated with extreme prematurity in young adults, JAMA Netw. Open 5 (1) (2022 Jan 4) e2145702, https://doi.org/10.1001/jamanetworkopen.2021.45702.
[47] M. Johansson, Y.F. Kaul, C. Montgomery, E. Larsson, L. Hellström-Westas, O. Kochukhova, Different aspects of visual perception are important for 12-year social functioning depending on gestational age, Acta Paediatr. 112 (7) (2023 Jul) 1537–1547, https://doi.org/10.1111/apa.16794.
[48] M.J.G. Kooiker, M.M. van Gils, Y.J. van der Zee, R.M.C. Swarte, L.S. Smit, S. Loudon, et al., Early screening of visual processing dysfunctions in children born very or extremely preterm, Front. Hum. Neurosci. 15 (2021) 729080, https://doi.org/10.3389/fnhum.2021.729080.
[49] C.S. Molloy, P.J. Anderson, V.A. Anderson, L.W. Doyle, The long-term outcome of extremely preterm (<28 weeks' gestational age) infants with and without severe retinopathy of prematurity, J. Neuropsychol. 10 (2) (2016 Sep) 276–294, https://doi.org/10.1111/jnp.12069.
[50] T.M. O'Shea, E.N. Allred, K.C.K. Kuban, D. Hirtz, B. Specter, S. Durfee, et al., Intraventricular hemorrhage and developmental outcomes at 24 months of age in extremely preterm infants, J. Child Neurol. 27 (1) (2012 Jan) 22–29, https://doi.org/10.1177/0883073811424462.
[51] A. Phadke, M.E. Msall, P. Droste, E.N. Allred, T.M. O'Shea, K. Kuban, et al., Impaired visual fixation at the age of 2 years in children born before the twenty-eighth week of gestation. Antecedents and correlates in the multicenter ELGAN study, Pediatr. Neurol. 51 (1) (2014 Jul) 36–42, https://doi.org/10.1016/j.pediatrneurol.2014.03.007.
[52] D. Ricci, S. Lucibello, L. Orazi, F. Gallini, S. Staccioli, F. Serrao, et al., Early visual and neuro-development in preterm infants with and without retinopathy, Early Hum. Dev. 148 (2020) 105134, https://doi.org/10.1016/j.earlhumdev.2020.105134.
[53] N. Simic, C. Westall, E.V. Astzalos, J. Rovet, Visual abilities at 6 months in preterm infants: impact of thyroid hormone deficiency and neonatal medical morbidity, Thyroid 20 (3) (2010 Mar) 309–315, https://doi.org/10.1089/thy.2009.0128.
[54] C. Slidsborg, R. Bangsgaard, H.C. Fledelius, H. Jensen, G. Greisen, M. la Cour, Cerebral damage may be the primary risk factor for visual impairment in preschool children born extremely premature, Arch. Ophthalmol. 130 (11) (2012 Nov) 1410–1417, https://doi.org/10.1001/archophthalmol.2012.1393.
[55] T. Tachikawa, R. Ueno, T. Mita, D. Yuzurihara, O. Katsumi, T. Noda, et al., Refractive state and visual acuity of children with extremely low birth weight at 3 years old in Japan, Jpn. J. Ophthalmol. 64 (5) (2020 Sep) 539–548, https://doi.org/10.1007/s10384-020-00754-z.
[56] D. Tsamadou, K. Källén, A. Al-Hawasi, A. Hellström, G. Holmström, F. Pedrosa-Domellöf, et al., Visual acuity outcomes up to 12 years and risk factors for visual impairment in a national cohort of extremely preterm born children - the Extremely Preterm Infants in Sweden Study (EXPRESS), Acta Ophthalmol. 104 (1) (2026 Feb) 65–74, https://doi.org/10.1111/aos.17525.
[57] M. Wirth, A. Naud, E. Schmitt, I. Clerc-Urmès, J.M. Hascoët, Visual maturation at term equivalent age in very premature infants according to factors influencing its development, Front. Physiol. 9 (2018) 1649, https://doi.org/10.3389/fphys.2018.01649.
[58] A. Cavallini, E. Fazzi, V. Viviani, M.G. Astori, S. Zaverio, P.E. Bianchi, et al., Visual acuity in the first two years of life in healthy term newborns: an experience with the teller acuity cards, Funct. Neurol. 17 (2) (2002) 87–92.
[59] J.R. Porteny, P. Scudder, B.A. Darlow, D.K. Vanderveen, O. Dammann, A scoping review of adverse visual outcomes among preterm infants without, versus those with, retinopathy of prematurity, Surv. Ophthalmol. 71 (3) (2026) 992–996, https://doi.org/10.1016/j.survophthal.2025.11.009.

[60] A. Hellström, L.E.H. Smith, O. Dammann, Retinopathy of prematurity, Lancet 382 (9902) (2013 Oct 26) 1445–1457, https://doi.org/10.1016/S0140-6736(13)60178-6.
[61] T. Zhou, P.O. Kassis, P. Hamel, C. Qian, S. Chemtob, A.M. Nuyt, T. Luu, 21 long-term ophthalmologic outcome of young adults born extremely preterm, Paediatr. Child Health 26 (Suppl. 1) (2021 Oct 29) e13–e14, https://doi.org/10.1093/pch/pxab061.015.
[62] S.N. Graven, Early neurosensory visual development of the fetus and newborn, Clin. Perinatol. 31 (2) (2004 Jun) 199–216, v, https://doi.org/10.1016/j.clp.2004.04.010.
[63] M.Y. Chang, M.S. Borchert, Advances in the evaluation and management of cortical/cerebral visual impairment in children, Surv. Ophthalmol. 65 (6) (2020) 708–724, https://doi.org/10.1016/j.survophthal.2020.03.001.
[64] A.L. Solebo, J.S. Rahi, Vision screening in children: why and how? Ophthalmic Epidemiol. 21 (4) (2014 Aug) 207–209, https://doi.org/10.3109/09286586.2014.926557.
[65] N. Padilla, G. Alexandrou, M. Blennow, H. Lagercrantz, U. Ådén, Brain growth gains and losses in extremely preterm infants at term, Cereb. Cortex 25 (7) (2015 Jul) 1897–1905, https://doi.org/10.1093/cercor/bht431.
[66] J.J. Volpe, Dysmaturation of premature brain: importance, cellular mechanisms, and potential interventions, Pediatr. Neurol. 95 (2019 Jun) 42–66, https://doi.org/10.1016/j.pediatrneurol.2019.02.016.
[67] G. Dutton, M. Bax (Eds.), Visual Impairment in Children Due to Damage to the Brain, Mac Keith Press, London, 2010, https://doi.org/10.1002/9781444328295.
[68] P.S. McQuillen, D.M. Ferriero, Perinatal subplate neuron injury: implications for cortical development and plasticity, Brain Pathol. 15 (3) (2005 Jul) 250–260, https://doi.org/10.1111/j.1750-3639.2005.tb00528.x.
[69] B.M. Honan, S.A. McDonald, C.P. Travers, V.V. Shukla, N. Ambalavanan, C. M. Cotten, et al., Cerebral injury and retinopathy as risk factors for blindness in extremely preterm infants, Arch. Dis. Child. Fetal Neonatal Ed. 110 (3) (2025 Apr 17) 253–260, https://doi.org/10.1136/archdischild-2024-327707.
[70] V. Pierrat, L. Marchand-Martin, S. Marret, C. Arnaud, V. Benhammou, G. Cambonie, et al., Neurodevelopmental outcomes at age 5 among children born preterm: EPIPAGE-2 cohort study, BMJ 373 (2021 Apr 28) n741, https://doi.org/10.1136/bmj.n741.
[71] I. Adams-Chapman, R.J. Heyne, S.B. DeMauro, A.F. Duncan, S.R. Hintz, A. Pappas, et al., Neurodevelopmental impairment among extremely preterm infants in the neonatal research network, Pediatrics 141 (5) (2018 May) e20173091, https://doi.org/10.1542/peds.2017-3091.
[72] J. Atkinson, O. Braddick, S. Anker, M. Nardini, D. Birtles, M.A. Rutherford, et al., Cortical vision, MRI and developmental outcome in preterm infants, Arch. Dis. Child. Fetal Neonatal Ed. 93 (4) (2008 Jul) F292–F297, https://doi.org/10.1136/adc.2007.116988.
[73] L.M. Dubowitz, V. Dubowitz, A. Morante, M. Verghote, Visual function in the preterm and fullterm newborn infant, Dev. Med. Child Neurol. 22 (4) (1980 Aug) 465–475, https://doi.org/10.1111/j.1469-8749.1980.tb04351.x.
[74] E. Fazzi, L. Malerba, J. Galli, S. Aversa, L.B. Merabet, F. Risso, et al., Neonatal Assessment Visual European Grid accuracy in detecting infants born preterm at risk of neurological impairment, Dev. Med. Child Neurol. (2026), https://doi.org/10.1111/dmcn.70452.
[75] J. Cheng, S.S. Paracha, S. Agrawal, Z. Wu, C. Sung, Recent advances in visual dysfunction and ocular biomarkers in neurological disorders, Eye Brain. 17 (2025) 49–67, https://doi.org/10.2147/EB.S516393.