




ORIGINAL ARTICLE

Amblyopia in 2026: definitions, diagnosis, treatment, and emerging therapies

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Amblyopia is a leading, yet largely preventable, cause of visual impairment and is now recognized as a binocular neurodevelopmental disorder characterized by interocular suppression and widespread functional deficits. This narrative review synthesizes contemporary evidence on the epidemiology, pathophysiology, diagnosis, and management of amblyopia, with a focus on clinically applicable guidance. Conventional treatments—including optimal refractive correction, occlusion therapy, and pharmacologic penalization with atropine—remain highly effective when appropriately prescribed, titrated, and monitored for adherence, even among selected older children. Emerging binocular approaches, such as dichoptic digital therapies, perceptual learning, and short-term monocular deprivation, aim to restore binocular balance. Although these strategies may yield improvements in stereopsis and contrast sensitivity, their effects are generally modest and task-specific. Overall, current evidence supports the integration of traditional and novel approaches into etiology-specific, measurement-driven care pathways. Future research should prioritize functional outcomes, long-term durability, and real-world effectiveness.

KEYWORDS: Amblyopia/diagnosis; Amblyopia/physiopathology; Amblyopia/epidemiology; Binocular vision; Vision disorders; Review

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INTRODUCTION

Amblyopia affects approximately 2%–5% of the population and remains the leading cause of monocular visual impairment in children and young adults^(1,4). Traditionally, it has been defined as reduced best-corrected visual acuity in one—or less commonly, both—eyes in the absence of an identifiable ocular or neurological pathology sufficient to explain the deficit.

Contemporary evidence reconceptualizes amblyopia as a binocular neurodevelopmental disorder characterized by interocular suppression and distributed functional deficits that persist even under binocular viewing conditions^(2,4).

In addition to reduced visual acuity, amblyopia is associated with a range of visual and functional impairments, including reduced contrast sensitivity, increased crowding, fixation instability, impaired binocular summation, and loss of stereopsis. These abnormalities extend beyond vision, contributing to deficits in balance, motor coordination, and overall quality of life^(2–11). Consequently, improvements in monocular acuity alone often fail to translate into fully restored real-world visual function.

These observations support a paradigm shift from exclusively monocular treatment strategies toward approaches that also address binocular dysfunction. Accordingly, this review integrates current evidence on amblyopia pathophysiology, diagnosis, and management, combining established and emerging therapies into practical, etiology-specific clinical frameworks^(2–4,12–18). The emphasis is placed on functional outcomes and clinical applicability rather than exhaustive systematic coverage.

Pathophysiology and Neuroplasticity

Seminal animal studies by Hubel et al. demonstrated that the visual cortex is highly sensitive to early binocular imbalance. Monocular deprivation alters ocular dominance columns and disrupts normal binocular connectivity^(19–21), establishing the concept of a critical period during which abnormal visual input can permanently reshape cortical organization.

Human psychophysical and neuroimaging studies further indicate that amblyopia involves multilevel dysfunction spanning the lateral geniculate nucleus, primary visual cortex, and extrastriate regions responsible for form, motion, and attention^(4,10,22–25). Functional deficits vary by etiology. Deprivation amblyopia is typically severe and widespread; anisometropic amblyopia is characterized by marked contrast sensitivity loss with relatively preserved peripheral fusion; and strabismic amblyopia exhibits pronounced foveal

suppression and impaired stereopsis^(5,23,26). These distinctions support etiology-specific diagnostic and therapeutic approaches.

Emerging evidence conceptualizes amblyopia as a disorder of excessive intracortical inhibition and interocular suppression, rather than irreversible loss of amblyopic-eye input^(10,25,27–29). Experimental paradigms that reduce cortical inhibition or transiently occlude the fellow eye can partially restore ocular dominance toward the amblyopic eye—even beyond the traditional critical period—indicating persistent residual plasticity^(27–29). Structural imaging using optical coherence tomography (OCT) and OCT angiography (OCTA) has identified macular and choroidal alterations in selected cohorts, suggesting a potential contribution of retinal and neurovascular factors in specific subtypes^(29,30). However, these findings are inconsistent and currently serve as adjuncts rather than alternatives to functional assessment.

Functional Impact of Amblyopia

The impact of amblyopia extends beyond reduced monocular acuity. Affected individuals frequently demonstrate impaired stereoacuity, deficits in fine motor coordination, altered postural control, and reduced performance in tasks requiring depth perception, including sports, driving, and certain occupations^(2–4,6–7,11). In children, amblyopia and strabismus have been associated with measurable abnormalities in balance and gait, with potential consequences for physical activity and injury risk⁽⁷⁾.

Quality-of-life studies consistently show that amblyopia and its treatment—particularly occlusion therapy—can negatively affect self-perception, social functioning, and emotional well-being in both patients and caregivers^(4,6,31). In addition, higher-order perceptual and attentional deficits may persist even after normalization of visual acuity, underscoring the limitations of relying solely on high-contrast acuity measures to define treatment success^(4,24,32). These findings highlight the need for management strategies that emphasize binocular integration, stereopsis, and patient-reported outcomes alongside monocular acuity^(2–4,33,34).

Diagnosis and Functional Assessment

Diagnosis continues to rely primarily on age-appropriate visual acuity testing using standardized recognition optotypes once children can reliably identify or match symbols. Protocols developed by the Pediatric Eye Disease Investigator Group and similar frameworks provide reproducible measurements across clinical and research settings⁽³⁵⁾. In preverbal children, interocular differences are estimated using fixation preference, occlusion-resistance

scales, or grating acuity methods such as Teller acuity cards⁽²²⁾. Objective techniques, including sweep visually evoked potentials, can supplement behavioral testing by providing quantitative estimates of grating acuity when patient cooperation is limited⁽³⁶⁾.

Given the inherently binocular nature of amblyopia, assessment of stereoacuity and contrast sensitivity is essential. Stereo tests provide clinically relevant measures of functional binocularity and correlate with real-world visual performance, particularly in anisometropic and mixed forms^(3,5,26). Contrast-sensitivity testing, using chart-based or digital platforms, frequently reveals residual deficits despite improvements in visual acuity^(5,22–24,32).

Objective biomarkers are an evolving area of investigation. Abnormal fixational eye movements, including increased drift and microsaccadic instability, can now be quantified using high-resolution eye-tracking and may serve as indicators of disease severity and treatment response⁽³⁷⁾. Although OCT and OCTA can identify structural and neurovascular correlates in selected patients, their diagnostic specificity remains insufficient to replace functional testing^(29,30).

In clinical practice, integrating visual acuity, stereoacuity, and contrast sensitivity yields a more comprehensive functional profile, facilitates patient-centered goal setting, and provides multiple endpoints for monitoring treatment response^(3,5,22,24,29,30,32,35,37,38). Interpretation of these measures in combination is more informative than reliance on any single metric.

Screening and Early Detection

Early detection remains critical, as treatment efficacy declines with age. The US Preventive Services Task Force recommends at least one screening for amblyopia and its risk factors in children aged 3–5 yr⁽³⁹⁾. Instrument-based screening modalities, including photoscreeners and autorefractors, demonstrate good sensitivity and specificity in primary care and community settings and are particularly valuable in regions with limited access to pediatric ophthalmology services⁽¹²⁾.

Effective implementation of screening programs requires consideration of health system capacity, personnel training, and efficient referral pathways. National guidelines, such as those developed in Brazil, provide structured, context-specific recommendations for age-appropriate screening strategies and referral criteria⁽³⁸⁾.

Classic Monocular Therapies

Optical correction remains the cornerstone of amblyopia treatment. Full cycloplegic refraction followed by consistent

spectacle wear alone can produce meaningful improvements in visual acuity in a substantial proportion of children, particularly in anisometropic amblyopia^(12,13). An initial period of several weeks to months of optical treatment before introducing additional interventions is now standard practice. However, although spectacles alone can yield significant gains, especially in anisometropic cases, data from the Pediatric Eye Disease Investigator Group (PEDIG) indicate that children with severe amblyopia are less likely to achieve adequate improvement and typically require escalation to penalization.

When improvement in visual acuity plateaus with optical correction, treatment is escalated to monocular penalization using patching or atropine. Randomized PEDIG trials have clarified dose–response relationships. In moderate amblyopia, 2 h of daily patching produces outcomes comparable with 6 h at approximately 4 months, although higher doses may accelerate early improvement^(12,26). In severe amblyopia, approximately 6 h per day yields results similar to full-time occlusion, rendering full-time patching largely unnecessary⁽³³⁾. Once-daily or weekend-only atropine represents an effective alternative, often improving treatment acceptability while achieving comparable mean visual outcomes⁽¹³⁾.

Treatment success depends not only on modality but also on sequencing. Optical optimization should precede penalization (patching or atropine), with binocular strategies considered when response plateaus. Penalization reduces the effective visual input of the fellow eye, including contrast sensitivity, thereby decreasing interocular suppression and promoting use of the amblyopic eye during daily activities. In clinical practice, simplified regimens such as weekend-only atropine can enhance adherence. Patients are typically monitored at 6–8-week intervals during treatment escalation, with attention to adverse effects including near blur, photophobia, and rare cases of reverse amblyopia—particularly when combined with optical undercorrection or in highly hyperopic children.

Older children retain meaningful, although reduced and slower, potential for visual improvement. In those aged 7–13 yr, higher doses and longer durations of patching or atropine can still produce clinically significant gains, especially in previously untreated individuals⁽³⁰⁾. Behavioral strategies to improve adherence—such as integrating patching into daily routines, encouraging near or distance activities during occlusion, and involving families in goal setting—are critical for translating clinical trial efficacy into real-world effectiveness^(31,34,40). Contemporary Brazilian guidelines synthesize these data into practical, context-adapted treatment algorithms⁽³⁸⁾.

Recurrence and Rules for Nonimprovement

Recurrence of amblyopia after treatment cessation remains a significant concern. Approximately one-quarter of successfully treated children experience some loss of visual acuity after discontinuation of patching or atropine. The risk is higher in those with greater initial gains, younger age at cessation, and persistent risk factors such as significant anisometropia or unstable ocular alignment^(41,42).

Current evidence favors gradual tapering over abrupt cessation of therapy. This approach is typically implemented by reducing the treatment dose by half every few weeks over a minimum period of 5 weeks. High-risk patients require closer follow-up during this phase^(33,41,42). Clear communication with patients' families regarding the risk of recurrence and the necessity of adherence to follow-up schedules is essential.

Recent studies have proposed explicit criteria for nonresponse, including the expectation of at least a 0.1 logMAR improvement within 6–8 weeks of appropriately dosed patching or atropine therapy. Failure to achieve this benchmark should prompt reevaluation^(15,33). These criteria help avoid prolonged use of ineffective treatments and facilitate timely assessment of adherence, reconsideration of the diagnosis, modification of treatment intensity or modality, or introduction of binocularly targeted therapies^(15,33,41,42).

Binocular and Emerging Therapies

Recognition of amblyopia as a binocular disorder has led to the development of therapies aimed at restoring interocular balance rather than solely strengthening the amblyopic eye^(9,10,16,25,27,28,43–45). At present, these therapies should be considered adjunctive, typically introduced after established monocular treatments, particularly in younger children.

Dichoptic digital therapies, including game- and movie-based platforms, present separate images to each eye with contrast adjustments to reduce suppression and promote binocular integration. Early studies reported modest improvements in visual acuity and stereopsis, particularly with good adherence⁽¹⁶⁾. However, more recent randomized trials and meta-analyses indicate that dichoptic therapy alone does not consistently outperform conventional patching in young children. Nevertheless, it may serve as a useful adjunct or alternative in selected cases, particularly where treatment engagement is challenging^(9,16,43–45).

Perceptual learning approaches involve repetitive training of specific visual tasks, such as contrast detection and Vernier acuity, sometimes incorporating action video game elements. These methods have demonstrated

transfer effects, including improvements in visual acuity and stereoacuity, in certain populations—especially older children and adults. However, variability in protocols and limited data on long-term outcomes remain important limitations^(17,18,27,28).

Short-term monocular deprivation, also referred to as inverse patching, involves brief occlusion of the fellow eye. Paradoxically, this enhances the contribution of the previously deprived eye during subsequent binocular viewing. Repeated sessions may produce incremental changes in ocular dominance and binocular balance, resulting in modest but potentially meaningful functional improvements^(28,29).

Overall, binocular therapies generally yield smaller average gains in visual acuity than patching in young children. However, they offer several advantages: modest improvements in stereopsis and contrast sensitivity in selected patients, enhanced treatment engagement, and expanded therapeutic options for older individuals in whom traditional penalization may be less effective or less acceptable^(9,10,16,25,27,28,43–45).

Integrating Evidence into Clinical Pathways

Effective clinical application requires etiology-specific, measurement-driven management pathways that integrate both conventional and emerging therapies^(12,13,16,26,29,30,33,38,39,43). A pragmatic framework is outlined below:

Deprivation amblyopia: The primary objective is the prompt removal of the underlying cause (e.g., cataract or ptosis), followed by aggressive optical rehabilitation. Penalization therapy (patching or atropine) is initiated when indicated. Prognosis depends strongly on the age at intervention and duration of deprivation; therefore, realistic expectations should be established. Close monitoring—often every 4–6 weeks during early treatment—is necessary to guide therapy and detect recurrence^(12,13,17–19,37,40–43).

Anisometric amblyopia: Full and consistent optical correction is the first-line treatment and may be sufficient in many cases. Prognosis is generally favorable, particularly with early detection and good adherence to spectacle wear. Patients should be reassessed at 6–8-week intervals. If improvement plateaus, patching or atropine should be introduced, with consideration of binocular adjuncts to address suppression^(9,12,13,16,26–30,33,38,43–45).

Strabismic amblyopia: Penalization therapy improves fixation and reduces suppression, while ocular alignment is addressed as indicated. Recovery of stereopsis is often limited; thus, restoration of normal binocular vision should not be expected in most cases. Following alignment, binocular adjunctive therapies may support fusion and provide modest

improvements in stereopsis in selected patients. Continued monitoring is essential to detect recurrence^(12,13,16,26,33,38,43).

Mixed amblyopia (anisometropia with strabismus): Management requires a combined approach, including optical correction, penalization (patching or atropine), and alignment procedures when necessary, followed by binocular training. Bifocals may be considered in patients with partially accommodative esotropia and demonstrable binocular potential. Prognosis is typically slower, with earlier plateaus; counseling should reflect these expectations. Long-term follow-up with reassessment every 6–8 weeks during active treatment is critical^(12,13,16,26,30,33,38,43).

Across all subtypes, regular follow-up at 6–8-week intervals during active treatment enables objective assessment of therapeutic response, timely modification based on predefined nonresponse criteria, and reinforcement of adherence^(15,31,33,34,40–42). Screening recommendations and local clinical guidelines provide an essential public health framework within which individualized patient care is delivered^(12,38,39,46).

Future Directions

Several key priorities should guide future research. First, clinical trials should incorporate functionally relevant outcome measures, including stereopsis, contrast sensitivity, reading ability, motor performance, and quality of life, rather than relying predominantly on monocular visual acuity^(2–4,6,24,33,34). These measures better reflect real-world visual function and patient-centered outcomes.

Second, strategies to improve treatment adherence—including behavioral interventions, digital tools, and system-level approaches—require rigorous evaluation, as adherence remains a major determinant of therapeutic success^(31,34,40).

Third, the development and validation of predictive biomarkers may enable more personalized treatment. Potential biomarkers derived from fixational eye movements, structural and vascular imaging, and cortical activity could help clinicians select the most appropriate therapy for individual patients and monitor treatment response with greater precision^(27–30,32,37).

Finally, there is increasing interest in expanding safe and effective treatment options for adolescents and adults, in whom residual neural plasticity persists but optimal therapeutic protocols remain incompletely defined^(4,9,10,16,25,27,28,43–45).

Amblyopia management is transitioning from a predominantly monocular framework focused on letter-chart acuity to a broader, systems-based perspective that recognizes amblyopia as a binocular neurodevelopmental

disorder. Conventional treatments—optical correction and penalization—remain the cornerstone of therapy but are now applied using optimized dosing and tapering strategies to enhance both efficacy and durability.

Emerging binocular therapies provide additional approaches to restore interocular balance and improve stereopsis, particularly in patients with incomplete responses or in older age groups. The integration of conventional and emerging modalities into etiology-specific, measurement-driven clinical pathways represents a critical step toward more individualized care.

Future progress will depend less on the discovery of entirely new interventions and more on refining the combination, sequencing, and personalization of existing and emerging therapies across the lifespan.

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