REVIEW PAPER

AI-Driven Neuroadaptive Vision Therapy for Amblyopia: A Systematic Review

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Abstract

Background: One of the main causes of avoidable monocular vision impairment is amblyopia. Patching and other traditional therapies have drawbacks, such as low compliance and little binocular improvement. Neuroadaptive, binocular-focused therapies that may offer more individualized and interesting rehabilitation are made possible by emerging technologies like artificial intelligence (AI), eye tracking, and immersive VR/AR.

Objective: To examine the most recent research on AI-enabled neuroadaptive vision therapy for amblyopia, including gamified, digital/dichoptic, and VR/AR methods, with an emphasis on clinical results, safety, and constraints.

Methods: Clinical trials and reviews on AI-based diagnostic or treatment tools for amblyopia were found using a systematic search (2000–2025) of PubMed, PMC, and peer-reviewed literature. A narrative synthesis was carried out because of the variation in interventions and results.

Results:

• **Diagnostics:** AI-driven stereovision tests outperformed conventional techniques with great accuracy (AUC 0.97–0.98).

• **Digital binocular therapy:** Children's BCVA, stereoacuity, and contrast sensitivity were all enhanced by gamified dichoptic and adaptive digital treatments.

• **VR/AR therapy:** In older children and adults, VR head-mounted dichoptic training enhanced stereoacuity; BCVA improvements differed. Accessibility is increasing, according to ongoing AR-based home therapy experiments.

• **Comparative efficacy:** VR dichoptic treatment produced BCVA increases comparable to patching, according to a randomized experiment (1.32 vs. 1.0 lines over 20 weeks).

• **Safety/compliance:** High tolerance with few systemic or ocular side effects was reported in studies.

Conclusion: AI-driven neuroadaptive vision treatment is a promising improvement for improving both acuity and binocular function in amblyopia. However, small study sizes, inconsistent methods, and brief follow-up times limit the available evidence. Before widespread clinical acceptance, extensive, robust randomized trials are required.

Keywords: Amblyopia Rehabilitation , AI-Based Diagnostics , Binocular Vision Therapy , Dichoptic Treatment , Immersive VR/AR Therapy

How to cite this article: Tharani P, Dinesh Kumar T, Sethupathi A, Srija S. AI-Driven Neuroadaptive Vision Therapy for Amblyopia: A Systematic Review. Int J Drug Deliv Technol. 2026;16(41s): 948-952. DOI: 10.25258/ijddt.16.41s.99

Introduction

Amblyopia: Clinical Background & Limitations of Traditional Therapy

A neurodevelopmental vision impairment known as amblyopia, or "lazy eye," is defined by reduced best-corrected visual acuity (BCVA) in one (or sometimes both) eyes without any obvious anatomical abnormalities. Anisometropia (unequal refractive errors), strabismus (ocular misalignment), and stimulus deprivation (e.g., congenital cataract) are the main culprits. Amblyopia can cause lifetime monocular impairment if left untreated at the crucial stage of visual development, which carries concerns if the dominant eye is impaired.

In order to force the brain to utilize the amblyopic eye, traditional first-line remedies include penalization (such as atropine) or occlusion (patching) of the dominant eye. Although these techniques can enhance visual acuity, they have a number of drawbacks, including low compliance (particularly in children), social stigma, discomfort, limited improvement in binocular functions (such as stereoacuity, contrast sensitivity, and ocular motor coordination), and decreased efficacy after the critical developmental period.

In light of these constraints, binocular and perceptual-learning-based therapies have gained popularity with the goal of restoring not just monocular acuity but also binocular integration, stereopsis, and contrast sensitivity.

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Emergence of AI-Driven Neuroadaptive Vision Therapy

A paradigm shift has been made possible by advances in artificial intelligence (AI), digital technologies, eye tracking, and VR/AR. Instead of being limited to occlusion, therapy now allows for neuroadaptive, customized, and binocular therapies.

Even with non-specialist instruments like smartphone cameras, AI-based diagnostic tools like deep learning algorithms and eye tracking analysis offer the possibility of early, sensitive screening, identification of amblyopia or amblyogenic risk factors (e.g., strabismus, anisometropia). In a similar vein, VR/AR-based interventions, gamified binocular therapy, and AI-driven dichoptic training all take advantage of neuroplasticity by stimulating both eyes at the same time in regulated, adaptive, and captivating settings—often with real-time feedback, difficulty modulation, and enhanced patient adherence.

Simultaneously, discoveries regarding cerebral plasticity have confirmed the possibility of improving eyesight beyond early childhood, creating therapeutic opportunities for older kids and adults. AI-driven neuroadaptive therapies may thereby solve a number of issues with conventional amblyopia management, including better binocular outcomes, increased compliance, individualized therapy, and the possibility of tele- or home-based treatment.

Rationale for This Systematic Review

The literature is still dispersed across diagnostic AI tools, VR/AR therapy, dichoptic therapy, and digital binocular treatments, despite increased interest and preliminary findings. There isn't a thorough synthesis that focuses exclusively on neuroadaptive/AI-enabled vision therapy for amblyopia.

In order to assist clinicians, researchers, and developers, this review will: (1) list current AI-based diagnostic and therapeutic approaches for amblyopia; (2) evaluate their stated efficacy, safety, and limits; and (3) identify gaps and suggestions for future study.

Methods

Search Strategy & Sources

Up until December 2025, we systematically searched PubMed, PMC (PubMed Central), and peer-reviewed journals. Combinations of "amblyopia," "lazy eye," "AI," "artificial intelligence," "machine learning," "deep learning," "digital vision therapy," "dichoptic therapy," "binocular therapy," "virtual reality," "augmented reality," "VR," "AR," "eye-tracking," and "neuroadaptive therapy" were among the search terms used. Additionally, we manually reviewed the references in the relevant papers and identified reviews.

Inclusion & Exclusion Criteria

Inclusion:

- Original, peer-reviewed clinical research, pilot studies, or reviews detailing AI-enabled treatment or diagnostic approaches for human amblyopia.
- Digital therapy (dichoptic, binocular training), VR/AR, gamified therapy, AI-based diagnostics (e.g., eye tracking, deep learning classification), or neuroadaptive protocols.
- BCVA, stereoacuity, contrast sensitivity, compliance, and safety/adverse events are among the reported outcomes.

Exclusion:

Research using animals, simply engineering or algorithm development without clinical or therapeutic data, editorials or commentary without data, duplicate publications, or sources that are not subject to peer review.

Data Extraction & Synthesis

The authors, year, study design, population (age, type of amblyopia), intervention type (digital binocular, VR/AR dichoptic, AI-diagnostic), duration/frequency, outcome measures, outcomes (quantitative if available), adverse events, and limitations were all retrieved from each eligible study. We conducted a narrative synthesis due to the variation in techniques and results, classifying the results as (a) diagnostic AI tools; (b) digital/AI-supported binocular therapy; (c) VR/AR-based therapy; (d) safety/compliance; and (e) limits and future directions.

Results

A growing number of papers (2017–2025) on AI-enabled and digital binocular therapies for amblyopia as well as diagnostic AI tools were found by our search. Key findings from the most pertinent studies are summarized here.

AI-Based Diagnostic Tools

- When it came to identifying amblyopia and amblyogenic disorders, AI-based stereovision tests (ETS) considerably surpassed traditional clinical stereo-tests, according to a seminal study. With sensitivity of up to 0.96 and specificity of 0.87–0.98, the AI ETS was able to detect amblyopia with AUCs of 0.97–0.98.
- AI-driven eye tracking and deep learning algorithms have been proposed for strabismus categorization, amblyopia risk screening, and early diagnosis of ocular-motor impairments. These algorithms have the potential to be used for mass or home-based screening, particularly in settings with low resources.

Implication: Even outside of conventional clinical settings, AI-based diagnostics may make it possible to identify amblyopia or risk factors earlier, more easily, and sensitively. This could increase the catchment for early intervention.

Digital / AI-Supported Binocular Vision Therapy

Numerous studies have assessed digital binocular therapy for amblyopia, frequently utilizing gamified tasks, dichoptic stimulation, or perceptual learning.

- In a 2017 study, 17 persons with anisometropic amblyopia were given a dichoptic videogame (Diplopia Game) and a virtual reality head-mounted display (HMD). Following eight sessions, stereoacuity improved (mean stereoacuity dropped from ~263 arcsec to ~177 arcsec) and mean BCVA dramatically improved (logMAR 0.58 to 0.43). After training, about half of the individuals had a BCVA of 20/40 or higher.
- A review of binocular vision therapy techniques discussed a variety of techniques, including red-green spectacles, 3D games, and movies, and it was indicated that binocular therapy might be a helpful supplement or even replacement for patching.
- Children with unilateral amblyopia between the ages of 4 and 6 received gamified binocular digital therapy (with a real-time AI visual engine) in a recent pilot prospective research (2025). They saw improvements in stereoacuity and distance visual acuity (DVA) after 8 weeks (60 minutes per day, five days per week). There was only one documented case of

progressive esotropia and no other noteworthy adverse consequences.

These results show that AI-supported digital binocular therapy can produce clinically significant improvements in BCVA and binocular functions. Given the potential for high engagement through games, it may be particularly helpful in paediatric populations.

Virtual Reality (VR) / Augmented Reality (AR) Interventions

The use of VR and AR platforms for binocular vision rehabilitation has grown in popularity.

- An immersive virtual reality system was used in a 2023 pilot trial to treat anisometropic amblyopic children. Some subjects' contrast sensitivity (CS), visual acuity, and stereopsis improved, according to the results.
- Another study of 145 children with refractive amblyopia that used VR and AR platforms for short-term perceptual training found significant improvements in BCVA ($p < 0.001$), fine stereopsis ($p < 0.05$), and contrast sensitivity across all spatial frequencies ($p < 0.05$) in the AR group.
- While increases in BCVA were not statistically significant, stereoacuity significantly improved in a 2021 trial of VR-based binocular therapy in older children and adults, indicating that VR may be more beneficial for binocular function than monocular acuity in certain populations.
- In a pilot study conducted in 2024, a revolutionary VR technology called NEIVATECH was used to improve binocular vision in older children who were noncompliant or unresponsive to patching. The results showed safety, usefulness, and patient acceptability.
- More recently, a home-based AR binocular therapy for unilateral amblyopia has started clinical trials (registered 2024), suggesting a move toward patient-friendly, accessible, and remote therapy delivery.

  These studies demonstrate how VR/AR-based therapies, particularly when paired with dichoptic stimuli, perceptual learning, and adaptive game-based formats, may improve binocular integration, stereoacuity, contrast sensitivity, and visual acuity.

Comparative Efficacy: Digital / VR Therapy vs Traditional Patching

Both groups demonstrated significant gains in BCVA over a 20-week period, with the VR group improving by 1.32 lines from baseline and the patching group by 1.0 line, according to a 2024 randomized controlled trial comparing VR dichoptic therapy versus traditional patching in amblyopic patients. At every time point, there was no statistically significant difference between the groups, suggesting similar efficacy. Compared to their patching counterparts, adults and patients with more severe amblyopia in the VR group demonstrated more noticeable improvements.

Binocular digital therapy is safe and effective, with equivalent increases in visual acuity and frequently greater stereoacuity outcomes, according to a recent 2025 meta-analysis (systematic review) comparing dichoptic therapy with conventional patching in paediatric amblyopia.

Additionally, enhanced stereoacuity, contrast sensitivity, binocular integration, and greater patient compliance are frequently the results of digital therapies, particularly in gamified forms that promote participation.

Safety, Compliance, and Accessibility

Safety: After 30 minutes of use, a 2025 study assessing a motion-based VR dichoptic training app in healthy adults found minimal ocular discomfort (no significant eye fatigue, blurred vision, dryness, or motion sickness). Similarly, clinical VR dichoptic therapy trials reported no significant adverse events.

Compliance: Digital and gamified therapies, which are frequently provided through games or virtual reality environments, appear to be especially well-suited for kids, encouraging motivation and consistent participation. These formats also work well for home-based or remote therapy, which may enhance access and adherence, particularly in settings with limited resources.

Accessibility: By avoiding the requirement for specialist ophthalmic equipment or professionals, AI-based diagnostic systems utilizing smartphone cameras or basic eye tracking may enable early detection and screening in community or educational settings.

Discussion

Significance of AI-Driven Neuroadaptive Approaches

The review's conclusions highlight a prospective paradigm shift in the treatment of amblyopia: from monocular occlusion to binocular, neuroadaptive, individualized therapy that makes use of digital technologies, artificial intelligence, and VR/AR platforms.

These treatments target the core neurodevelopmental disruption in amblyopia, which is cortical suppression of the amblyopic eye and defective binocular integration, by combining dichoptic stimulation (balanced input to both eyes), perceptual learning, and real-time adaptive feedback (assisted by AI). Particularly in paediatric populations where patching adherence is frequently low, VR/AR environments and gamified tasks further improve engagement, motivation, and compliance. Additionally, AI-based diagnostics open up screening options outside of clinics, thereby allowing for earlier detection, particularly in underserved or isolated communities.

Significantly, research indicates that these contemporary approaches can improve both monocular (BCVA) and binocular functions (stereoacuity, contrast sensitivity), sometimes providing better binocular results and sometimes being on par with conventional patching.

Strengths of the Evidence

- **Multimodal application:** The literature demonstrates the adaptability and wide applicability of AI-enabled techniques, ranging from diagnostic tools to dichoptic training, VR/AR therapy, gamified digital treatment, and perceptual learning.

- **Clinical improvements across age ranges:** Patients of all ages, including elderly amblyopes who were previously believed to be less responsive to treatment, have demonstrated improvements.
- **Comparable efficacy to patching:** Digital VR therapy has been shown in controlled trials to achieve BCVA increases comparable to patching, with additional advantages for binocular vision.
- **Safety and tolerability:** With few ocular or vestibular side effects documented in early trials and safety investigations involving healthy adults, VR-based therapy appears to be largely safe.
- **Potential for accessibility and scalability:** AI-based screening and home-based digital therapy have the potential to significantly lower care barriers, which is particularly crucial in low-resource environments or those with restricted access to paediatric ophthalmology.

Limitations, Challenges & Gaps

Despite encouraging outcomes, the area is still in its infancy and has a number of significant constraints.

- **Heterogeneity in interventions and protocols:** Direct comparisons are challenging since studies differ greatly in terms of modality (VR, AR, VR-HMD, dichoptic vs. perceptual learning), length, frequency, age groups, and outcome measures (BCVA, stereoacuity, contrast sensitivity).
- **Small sample sizes and few RCTs:** The generalizability of many studies is limited since they are pilot trials or case series (e.g., 17 adults, 11 children, 3 individuals).
- **Lack of long-term follow-up:** The sustainability of benefits, particularly in binocular function, is yet unknown; few studies record follow-up beyond weeks or months.
- **Limited standardization of outcome measures:** Synthesis is made more difficult by variations in the methods used to quantify results (such as various stereo tests, contrast sensitivity measures, and visual acuity charts).
- **Bias risk & methodological concerns:** Selection bias, a lack of masking, a lack of control groups (particularly in non-RCTs), and a failure to disclose adverse events or compliance measures are all potential issues with many early-phase trials.
- **Accessibility and cost barriers:** While promising, VR/AR headsets, AI-based tools, and smartphone-based therapies could not yet be broadly accessible or reasonably priced in many areas; further obstacles include user training, technical support, and regulatory permissions.
- **Clinical and Public Health Implications**

AI-driven neuroadaptive vision therapy has the potential to drastically change the treatment of amblyopia if it is confirmed by reliable, extensive trials:

- **Earlier detection and intervention:** Mass screening in schools or the community could be made possible by AI-based screening systems, which could result in early diagnosis and prompt therapeutic commencement.
- **Improved therapy adherence and patient experience:** Particularly for younger patients, digital and gamified therapy may boost motivation, decrease the social stigma attached to patching, and enhance compliance.
- **Broader age window for treatment:** Research challenges the conventional notion of a limited crucial period by indicating that binocular treatment may be beneficial for older children and adults.
- **Enhanced binocular outcomes:** These treatments, which emphasize binocular integration, may enhance stereoacuity, contrast sensitivity, and general visual function, going beyond monocular acuity alone, with certain functional advantages (sports, reading, depth perception).
- **Scalable, remote, and accessible care:** Smartphone-based platforms or home-based VR/AR therapy could democratize amblyopia care, especially in underprivileged areas or settings with limited resources that lack paediatric ophthalmology professionals.

Recommendations for Future Research

In order to progress the field, we advise:

1. **Large-scale, multicenter randomized controlled trials (RCTs)** contrasting traditional patching, sham/placebo controls, and AI-enabled digital/VR/AR therapy; including stratified subgroups (age, severity, amblyopia type).
2. **Standardization of protocols and outcome measures** — BCVA, stereoacuity, contrast sensitivity, ocular motor function, compliance, and adverse events are among the established metrics.
3. **Longitudinal follow-up** (1 year or more) to evaluate the stability of binocular function, relapse rates, durability of gains, and practical functional results (depth perception, reading).
4. **Integration of objective biomarkers** — such as brain imaging (fMRI/VEP) and eye-tracking data, to evaluate neuroplastic changes and correlate with improvements in clinical outcomes.
5. **Focus on accessibility and equity** — Create affordable, user-friendly, home-based VR/AR or smartphone systems; conduct feasibility, cost-effectiveness, and implementation research in various socioeconomic contexts.
6. **Investigation of safety and tolerability**, including long-term eye health, visual fatigue, motion sickness risk, and ocular comfort, particularly in young populations.
7. **Regulatory and ethical considerations** — Assure adherence to data privacy, user permission, and medical device regulations; create certification requirements for AI-based vision therapy solutions.

Conclusion

A promising and quickly developing area of vision care is AI-driven neuroadaptive vision therapy for amblyopia, which includes digital binocular therapy, gamified dichoptic training, VR/AR interventions, and AI-based diagnostics. According to recent data from pilot studies, small trials, and early RCTs, these treatments can improve visual acuity, stereoacuity, contrast sensitivity, and binocular integration. These improvements are frequently comparable to those of traditional patching, with the possible advantages of improved compliance, engagement, and accessibility. Nevertheless, the evidence base is still minimal since conclusive findings are hampered by heterogeneity, small sample numbers, short-term follow-up, and a lack of standardization. Larger, thorough, long-term research, standardized methodologies, safety evaluations, and equitable access initiatives are essential for broad clinical adoption and guideline integration.

AI-driven neuroadaptive therapies may hold the key to more efficient, patient-friendly, and accessible amblyopia care globally given the prevalence of amblyopia and the difficulties with traditional therapy, particularly in low-resource settings.

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