Review Article

Effectiveness of Psychophysical Visual Stimuli-Based Interventions in Amblyopia Treatment: A Systematic Review

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Running title: Visual stimuli interventions for Amblyopia

Abstract
Introduction: Active vision therapy, integrating perceptual learning with dichoptic or binocular environments, has shown potential effectiveness in treating amblyopia. However, uncertainties remain regarding the optimal types of stimuli and the best approaches and sequences for their presentation. This systematic review evaluates the effectiveness of psychophysical visual stimuli-based interventions, particularly perceptual learning and dichoptic training, in treating amblyopia.
Materials and methods: A comprehensive literature search across major databases, such as PubMed and Google Scholar, yielded 26 studies involving 993 amblyopic patients. These studies investigated various visual training methods, including perceptual learning, dichoptic

stimulation, and combinations of both, using stimuli such as Gabor patches, letter optotypes, Vernier stimuli, and random-dot stereograms.
Results: The findings indicate that perceptual learning enhances visual acuity, contrast sensitivity, and stereopsis—even in adult patients—by leveraging neural plasticity. Dichoptic training, which engages both eyes simultaneously, shows promise in reducing suppression and improving binocular integration, offering a potential advantage over traditional patching therapy. Gabor patches emerged as particularly effective, stimulating the visual cortex to drive neural efficiency.
Conclusion: Vision therapy appears to be an effective strategy for treating amblyopia and may reduce overall treatment time when used alongside patching. In addition, it is imperative to tailor stimuli to align with the individual characteristics of each patient during both monocular and binocular training.
Keywords: Amblyopia; Orthoptics; Psychophysics; Systematic review

Introduction

Amblyopia is a developmental visual disorder characterized by reduced visual acuity in one or both eyes, in the absence of ocular pathology and not immediately correctable with lenses (1). It is commonly caused by strabismus or refractive disorders and affects approximately 2–4% of the general population (2, 3). Neuroimaging studies have demonstrated cortical abnormalities in individuals with amblyopia, indicating that visual deficits—including both monocular and binocular impairments—stem from anomalies in the striate and extra-striate cortex (4, 5).

Amblyopia develops during the critical plasticity period of the visual system, which typically spans the first 7–9 years of life (6). It is important to note that certain risk factors may increase the likelihood of developing amblyopia in childhood, including a family history of amblyopia, prematurity, low birth weight, and conditions such as Down syndrome or cerebral palsy (7). Therefore, early detection and intervention are essential to effectively manage amblyopia and prevent long-term visual impairment.

In recent years, novel methods have emerged to complement traditional treatments such as corrective lenses, patching, and penalization with atropine drops or Bangerter filters (1, 7). These innovative approaches include computer-based active vision therapy utilizing a variety of psychophysical stimuli (8). The rationale behind these interventions is supported by neurophysiological studies highlighting the effects of video games on neuromodulatory pathways and attentional improvement (9, 10).

The introduction of such novel techniques has enabled clinicians to develop advanced protocols incorporating perceptual learning (11–13), dichoptic training (14–16), and binocular therapy (17–19).

The use of perceptual learning and/or dichoptic or binocular therapy within active vision therapy requires careful consideration of the types of stimuli used and their mode of presentation. The selection and sequencing of stimuli are critical to the effectiveness of therapy. During the monocular phase, stimuli and environments are chosen to address visual deficits, while in the binocular phase, the emphasis shifts to enhancing interocular fusion and stereopsis (20).

Importantly, active visual therapy—incorporating perceptual learning, dichoptic stimulation, and binocular training with anaglyph glasses—represents a promising field of investigation (21). This line of research holds the potential to augment and refine conventional amblyopia treatment strategies.

The present review aimed to collect and evaluate the scientific literature on the use of psychophysical visual stimuli in active vision therapy for amblyopia, with a focus on assessing the quality of the evidence presented.

Materials and methods

Study design

A systematic review was conducted to evaluate various research studies assessing the effects of different types of stimuli on the treatment of patients with amblyopia.

Review protocol

The review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

Eligibility criteria

Inclusion criteria encompassed articles that examined psychophysical visual stimuli used in active vision training, including perceptual learning, dichoptic stimulation, and binocular training for amblyopia. No restrictions were applied regarding the publication timeframe or study design. Eligible articles included original research, randomized clinical trials, case series, non-randomized interventional studies, and case reports.

Studies involving animal models or those primarily focused on traditional treatment methods, such as corrective lenses, patching, or penalization with atropine drops or Bangerter filters, were excluded.

Sources of information

Four electronic databases were reviewed, including Google Scholar, Web of Science, ResearchGate, and PubMed.

Search strategy

To ensure a comprehensive literature review, an extensive database search was conducted between December 2023 and December 2024. Major databases, including Google Scholar, Web of Science, ResearchGate, and PubMed, were used in conjunction with two specific search strategies (Table 1) to identify relevant studies. The Zotero reference management software was used to organize the collected literature.

Table 1. Search strategies

Strategy 1. Free language	
#1	Vision therapy
#2	Dichoptic
#3	Dichoptic vision therapy

#4	Perceptual learning
#5	Video games
#6	Behavioral training
#7	Computer games
#8	Virtual reality
#9	Orthoptics
#10	Binocular vision therapy
#11	#1 OR #2 OR #3 OR #4 OR #5 OR #6 OR #7 OR #8 OR #9 OR #10
#12	Amblyopia
#13	Anisometropic amblyopia
#14	Strabismic amblyopia
#15	Lazy eye
#16	#12 OR #13 OR #14 OR #15
#17	Child
#18	Children
#19	Childhood
#20	Young
#21	Adults
#22	Preschool
#23	17 OR #18 OR #20 OR #21 OR #22
#24	Visual acuity
#25	VA
#26	Stereopsis

#27	Contrast sensitivity
#28	Vernier acuity
#29	Letter acuity
#30	#24 OR #25 OR #26 OR #27 OR #28 OR #29
#31	Gabor’s patches
#32	Vernier stimuli
#33	Random-dot stereograms
#34	Psychophysical stimuli
#35	Letter optotypes
#36	#31 OR #32 OR #33 OR #34 OR #35
#37	#11 AND #23 AND #30 AND #36
Strategy 2. Controlled vocabulary (MeSH terms)	
#1	“Video games” [mesh]
#2	“Computer games” [mesh]
#3	“Virtual reality” [mesh]
#4	“Virtual reality exposure therapy” [mesh]
#5	“Orthoptics” [mesh]
#6	#1 OR #2 OR #3 OR #4 OR #5
#7	“Amblyopia” [mesh]
#8	“Child” [mesh]
#9	“Young adult” [mesh]
#10	“Adolescent” [mesh]
#11	“Preschool” [mesh]
#12	#8 OR #9 OR #10 OR #11 OR #11

#13	“Visual acuity” [mesh]
#14	“Depth perception” [mesh]
#15	“Contrast sensitivity” [mesh]
#16	#13 OR #14 OR #15
#17	“Psychophysics” [mesh]
#18	#6 AND #7 AND #12 AND #16 AND #17

Search terms included both free-text and controlled vocabulary keywords: “amblyopia,” “dichoptic vision therapy,” “perceptual learning,” “video game-based therapy,” “behavioral training,” “letter optotypes,” “Gabor patches,” “Vernier stimuli,” “virtual reality,” “random-dot stereograms,” “psychophysical stimuli,” “lazy eye,” “visual acuity,” “binocular vision therapy,” “children,” “young,” and “adult.” To improve the readability and linguistic precision of certain manuscript sections, the Chat Generative Pre-trained Transformer (ChatGPT) was used exclusively for language editing. This tool did not contribute to the generation of scientific content, data analysis, or interpretation of results. All outputs from this tool were thoroughly reviewed and revised by the author to ensure accuracy and compliance with academic standards.

Results

1. Search Results

A comprehensive search initially identified 632 documents. After removing duplicates and screening titles and abstracts, 84 articles were selected for full-text review. Of these, 58 articles were excluded for not meeting the inclusion criteria. Ultimately, 26 articles were included in this review (Figure 1).

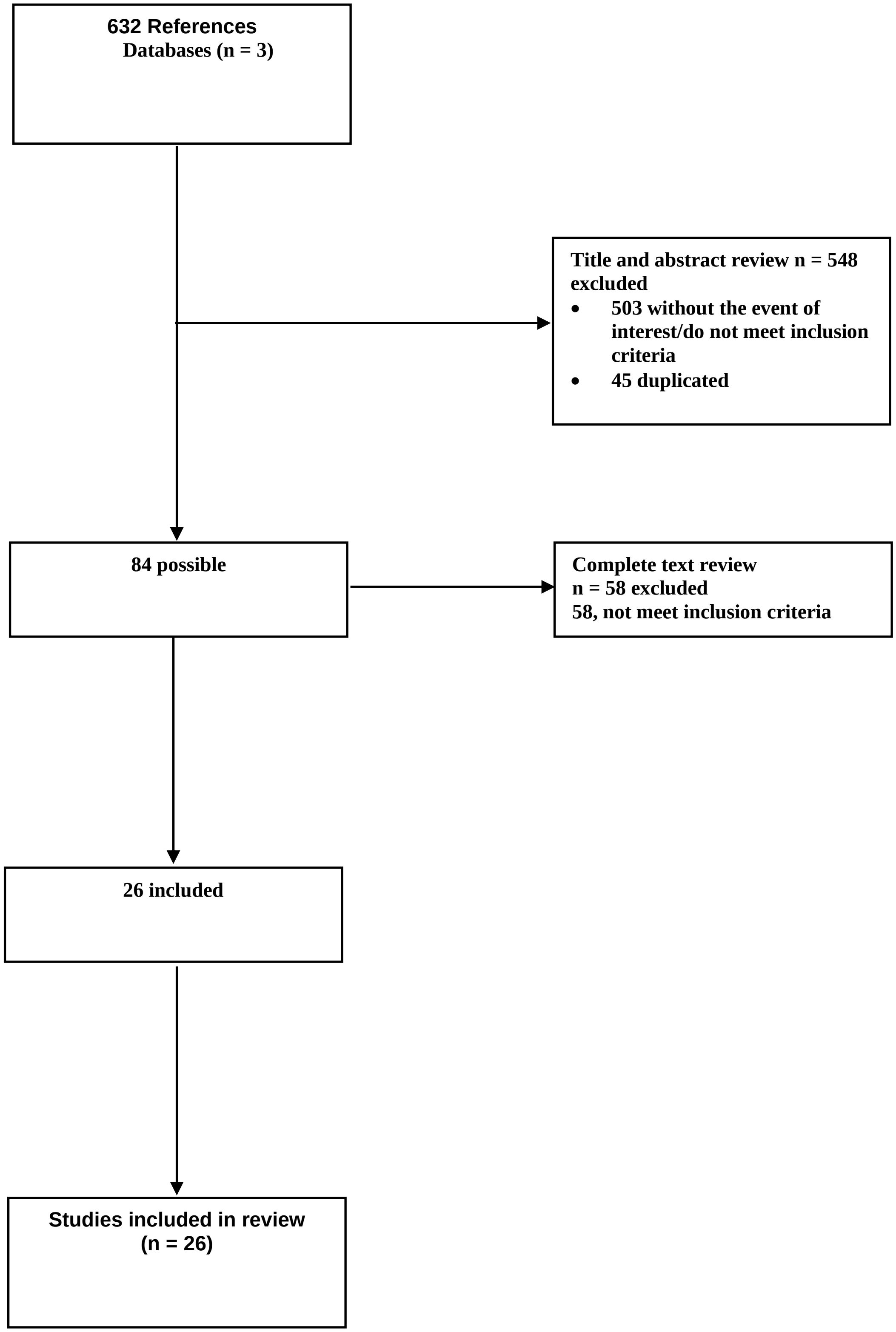

Figure 1: Flowchart showing the study selection process for the systematic review.

2. Study characteristics

Data were gathered from 993 amblyopic patients across the 26 reviewed studies (see Table 2). The included studies consisted of 21 cross-sectional studies (12, 22–41), two randomized controlled trials (42, 43), two pilot studies (44, 45), and one case report (46), published between 1995 and 2024. All studies examined the effects of visual training methods, including dichoptic training and perceptual learning, using various visual stimuli in individuals with amblyopia.

The articles were categorized based on the type of visual stimuli used in the interventions. These included letter optotypes, Gabor patches, Vernier stimuli, and random-dot stereograms. These four types of stimuli, as detailed in Table 2, have demonstrated clinical efficacy and are compatible with integration into amblyopia training software, offering the flexibility to adjust stimuli presentation according to the patient's progress.

The reviewed interventions emphasized recent advances in computer-based active vision therapy aimed at enhancing visual function in amblyopic patients. These included perceptual learning, dichoptic stimulation, and, in some cases, a combination of both approaches.

A total of 21 studies investigated visual training interventions using Gabor patch stimuli. Of these, some applied perceptual learning (12, 27–30, 34–39, 41, 42, 45), one study used dichoptic training (33), and others employed a combination of perceptual learning and dichoptic methods (31, 32, 42). In addition, four studies (22, 23, 26, 46) explored the use of letter optotype stimuli in perceptual learning-based treatments for amblyopia.

Three studies (40, 41, 43) utilized random-dot stereogram stimuli in amblyopia treatment. Among these, two studies (41, 43) implemented perceptual learning methods, while one study (40) combined perceptual learning and dichoptic training. One study (25) applied a combined approach using both Gabor patch and letter optotype stimuli through perceptual learning techniques. The remaining two studies (38, 39) investigated the role of Vernier stimuli in improving visual function in adult patients with amblyopia using perceptual learning protocols.

Table 2. Main outcomes of the included studies.

Study	Sample	Cause of Amblyopia	Intervention	Stimulus	Outcome
Polat et al., 2004 (24)	77	41 aniso, 36 strab	PL	Gabor's patch	Two-fold improvement in CS and letter-recognition tasks
Hussain et al., 2012 (22)	10	6 strab, 4 mixed	PL	Letter optotypes	Reduced visual crowding in the amblyopic fovea
Chung et al., 2012 (23)	5	1 aniso, 4 strab	PL	Letter optotypes	Improvement in VA, letter CS, size of the visual span, and reduced crowding
Avram et al., 2013 (46)	5	Aniso	PL	Letter optotypes	Significant improvement of VA and CS after training
Zhang et al., 2013 (25)	341	Aniso, strab, ametropic and mixed	PL	Gabor's patch Letter optotype	Improvement in VA with PL was similar to with patching
Poltavski et al., 2024 (26)	40	Aniso	PL	Letter optotype	Improvement in BCVA with PL was similar to with patching
Li et al., 2004 (27)	7	2 Aniso, 3 strab, and 2 mixed	PL	Gabor's patch	Significant improvements in position and VA after intensive training
Li et al., 2005 (28)	5	1 Aniso, 3 strab, and 1 mixed	PL	Gabor's patch	Substantial improvement in Snellen acuity after practice
Chen et al., 2008 (44)	26	Aniso	PL	Gabor's patch	Improvement in VA by approximately three lines after training
Liu et al., 2011 (29)	23	16 Aniso, 4 ametropic and 3 mixed	PL	Gabor's patch	Improvement in grating acuity and Stereoacuity

Zhang et al., 2014 (30)	19	12 Aniso, 2 strab, and 5 mixed	PL	Gabor's patch	Improvement of VA, CS, and stereoacuity after training
Vedamurthy et al., 2015 (31)	23	10 Aniso, 13 strab	DT and PL	Gabor's patch	Improvement in suppression, Gabor resolution, VA and stereopsis
Vedamurthy et al., 2015 (32)	38	16 Aniso, 22 strab	DT and PL	Gabor's patch	Improvement in VA
Liu et al., 2018 (33)	13	9 aniso, 1 strab, 3 mixed	DT	Gabor's patch	Stereopsis improved 26.5% ± 6.9%
Shuai et al., 2019 (34)	24	12 aniso, 12 strab	PL	Gabor's patch	Significant improvements 0f VA in AA and Stereoacuity in SA
Barollo et al, 2017 (12)	10	2 Aniso, 5 strab, 1 ametropic, 1 unclassified, and 1 mixed	PL	Gabor's patch	Reduced contrast-detection thresholds
Battaglini et al., 2021 (45)	6	organic bilateral amblyopia	PL	Gabor's patch	Improvement in contrast thresholds
Magdalene et al., 2022 (35)	45	39 aniso, 1 strab, 2 mixed, and 3 dep	PL	Gabor's patch	Improvement in distance BCVA
Pérez-Benito et al., 2023 (42)	120	Aniso, strab, and mixed	DT and PL	Gabor's patch	Improvement of VA and stereoacuity after training
He et al., 2023 (36)	49	36 Aniso, 4 strab, and 9 ametropic	PL	Gabor's patch	Improvement of VA and CSF
Zhou et al., 2024 (37)	31	Aniso	PL	Gabor's patch	Improvement of VA between 0.5 and 1.5 lines

Levi et al., 1996 (38)	6	Aniso	PL	Vernier's Stimulus	Vernier acuity improved 46 ± 7%
Levi et al., 1997 (39)	11	4 Aniso, 4 strab, and 3 mixed	PL	Vernier's Stimulus	significant and substantial improvements in Vernier acuity
Vedamurthy et al., 2016 (40)	11	2 Aniso, 4 strab, and 5 mixed	DT and PL	RDS	Reduced suppression and improved stereoacuity
Martín-González et al., 2020 (41)	16	2 aniso, 8 strab, 4 mix, 2 ametropic	PL	RDS	Significant improvement of stereopsis
Portela-Camino et al., 2018 (43)	32	2 aniso, 18 strab, 10 mixed, ametropic	PL	RDS	Stereopsis increased about 50%

Abbreviations: Aniso, anisometropia; Strab, strabismus; Dep, derivational; DT, dichoptic training; PL, perceptual learning; VA, visual acuity; BCVA, best-corrected visual acuity; CS, contrast sensitivity; CSF, contrast sensitivity function; RDS, random-dot stereogram

Discussion

This systematic review was conducted to assess the efficacy of psychophysical visual stimuli, namely perceptual learning and dichoptic training techniques, in managing amblyopia. The findings highlight the effectiveness of specific stimuli—such as Gabor patches, letter optotypes, Vernier stimuli, and random-dot stereograms—in improving visual function across different types and severities of amblyopia.

The studies reviewed provide strong evidence that perceptual learning and dichoptic training are promising therapeutic interventions with wide-ranging implications for improving visual acuity, contrast sensitivity, and stereopsis, as well as reducing crowding effects.

1. Perceptual learning in amblyopia treatment

Perceptual learning has emerged as a valuable strategy for enhancing visual function in individuals with amblyopia. Evidence shows that intensive training may lead to meaningful improvements in visual acuity and other visual tasks, even in adults with long-standing amblyopia (27, 44). Several reports (28, 29) demonstrated that perceptual learning training using Gabor patches and letter optotypes effectively improves visual acuity and contrast sensitivity in both children and adults. These improvements suggest that perceptual learning can induce plasticity in the visual system, making it a potential therapeutic approach beyond the traditional critical period of visual development.

Training aimed at improving peripheral visual tasks also showed promising results. Enhancing letter recognition performance through training at 10° eccentricity in the visual field resulted in significant improvements (47), indicating that perceptual learning interventions are versatile and can address both central and peripheral visual deficits.

Moreover, perceptual learning using letter optotypes has been considered effective in several studies (23, 26, 46) for improving visual acuity and reducing crowding effects in both pediatric and adult amblyopes. According to these studies, letter optotype-based tasks are practical and can be easily delivered through various formats, such as video games or software platforms. Clinically, improving visual acuity—especially in anisometropic amblyopia—may provide additional benefits for daily visual functions, particularly reading and object recognition, which are important for everyday activities.

2. Crowding and contrast sensitivity

One of the major challenges in amblyopia is the crowding effect, where object recognition is impaired in visually cluttered environments. The reviewed studies demonstrate that perceptual learning regimens targeting crowding can significantly reduce this impairment (23, 24). Improvements were observed in letter identification and acuity, suggesting that perceptual learning not only mitigates the crowding effect but may also enhance performance in practical visual tasks such as reading.

Furthermore, contrast sensitivity—a commonly impaired aspect of visual function in amblyopia—consistently improved following perceptual learning interventions. Training protocols involving Gabor patches resulted in significantly lowered contrast detection thresholds (12, 24), indicating that such stimuli are effective in enhancing fine visual discrimination. These findings underscore the potential of perceptual learning to restore higher-order visual processing, which is a critical component of functional vision in daily life.

Recently, dichoptic training has emerged as an effective approach for addressing binocular deficits in amblyopia, particularly by reducing suppression and enhancing stereopsis. Unlike traditional monocular patching—which strengthens the amblyopic eye at the expense of binocular balance—dichoptic training stimulates both eyes simultaneously to promote binocular integration (31). This method presents distinct stimuli to each eye in a manner that reduces interocular suppression while improving the function of the amblyopic eye without compromising the dominant eye.

Several studies (31, 34) have shown that dichoptic interventions can significantly improve visual acuity, contrast sensitivity, and stereopsis. Notably, specially designed video games incorporating dichoptic stimuli have proven both effective and engaging. These games often employ Gabor patches or similar visual elements to stimulate both eyes concurrently, facilitating binocular cooperation and reducing interocular imbalance (31).

The benefits of dichoptic training extend beyond simple visual acuity improvements. Multiple studies (32, 42) using customized dichoptic video games have reported gains in stereopsis, contrast sensitivity, and reduced suppression in both children and adults with amblyopia. These improvements reflect enhanced binocular integration and depth perception.

Moreover, findings from other studies (32, 48) indicate that dichoptic training may not only complement but, in some cases, surpass traditional therapies. Compared to patching, video game-based dichoptic treatments were more time-efficient and achieved greater improvements in best-corrected visual acuity. Collectively, these results position dichoptic training as a promising, holistic alternative to monocular therapies, offering simultaneous enhancement of both monocular and binocular visual functions.

4. Effectiveness of Gabor patches

Gabor patches have been among the most effective stimuli that have repeatedly evoked perceptual learning in amblyopes. Their spatial properties closely resemble the receptive fields of neurons in the visual cortex, making them particularly suited to promote neural plasticity (49). Indeed, studies (25, 27) across different patient groups documented that training with Gabor patches significantly improved visual acuity, contrast sensitivity, and stereoacuity. This suggests that Gabor patches are well suited for optimizing neuronal efficiency by increasing contrast sensitivity and reducing the signal-to-noise ratio in the primary visual cortex.

Additionally, dichoptic training with Gabor patches has proved effective in amblyopia treatment. Thus, Gabor patches with dichoptic presentation have the added advantage of allowing both eyes to be selectively stimulated to promote binocular integration and reduce suppression (31, 34). This technique not only improves monocular visual functions such as visual acuity and contrast sensitivity, but it also promotes binocular vision in problems of stereopsis and depth perception.

5. Vernier acuity and stereopsis

Perceptual learning tasks focusing on Vernier acuity also effectively improved visual function in amblyopia. Significant gains in Vernier acuity were observed following extensive training (50, 51), suggesting that perceptual learning can enhance fine visual tasks that require precise alignment or discrimination. Improvements in Vernier acuity were particularly evident in tasks involving line tilt detection and stereoacuity, both critical aspects of visual hyperacuity (52).

Notably, Levi and Polat (38) demonstrated that neural plasticity in adults with amblyopia could be leveraged to enhance Vernier acuity through perceptual learning, revealing the potential for significant gains in fine spatial discrimination. This improvement is critical, reflecting enhanced visual processing capabilities beyond basic acuity measures.

Further supporting these findings, Levi, Polat, and Hu (39) showed that practice could substantially improve Vernier acuity in adults with amblyopia. Their study highlighted that adult amblyopes could achieve better alignment detection with consistent practice, suggesting that perceptual learning can lead to meaningful enhancements in high-resolution visual tasks. This evidence underscores the potential for perceptual learning to improve complex visual functions, which are crucial for activities requiring high spatial resolution

Stereopsis, which is often compromised in individuals with amblyopia, showed substantial improvement following perceptual learning interventions. Studies (52, 55) involving training programs focused on stereoacuity demonstrated significant gains in-depth perception, even in adult patients previously considered stereo-blind. These findings are particularly encouraging as they challenge the traditional view that stereopsis cannot be recovered after the critical period of visual development. Perceptual learning interventions have proven to be effective in restoring binocular vision and depth perception, even in patients with severe amblyopia.

6. Comparison with conventional therapies

Perceptual learning, particularly through dichoptic training and Gabor patch interventions, presents a targeted and effective alternative to conventional amblyopia therapies. Traditional methods, such as patching and refractive correction, primarily aim to improve visual acuity in the amblyopic eye but often lead to reduced binocular function (27). In contrast, perceptual learning addresses a broader spectrum of visual deficits—including contrast sensitivity, crowding, and stereopsis—making it a more comprehensive treatment approach (23). Dichoptic training, in particular, offers an advantage over monocular therapies by engaging both eyes simultaneously, promoting binocular integration and reducing interocular suppression (31). This dual-eye approach not only enhances overall visual function but also contributes to more lasting improvements in stereopsis and depth perception. Moreover, the versatility of perceptual learning, especially when combined with conventional treatments, enables more personalized therapy regimens tailored to individual patient needs (48).

7. Effects Based on Depth of Amblyopia, Patient Age, and Binocular Vision Status

The effects of perceptual learning and dichoptic training vary depending on the depth of amblyopia, patient age, and the status of binocular vision. In individuals with mild to moderate amblyopia, perceptual learning using Gabor patches and letter optotypes has been shown to significantly improve contrast sensitivity and visual acuity (27, 28, 29). In cases of severe amblyopia, the therapeutic response tends to be more complex and typically requires extended training durations to achieve comparable outcomes (31, 34). Age is also a critical determinant of treatment efficacy. Younger patients, particularly children, often exhibit earlier and more durable improvements in visual performance following intervention (23, 26). Nevertheless, evidence suggests that older adults can also experience meaningful visual enhancements through neuroplastic changes induced by perceptual learning (27, 44). For instance, Gabor patch training has been reported to improve both contrast sensitivity and binocular vision in amblyopic individuals (25, 27). Additionally, the baseline status of binocular vision plays a substantial role in shaping treatment outcomes. Dichoptic training, which targets binocular function, has been found to reduce interocular suppression and enhance stereopsis. Video game-based dichoptic interventions, in particular, show promise in improving both monocular visual functions and binocular cooperation (31, 32, 42). Collectively, these findings underscore that perceptual learning and dichoptic therapies offer a flexible and effective approach to improving visual outcomes across a wide range of amblyopia profiles.

8. Limitations and future research

Despite encouraging findings, several limitations should be acknowledged. Many of the studies included in this review involved small sample sizes, which limits the generalizability of the results. Additionally, considerable variability exists in training protocols and outcome measures across studies, making it difficult to determine which specific interventions are most effective. Another important limitation is the frequent absence of long-term follow-up data, which hampers understanding of the durability of visual improvements achieved through perceptual learning (28, 34). To address these gaps, future research should prioritize large-scale randomized controlled trials with standardized protocols and outcome measures to establish a stronger evidence base for the clinical application of perceptual learning in amblyopia. Furthermore, the long-term sustainability of treatment effects remains unclear, underscoring the need for longitudinal studies to assess whether perceptual learning can help prevent regression of visual function after therapy completion (12, 32). Investigating the integration of perceptual learning with conventional therapies such as patching or refractive correction may also offer a more comprehensive and effective treatment strategy. This combined approach could simultaneously address suppression and core visual deficits, potentially enhancing treatment outcomes and enabling more personalized therapeutic regimens for individuals with amblyopia (42).

Conclusion

This systematic review provides evidence that psychophysical visual stimuli, particularly those used in perceptual learning, can serve as effective interventions for amblyopia. These approaches consistently resulted in improvements in visual acuity, contrast sensitivity, crowding, and stereopsis across varied populations. Among these, dichoptic training emerged as a promising alternative to conventional therapies by promoting binocular integration and reducing interocular suppression. With the evolving research in the field, perceptual learning-based interventions may form an essential part of amblyopia management and thus provide patients personalized, effective treatment options.

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Authors's contributions

All authors equally contributed to preparing this article

Conflict of interest

The authors declare no conflicts of interest

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