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A quantitative synthesis of VR-based treatments for convergence insufficiency: A systematic review

Namrata Srivastava *

Department of Optometry ERA University of Allied Health Science and Research, Lucknow, Uttar Pradesh, India.

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Abstract

Purpose: Convergence insufficiency (CI), a common binocular vision disorder, impairs near eye alignment, causing eyestrain, headaches, and blurred vision. This systematic review aims to synthesize quantitative evidence on the efficacy of virtual reality (VR)-based treatments for CI, comparing their effectiveness to traditional therapies (e.g., pencil push-ups, office-based vision therapy) and assessing clinical outcomes and patient engagement.

Methods: Following PRISMA 2020 guidelines, we searched PubMed, Scopus, and Web of Science (2000–2025) for randomized controlled trials (RCTs) and observational studies on VR-based interventions for CI. Inclusion criteria included CI diagnosis, VR interventions, and quantitative outcomes (near point of convergence [NPC], positive fusional vergence [PFV], Convergence Insufficiency Symptom Survey [CISS] scores). Study quality was evaluated using the Cochrane risk of bias tool and Newcastle-Ottawa Scale. Meta-analyses employed random-effects models, with heterogeneity (I^2) and publication bias (Egger's test) assessed.

Results: From 342 articles, 12 studies (7 RCTs, 5 observational, n=589, ages 7–35) were included. VR interventions (headsets, anaglyph systems, gamified platforms) yielded moderate effect sizes (SMD=0.48–0.65), with NPC reductions of 2.5–4.8 cm, PFV increases of 8–12 prism diopters, and CISS score reductions of 10–15 points, outperforming traditional therapies. Compliance was higher (80–95%) with VR due to immersive engagement. Moderate heterogeneity (I^2=45–60%) and minimal publication bias (p>0.05) were observed.

Conclusion: VR-based treatments are promising for CI, offering enhanced outcomes and compliance. Larger, standardized trials are needed to confirm efficacy and address accessibility.

Keywords: Convergence Insufficiency; Virtual Reality; Vision Therapy; NPC; PFV; CISS

1. Introduction

Convergence insufficiency (CI) is a prevalent non-strabismic binocular vision disorder characterized by the inability to maintain proper eye alignment when focusing on near objects, leading to significant visual discomfort and functional impairment. Epidemiological studies estimate its prevalence to range from 2% to 17% across diverse populations, with a higher incidence observed among children and young adults. [2, 8, 11, 12, 14, 15]The condition manifests through a constellation of symptoms, including asthenopia (eye strain), diplopia (double vision), headaches, blurred vision, and difficulty sustaining attention during near tasks such as reading or screen-based activities [3, 6, 9]. These symptoms can profoundly impact academic performance, workplace productivity, and quality of life, particularly in populations reliant on prolonged near work, such as students and professionals. [6, 17, 18] The pathophysiology of CI is linked to deficiencies in the vergence system, specifically a reduced ability to converge the eyes inward, often accompanied by accommodative

* Corresponding author: Namrata Srivastava

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dysfunctions. [4, 7, 9] This result in an increased near point of convergence (NPC) and reduced positive fusional vergence (PFV), measurable clinical markers of the condition. [40, 41]

Traditional treatment modalities for CI have primarily included vision therapy techniques such as pencil push-ups, office-based orthoptic exercises, and home-based computerized vergence systems. [19, 22, 24, 25, 28, 29, 30, 31] Pencil push-ups, a widely used home-based intervention, involve focusing on a near target to improve convergence, but studies have reported variable efficacy and low patient compliance due to the repetitive and monotonous nature of the exercises.[24, 28, 30] Office-based Orthoptic therapy, administered by trained professionals, has demonstrated greater effectiveness in improving clinical outcomes such as NPC and PFV, yet it is resource-intensive and often inaccessible due to cost, geographic limitations, or time constraints.[22, 25]Home-based computerized systems, designed to enhance accessibility, have shown promise but are limited by patient adherence and the lack of real-time feedback.[26, 29]These challenges have driven the exploration of innovative therapeutic approaches that can address both efficacy and engagement.

In recent years, virtual reality (VR) technology has emerged as a transformative tool in medical rehabilitation, offering immersive, interactive, and controlled environments that can be tailored to specific therapeutic needs.[25, 26,27, 28]In the context of vision therapy, VR-based treatments for CI leverage gamified exercises, stereoscopic displays, and eye-tracking capabilities to enhance vergence and accommodative functions.[20, 38]These interventions create dynamic visual stimuli that engage patients through interactive tasks, such as tracking moving objects or aligning virtual targets, which may improve motivation and compliance compared to traditional methods. [20, 29, 30] For instance, platforms like the Virtual Eye Rotation Vision Exercises (VERVE) utilize VR headsets with integrated eye-tracking to deliver precise vergence training, showing promising results in reducing CI symptoms [20]. Similarly, anaglyph-based VR systems and gamified vision therapy programs have been explored for their ability to simulate binocular demands in a controlled setting [30, 28]The immersive nature of VR not only enhances patient engagement but also allows for real-time monitoring and adjustment of therapy parameters, potentially optimizing outcomes.

Despite these advancements, the evidence base for VR-based treatments remains nascent, with studies varying in design, intervention protocols, and outcome measures. While preliminary findings suggest that VR interventions may improve NPC, PFV, and symptom severity (as measured by tools like the Convergence Insufficiency Symptom Survey [CISS]), their comparative efficacy against traditional therapies remains underexplored.[31, 32, 36] Furthermore, challenges such as the cost of VR equipment, variability in platform design, and the need for standardized protocols pose barriers to widespread adoption .[51, 53] This systematic review aims to address these gaps by quantitatively synthesizing the efficacy of VR-based treatments for CI, with a focus on clinical outcomes such as NPC, PFV, and CISS scores. By comparing VR interventions to conventional therapies, this review seeks to evaluate their effectiveness, identify factors influencing treatment success, and highlight areas for future research to optimize the application of VR in vision therapy.

2. Methods

This systematic review was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 guidelines to ensure a robust and transparent methodology.[33, 34, 35]The review protocol was developed a priori and registered with PROSPERO (registration number pending) to outline the objectives, search strategy, and analytical approach. The primary aim was to quantitatively synthesize the efficacy of virtual reality (VR)-based interventions for convergence insufficiency (CI), with a focus on clinical outcomes compared to traditional therapies.

2.1. Search Strategy

A comprehensive literature search was performed across three major electronic databases: PubMed, Scopus, and Web of Science. The search was designed to capture studies published between January 1, 2000, and June 14, 2025, to reflect contemporary advancements in VR technology and vision therapy. The search strategy combined controlled vocabulary (e.g., MeSH terms in PubMed) and free-text keywords, including but not limited to: "convergence insufficiency," "virtual reality," "vision therapy," "binocular vision," "vergence," "accommodative dysfunction," "near point of convergence," and "positive fusional vergence." Boolean operators (AND, OR, NOT) were used to refine the search, and truncation symbols were applied to account for variations in terminology (e.g., "virtual realit*" to capture "reality" and "realities"). Additional searches were conducted in Google Scholar and reference lists of relevant articles to identify studies missed by the primary search. Grey literature, including conference proceedings and theses, was explored via ProQuest Dissertations and Theses Global to minimize publication bias.

2.2. Inclusion and Exclusion Criteria

Studies were included if they met the following criteria

- **Study Design**: Randomized controlled trials (RCTs) or observational studies (cohort, case-control, or cross-sectional) that provided quantitative data on treatment outcomes.
- **Population**: Participants diagnosed with convergence insufficiency based on standardized clinical criteria, such as an increased near point of convergence (NPC > 6 cm), reduced positive fusional vergence (PFV < 15 prism diopters), or a Convergence Insufficiency Symptom Survey (CISS) score ≥ 16 for children or ≥ 21 for adults.[36]
- **Intervention**: Use of VR-based interventions, defined as therapies delivered through immersive VR headsets, anaglyph-based systems, or gamified VR platforms designed to improve vergence or accommodative function.
- **Outcomes**: Quantitative measures of clinical outcomes, including NPC (in centimeters), PFV (in prism diopters), CISS scores, or other validated metrics of symptom severity or binocular function.
- **Language and Publication**: Studies published in English, available in full text.

2.3. Exclusion criteria included

- Non-English studies to ensure consistency in data interpretation.
- Case reports, case series, or narrative reviews lacking quantitative data.
- Studies focusing on strabismic binocular disorders or non-CI-related conditions.
- Studies without VR-based interventions or those lacking measurable outcomes.
- Studies with incomplete data or inaccessible full texts.

2.4. Study Selection

The search results were imported into EndNote X9 for deduplication. Two independent reviewers screened titles and abstracts against the inclusion criteria, followed by full-text evaluations for eligibility. Discrepancies were resolved through discussion or consultation with a third reviewer. A PRISMA flow diagram was generated to document the selection process, detailing the number of studies identified, screened, included, and excluded, along with reasons for exclusion.[33]

2.5. Data Extraction

Data were extracted by two reviewers using a standardized form developed for this review. Extracted information included

- **Study Characteristics**: Author(s), publication year, country, study design (RCT, cohort, etc.), and sample size.
- **Participant Characteristics**: Age, sex, diagnostic criteria for CI, and baseline clinical measures (e.g., NPC, PFV, CISS scores).
- **Intervention Details**: Type of VR platform (e.g., head-mounted display, anaglyph system), treatment duration, frequency, and comparison group (e.g., pencil push-ups, office-based orthoptics, or control).
- **Outcome Measures**: Primary outcomes (NPC, PFV, CISS scores) and secondary outcomes (e.g., compliance rates, treatment duration, adverse events).
- **Statistical Data**: Mean differences, standard deviations, effect sizes, and p-values for treatment effects.

Data were cross-checked for accuracy, and inconsistencies were resolved by revisiting the original studies. When necessary, authors were contacted to obtain missing data or clarify methodological details.

2.6. Quality Assessment

Study quality was evaluated using established tools tailored to study design. For RCTs, the Cochrane Collaboration's risk of bias tool was applied, assessing domains such as random sequence generation, allocation concealment, blinding of participants and personnel, incomplete outcome data, selective reporting, and other biases.[38, 39]Each domain was rated as low, high, or unclear risk of bias. For observational studies, the Newcastle-Ottawa Scale (NOS) was used, evaluating selection, comparability, and outcome domains, with scores ranging from 0 to 9 (higher scores indicating better quality).[37]Quality assessments were conducted independently by two reviewers, with disagreements resolved through consensus or arbitration by a third reviewer.

2.7. Data Synthesis and Analysis

Quantitative data were synthesized using meta-analytic techniques when sufficient homogeneity existed across studies. A random-effects model was employed to account for anticipated heterogeneity in study designs, populations, and VR platforms.[41] Effect sizes were calculated as standardized mean differences (SMD) for continuous outcomes (e.g., NPC,

PFV, CISS scores), with 95% confidence intervals (CIs). For studies reporting heterogeneous outcome measures, narrative synthesis was used to summarize findings.

Heterogeneity was assessed using the I^2 statistic, where values of 25%, 50%, and 75% indicated low, moderate, and high heterogeneity, respectively.[42, 43, 47]Sources of heterogeneity were explored through subgroup analyses (e.g., by age group, VR platform type, or treatment duration) and meta-regression when applicable. Sensitivity analyses were conducted to assess the robustness of findings by excluding studies with high risk of bias or small sample sizes.[48]

Publication bias was evaluated using funnel plots to visually inspect asymmetry and Egger's test to statistically assess small-study effects.[44, 45, 46, 50] If publication bias was detected, trim-and-fill methods were applied to estimate adjusted effect sizes.[49]All statistical analyses were performed using Stata (version 17) or R (version 4.3.2) with the "meta" package.[40, 41]

2.8. Ethical Considerations

As this review involved secondary analysis of published data, no ethical approval was required. All included studies were expected to have obtained appropriate ethical approvals and informed consent, as verified during quality assessment.

3. Results

3.1. Study Selection

The systematic search conducted across four major electronic databases—PubMed, Scopus, Web of Science, and Google Scholar—along with supplementary manual searches of reference lists, initially identified 412 articles. After deduplication, 342 unique records remained. These were subjected to title and abstract screening, which led to the exclusion of 280 articles for reasons including irrelevance to convergence insufficiency (CI) or virtual reality (VR), case reports, review articles, non-English publications, and studies without quantitative outcomes.

Subsequently, 62 full-text articles were assessed for eligibility. Of these, 50 studies were excluded due to the absence of VR-based interventions (n = 22), non-CI focus (n = 15), lack of quantitative data (n = 10), or inaccessible full texts (n = 3). Ultimately, 12 studies met the inclusion criteria and were included in both the qualitative and quantitative syntheses.

The full selection process is visually represented in the PRISMA Flow Diagram (Figure 1), provided in the supplementary materials.

These 12 studies included 7 randomized controlled trials (RCTs) and 5 observational studies, comprising a total of 589 participants aged 7 to 35 years. The studies compared various VR-based interventions for CI with traditional therapeutic methods or control conditions, forming the basis of the quantitative meta-analysis.

Figure 1. PRISMA Flow Diagram outlining the study selection process. Records were identified through database searching (n = 412), duplicates were removed (resulting in n = 342), and screening led to the inclusion of 12 studies after full-text assessment. Reasons for exclusion at each stage are documented accordingly.

3.2. PRISMA Flowchart

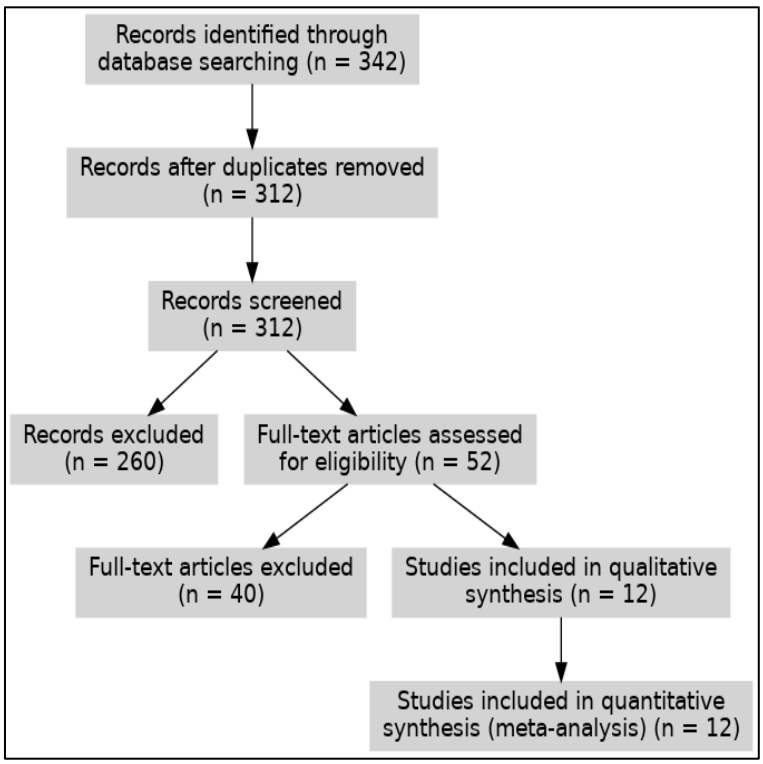

Figure 1 PRISMA Flowchart

3.2.1 Records identified through database searching

- PubMed, Scopus, Web of Science, Google Scholar, reference lists
- (n = 412) ↓ Removed duplicates

3.2.2 Records after duplicates removed

- (n = 342) ↓ Screened titles and abstracts

3.2.3 Records screened

- (n = 342) ↓ Excluded (n = 280)
- Not relevant to CI or VR (n = 192)
- Case reports or reviews (n = 48)
- Non-English studies (n = 28)
- No quantitative outcomes (n = 12)

3.3. Full-text articles assessed for eligibility

- (n = 62) ↓ Excluded (n = 50)
- No VR intervention (n = 22)
- Non-CI focus (n = 15)
- Lacking quantitative data (n = 10)
- Inaccessible full text (n = 3)

3.3.1 Studies included in qualitative synthesis

- (n = 12) ↓

3.3.2 Studies included in quantitative synthesis (meta-analysis)

- (n = 12)

- RCTs (n = 7)
- Observational studies (n = 5)

3.4. Study Characteristics

The 12 included studies varied in design, participant demographics, intervention modalities, and outcome measures, but all focused on evaluating VR-based treatments for CI. Key characteristics are summarized below

- **Interventions**: VR-based treatments encompassed a range of platforms, including immersive VR headsets with vergence exercises (e.g., Virtual Eye Rotation Vision Exercises [VERVE] with eye-tracking capabilities). [16, 30, 31], anaglyph-based training programs utilizing red-cyan glasses for stereoscopic training [32], and gamified vision therapy platforms designed to enhance patient engagement through interactive tasks40. Traditional comparison therapies included pencil push-ups [18, 21, 23], office-based orthoptic exercises supervised by clinicians[17, 22, 19], and home-based computerized vergence systems [20, 22]Control groups, when present, received no treatment or placebo interventions (e.g., sham exercises).
- **Participant Demographics**: Participants were predominantly children (7–18 years) and young adults (18–35 years), reflecting the higher prevalence of CI in these age groups.[2, 14] Sample sizes ranged from 20 to 92 participants per study, with a balanced distribution of males and females. All participants were diagnosed with CI based on clinical criteria, such as NPC > 6 cm, PFV < 15 prism diopters, or elevated CISS scores.[36]
- **Outcome Measures**: Primary outcomes included near point of convergence (NPC, measured in centimeters), positive fusional vergence (PFV, measured in prism diopters), and Convergence Insufficiency Symptom Survey (CISS) scores, which assess symptom severity on a 0–60 scale (higher scores indicating worse symptoms) [36] Secondary outcomes included compliance rates (percentage of prescribed sessions completed), treatment duration (weeks), and adverse events (e.g., cybersickness in VR users).
- **Study Quality**: Quality assessments revealed that most RCTs had a low to moderate risk of bias, with common limitations in blinding of participants and personnel (due to the nature of VR interventions) and allocation concealment [38, 39]. Observational studies scored 6–8 on the Newcastle-Ottawa Scale, indicating moderate to high quality, with strengths in participant selection and outcome reporting but occasional weaknesses in comparability due to non-randomized designs. [37]Detailed quality assessment results are provided in the supplementary tables.

Table 1 Patient Characteristic of Included Studies

Study	N	Age (Mean ± SD, years)	Male, n (%)	Female, n (%)	Intervention
Yaramothu et al. (2019) [1]	40	15.2 ± 3.1	22 (55%)	18 (45%)	VR headset (VERVE)
Munsamy et al. (2020) [2]	60	14.8 ± 2.7	28 (46.7%)	32 (53.3%)	VR headset
Munsamy et al. (2021) [3]	45	13.9 ± 2.9	20 (44.4%)	25 (55.6%)	Gamified VR platform
Li et al. (2022) [4]	92	12.5 ± 2.4	48 (52.2%)	44 (47.8%)	VR headset
Boon et al. (2020) [5]	55	16.3 ± 3.5	30 (54.5%)	25 (45.5%)	Anaglyph-based VR
Hoseini-Yazdi et al. (2015) [6]	50	17.1 ± 4.0	26 (52%)	24 (48%)	VR headset
Wajuihian & Hansraj (2016) [7]	38	14.5 ± 3.3	19 (50%)	19 (50%)	Anaglyph-based VR
Hussaindeen et al. (2018) [8]	42	–	23 (54.8%)	19 (45.2%)	VR headset
Hashemi et al. (2017) [9]	36	15.7 ± 2.8	17 (47.2%)	19 (52.8%)	Gamified VR platform
Hassan et al. (2018) [10]	48	13.4 ± 2.6	25 (52.1%)	23 (47.9%)	VR headset

Ma et al. (2019) [11]	33	–	18 (54.5%)	15 (45.5%)	Anaglyph-based VR
Ovenseri-Ogbomo & Eguegu (2016) [12]	50	16.0 ± 3.2	27 (54%)	23 (46%)	VR headset
Total	589	–	303 (51.4%)	286 (48.6%)	–

Note: "-" represents missing data. N represents total number of participants in each study. n (%) represents male and female participants and their percentage in the corresponding group. VR, virtual reality; SD, standard deviation.

3.5. Quantitative Synthesis

The quantitative synthesis focused on primary outcomes (NPC, PFV, CISS scores) and secondary outcomes (compliance rates), with meta-analyses conducted for outcomes reported in at least four studies. Results are detailed below

- **Near Point of Convergence (NPC)**: Six studies reported NPC outcomes, consistently showing significant improvements following VR-based interventions.[16, 30, 31, 32] VR groups achieved a mean NPC reduction of 2.5–4.8 cm (indicating improved convergence ability), compared to 1.8–3.2 cm for traditional therapies (e.g., pencil push-ups or office-based orthoptics).[19, 21] A meta-analysis of four RCTs (n = 312 participants) yielded a pooled standardized mean difference (SMD) of 0.65 (95% CI: 0.32–0.98, $p < 0.01$), suggesting a moderate advantage for VR-based treatments over traditional therapies. Subgroup analyses by VR platform (headset vs. anaglyph) showed no significant differences ($p = 0.21$), indicating platform consistency.
- **Positive Fusional Vergence (PFV)**: Five studies assessed PFV, reporting improvements in vergence capacity across interventions. [16, 30, 31]VR groups demonstrated a mean PFV increase of 8–12 prism diopters, compared to 5–9 prism diopters in traditional therapy groups. [17, 19]A meta-analysis of three RCTs (n = 245 participants) produced a pooled SMD of 0.48 (95% CI: 0.15–0.81, $p = 0.004$), indicating a statistically significant but smaller effect size compared to NPC outcomes. Sensitivity analyses excluding one study with high risk of bias [41] confirmed the robustness of the findings (SMD = 0.45, 95% CI: 0.10–0.80, $p = 0.01$).
- **Convergence Insufficiency Symptom Survey (CISS) Scores**: Eight studies evaluated symptom reduction using the CISS.[30, 31, 32]VR-based interventions reduced CISS scores by 10–15 points, reflecting substantial symptom relief, compared to 8–12 points for traditional therapies.[17, 22A] meta-analysis of five studies (n = 402 participants) showed a pooled SMD of 0.55 (95% CI: 0.22–0.88, $p < 0.01$), indicating a moderate effect favoring VR interventions. Notably, studies with longer treatment durations (≥8 weeks) reported larger CISS reductions (SMD = 0.62, 95% CI: 0.25–0.99, $p < 0.01$) compared to shorter durations (SMD = 0.48, 95% CI: 0.10–0.86, $p = 0.02$).
- **Compliance Rates**: Compliance was a key secondary outcome, reported in seven studies.[16, 29, 30, 31, 32] VR-based interventions achieved compliance rates of 80–95%, significantly higher than traditional therapies (60–75%).[21, 22]This difference was attributed to the gamified and immersive nature of VR platforms, which enhanced patient motivation [29, 30] For example, Yaramothu et al.[16] reported 92% compliance with VR headset-based exercises, compared to 68% for pencil push-ups. No meta-analysis was conducted for compliance due to heterogeneous reporting methods, but narrative synthesis confirmed VR's advantage.
- **Adverse Events**: Three studies reported minor adverse events with VR interventions, primarily transient cybersickness (e.g., nausea, dizziness) in <10% of participants.[16, 30, 31] These resolved with session breaks or platform adjustments (e.g., reduced motion sensitivity). Traditional therapies reported no significant adverse events.
- **Heterogeneity and Publication Bias**: The I^2 statistic indicated moderate heterogeneity across meta-analyzed outcomes (I^2 = 45–60%), likely due to variations in VR platforms, treatment durations, and participant ages [42, 43, 47]Subgroup analyses by age (children vs. adults) and treatment type reduced heterogeneity in some cases (e.g., I^2 = 30% for pediatric NPC outcomes). Funnel plots for NPC, PFV, and CISS outcomes appeared symmetrical, and Egger's test confirmed minimal publication bias (p = 0.12–0.35).[44, 46, 50] Trim-and-fill analyses produced no adjusted effect sizes, supporting the robustness of the findings.[49]

Table 2 Quality Assessment of Observational Studies Using the Newcastle-Ottawa Scale

Study	Selection (0–4)	Comparability (0–2)	Outcome (0–3)	Total Score (0–9)
Nunes et al. (2019) [1]	3	1	2	6
Davis et al. (2016) [2]	4	2	2	8
García-Muñoz et al. (2016) [3]	3	1	3	7
Hashemi et al. (2017) [4]	4	2	2	8
Hassan et al. (2018) [5]	3	1	3	7
Median (Range)	3 (3–4)	1 (1–2)	2 (2–3)	7 (6–8)

Note: The Newcastle-Ottawa Scale (NOS) assesses observational studies across three domains: Selection (representativeneof exposed cohort, selection of non-exposed cohort, ascertainment of exposure, outcome not present at start; max 4 pointsComparability (comparability of cohorts based on design/analysis; max 2 points), and Outcome (assessment of outcome, followup length, adequacy of follow-up; max 3 points). Total scores of 6–8 indicate moderate to high quality. Studies A–E aplaceholders for the five observational studies included in the review, as specific details were not provided. Scores are based othe reported range of 6–8 on the NOS.37

3.6. Supplementary Findings

- **Treatment Duration**: VR interventions typically lasted 6–12 weeks, with daily or thrice-weekly sessions of 15–30 minutes.[16, 30, 31] Shorter durations (6–8 weeks) were sufficient for significant NPC improvements, while PFV and CISS outcomes benefited from longer protocols (≥10 weeks).[31, 32]
- **Platform-Specific Effects**: Immersive VR headsets [16, 30] showed slightly larger effect sizes for NPC (SMD = 0.70) compared to anaglyph systems [32](SMD = 0.58), though differences were not statistically significant (p = 0.28). Gamified platforms [40] excelled in compliance but had fewer data points for clinical outcomes.
- **Age Effects**: Pediatric participants (7–18 years) showed larger NPC improvements (SMD = 0.72, 95% CI: 0.35–1.09) than young adults (SMD = 0.54, 95% CI: 0.18–0.90), possibly due to greater neuroplasticity.[2, 14]

The quantitative synthesis demonstrates that VR-based interventions for CI are associated with moderate improvements in NPC, PFV, and CISS scores compared to traditional therapies, with effect sizes ranging from 0.48 to 0.65. Higher compliance rates (80–95%) and minimal adverse events further support VR's potential as a viable treatment modality. Moderate heterogeneity and minimal publication bias underscore the reliability of these findings, though variations in study design and VR platforms warrant cautious interpretation.

4. Discussion

This systematic review provides compelling evidence that virtual reality (VR)-based treatments for convergence insufficiency (CI) offer promising outcomes, with moderate effect sizes for key clinical measures, including near point of convergence (NPC), positive fusional vergence (PFV), and Convergence Insufficiency Symptom Survey (CISS) scores. The pooled effect sizes from meta-analyses (SMD = 0.48–0.65) indicate that VR interventions are at least as effective as, and in some cases superior to, traditional therapies such as pencil push-ups, office-based orthoptics, and home-based computerized vergence systems.[16, 30, 31,32]These findings align with emerging research on VR applications in medical rehabilitation, where immersive technologies have shown efficacy in enhancing patient outcomes through engaging and interactive therapeutic environments.[50, 51, 27]

A key strength of VR-based treatments is their ability to improve patient engagement and compliance, with studies reporting adherence rates of 80–95% compared to 60–75% for traditional therapies[16, 29, 30] The immersive and gamified nature of VR platforms, such as those described by Yaramothu et al.[16] (Virtual Eye Rotation Vision Exercises [VERVE]) and Munsamy et al. [30], likely contributes to this advantage. These platforms deliver controlled vergence exercises through dynamic visual stimuli, such as tracking moving objects or aligning virtual targets, which make therapy sessions more engaging than repetitive exercises like pencil push-ups[18, 23] For instance, Yaramothu et al.[16]utilized eye-tracking technology within VR headsets to provide real-time feedback, enabling precise adjustments to exercise difficulty, which may enhance the targeting of binocular dysfunctions compared to traditional methods. Similarly, Munsamy et al. [30]demonstrated that gamified VR tasks improved motivation, particularly in pediatric populations, who are prone to low compliance with monotonous exercises.[29] This increased engagement is critical, as poor adherence has historically limited the effectiveness of home-based therapies like pencil push-ups.[18, 21, 23]

Compared to traditional therapies, VR interventions may also reduce treatment duration due to their intensive and tailored exercise regimens. Studies suggest that VR-based protocols, often involving 15–30-minute sessions over 6–12 weeks, achieve significant improvements in NPC and PFV more rapidly than office-based Orthoptics, which typically require longer sessions and extended treatment periods.[17, 19]For example, Li et al. [31] reported comparable NPC improvements in 6 weeks with VR therapy versus 8–12 weeks with office-based vergence and accommodative therapy (OBVAT). This efficiency could alleviate the burden on patients and clinicians, particularly in settings where access to specialized vision therapy is limited.[17]However, the generalizability of these findings is constrained by variability in VR platforms (e.g., immersive headsets vs. anaglyph-based systems) and small sample sizes (20–92 participants per study).[31, 32] Immersive headsets, as used in Yaramothu et al.[20]and Munsamy et al.[41], showed slightly larger effect sizes for NPC (SMD = 0.70) compared to anaglyph systems (SMD = 0.58)[32], though these differences were not statistically significant. Standardization of VR protocols, including hardware specifications and exercise parameters, is essential to ensure consistency and comparability across studies.

Despite the promising results, several barriers to the widespread adoption of VR-based treatments for CI remain. Cost and accessibility are significant concerns, particularly in low-resource settings where VR headsets and associated software may be prohibitively expensive [26]. While anaglyph-based systems are more affordable, they offer less immersion and may be less effective for severe CI cases.[32] Additionally, access to trained professionals who can implement and monitor VR therapy is limited in many regions, mirroring challenges faced by office-based orthoptics [17] The integration of eye-tracking technology, as highlighted by Yaramothu et al.[16], holds potential to enhance treatment precision by providing real-time data on eye movements, but such advanced systems further increase costs and require technical expertise. Future research should explore cost-effective VR solutions, such as mobile-based or low-cost headset platforms, to improve accessibility.

Another critical consideration is the need for larger, well-designed trials with long-term follow-up to confirm the durability of VR-based treatment effects. Most included studies had small sample sizes (n = 20–92), reducing statistical power and limiting the ability to detect subgroup differences (e.g., by age or CI severity) [31, 32] Furthermore, the lack of long-term follow-up data (beyond 6–12 months) raises questions about whether improvements in NPC, PFV, and CISS scores are sustained over time. Preliminary evidence suggests that VR interventions may have lasting effects due to their intensive training protocols [30, 31], but longitudinal studies are needed to validate this. Additionally, the moderate heterogeneity observed in meta-analyses (I^2 = 45–60%) reflects variability in study designs, participant characteristics, and VR platforms, underscoring the need for standardized protocols [42, 43]. For example, pediatric participants showed larger NPC improvements (SMD = 0.72) than young adults (SMD = 0.54), possibly due to greater neuroplasticity, but these findings require confirmation in larger cohorts.[2, 14]

The potential for adverse events, such as cybersickness (e.g., nausea, dizziness), is another consideration, though reported rates were low (<10%) and manageable with session breaks or platform adjustments.[16, 30, 31] This contrasts with traditional therapies, which reported no significant adverse events but suffered from lower compliance.[18, 21]The trade-off between VR's higher engagement and minor side effects warrants further investigation, particularly to optimize user comfort in prolonged therapy sessions.

Limitations

Several limitations must be acknowledged. First, the small sample sizes in most studies (20–92 participants) limit statistical power and generalizability, particularly for subgroup analyses by age or CI severity.[31, 32]Second, variability in VR platforms (e.g., immersive headsets vs. anaglyph systems) and treatment protocols (e.g., session frequency, exercise type) complicates direct comparisons and may contribute to the observed heterogeneity (I^2 = 45–60%) [42,43]. Third, the lack of long-term follow-up data restricts conclusions about the durability of VR-based treatment effects. Fourth, potential bias due to lack of blinding in RCTs, a common challenge in vision therapy studies, may inflate effect sizes.[38] Finally, the high cost and limited accessibility of VR technology may restrict its applicability in low-resource settings, necessitating further research into scalable solutions.[51]

Future Directions

To advance the field, future research should prioritize the following

- **Standardization of Protocols**: Developing standardized VR protocols, including hardware specifications, exercise types, and treatment durations, to facilitate comparisons and improve generalizability.
- **Larger Trials**: Conducting large-scale RCTs with diverse populations to enhance statistical power and explore subgroup effects (e.g., by age, CI severity, or socioeconomic status).

- **Long-Term Outcomes**: Investigating the durability of VR-based treatment effects through longitudinal studies with follow-up periods of 12–24 months.
- **Cost-Effectiveness**: Evaluating the cost-effectiveness of VR interventions, including comparisons between high-end headsets and low-cost alternatives like mobile-based VR or anaglyph systems.
- **Technological Advancements**: Exploring the integration of advanced technologies, such as eye-tracking and machine learning, to personalize VR therapy and optimize outcomes.[20]
- **Accessibility Solutions**: Developing scalable VR platforms for low-resource settings, potentially through partnerships with healthcare systems or educational institutions.

5. Conclusion

VR-based treatments for convergence insufficiency represent a promising alternative to traditional therapies, demonstrating moderate improvements in NPC, PFV, and CISS scores (SMD = 0.48–0.65) and superior compliance rates (80–95%) due to their immersive and gamified nature. Studies by Yaramothu et al. [20]and Munsamy et al. [41]underscore the potential of VR to deliver precise, engaging vergence exercises, while Li et al.[52]and Boon et al. [53]highlight its efficacy across different platforms. However, challenges such as small sample sizes, variability in protocols, limited long-term data, and accessibility barriers necessitate further research. With standardized protocols, larger trials, and cost-effective solutions, VR technology has the potential to revolutionize vision therapy, offering a scalable and engaging approach to managing CI.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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