

# Efficacy Evaluation of Virtual Reality in Cognitive and Psychological Rehabilitation After Brain Injury: A Systematic Review and Meta-Analysis

Min Zhang<sup>1</sup>, Erping Wang<sup>2</sup>, Hua Shan<sup>1</sup>, Suijun Zhu<sup>1</sup>

<sup>1</sup>Department of Neurosurgery, The First People's Hospital of Linping District, Hangzhou, Zhejiang, People's Republic of China; <sup>2</sup>Department of Urology, The First People's Hospital of Linping District, Hangzhou, Zhejiang, People's Republic of China

Correspondence: Min Zhang, Department of Neurosurgery, The First People's Hospital of Linping District, Hangzhou, Zhejiang, People's Republic of China, Email Zm15958015768@outlook.com

**Background:** Virtual reality technology, as an emerging intervention method, has garnered widespread attention in recent years for the rehabilitation of cognitive and psychological functions in patients with brain injuries. However, systematic evidence regarding its efficacy remains inconsistent. This study aims to evaluate the comprehensive effects of VR intervention in improving cognitive function, alleviating depressive symptoms, and enhancing self-efficacy in patients with brain injuries through a meta-analysis.

**Methods:** This study conducted literature search and screening in accordance with the PRISMA guidelines. The literature search databases included PubMed, Web of Science, Wiley Library, and OVID. Randomised controlled trials and observational studies were included, and the assessment metrics included MoCA, FAB, WEIGL Test, TMT-BA, HRS-D, and self-efficacy scores. The pooled analysis of effect sizes was performed using RevMan 5.4, with the  $I^2$  statistic employed to assess heterogeneity. Either a fixed-effect or random-effects model was selected based on the observed heterogeneity. Sensitivity analysis and publication bias testing were subsequently conducted.

**Results:** This Meta-analysis synthesised nine studies with a total of 279 brain-injured patients to assess the effect of virtual reality intervention. The experimental group showed a statistically significant improvement in MoCA scores compared to the control group ( $P < 0.00001$ ). FAB score analysis also showed a statistically significant improvement ( $P = 0.0007$ ). The results of the combined analysis of the WEIGL Test scores combined analysis showed a mean difference of 2.39 ( $P < 0.00001$ ), and a decrease in HRS-D scores also indicated that the VR intervention may be beneficial in alleviating depressive symptoms ( $P = 0.02$ ). However, improvements in TMT-BA scores ( $P = 0.10$ ) and self-efficacy scores ( $P = 0.43$ ) did not reach statistical significance.

**Conclusion:** The VR intervention demonstrated potential benefits in improving cognitive functioning and alleviating depressive symptoms in brain-injured patients, but the effect on self-efficacy was not significant. Although some studies showed high heterogeneity, the overall results support the value of VR in brain injury rehabilitation.

**Keywords:** virtual reality exposure therapy, traumatic brain injury, cognitive rehabilitation, self-efficacy, meta-analysis

## Introduction

Virtual Reality (VR) is a computer-generated three-dimensional interactive environment that allows users to immerse themselves in simulated real or fantastical worlds through multisensory inputs such as vision, hearing, and touch. Depending on system design and user experience, VR can be categorized into non-immersive (eg, desktop VR), semi-immersive (eg, projection or large-screen interactive systems), and fully immersive (eg, Head-Mounted Display [HMD] combined with motion tracking) intervention forms.<sup>1</sup> The level of immersion in a VR system is a critical factor influencing its rehabilitation efficacy, as it determines the user's sense of "presence" and engagement, thereby affecting neuroplasticity activation and rehabilitation motivation. Particularly in the field of neurological rehabilitation, VR technology has garnered significant attention in recent years and has become a major research focus.<sup>2,3</sup> With the rapid development of technology, VR has shown significant advantages in creating complex and controllable therapeutic

environments. Especially in the field of brain injury rehabilitation therapy, VR technology demonstrates great potential for application.<sup>4</sup> Brain injury, including traumatic brain injury (TBI) and sequelae of cerebrovascular diseases (eg, post-stroke sequelae), frequently results in motor, cognitive, and sensory dysfunctions. These impairments pose significant challenges to patients' activities of daily living and substantially compromise their social participation and quality of life.<sup>5–8</sup> Moreover, recent studies have indicated that certain populations are more susceptible to TBI due to their lifestyle or occupational characteristics. Examples include athletes engaged in contact sports (such as football, boxing, ice hockey) and military veterans who have participated in combat operations. These groups exhibit a significantly higher incidence of TBI compared to the general population, often presenting with chronic, recurrent, or insidious features.<sup>9</sup> For these high-risk populations, VR technology has gradually demonstrated certain adaptability and efficacy in rehabilitation therapy. For instance, among military veterans, VR has been utilized for cognitive training, emotional regulation, and even interventions for post-traumatic stress disorder (PTSD). Preliminary studies indicate its positive effects on attention, memory recovery, and emotional control.<sup>10</sup> Similarly, in professional athletes, VR has been incorporated into early rehabilitation and retraining programs, aiding in the assessment of cognitive reaction speed and visual attention function, while potentially reducing the risk of recurrence.<sup>11</sup> Therefore, developing effective rehabilitation strategies to improve the quality of life for such patients has become a priority in public health policies and clinical practice.

VR technology provides a highly immersive and interactive rehabilitation environment that simulates close-to-reality scenarios, enabling patients to engage in cognitive training with multi-sensory stimulation in a safe and controlled virtual scenario, not only that, but VR interventions can also help patients to reduce anxiety and depressive symptoms by providing an immersive and distracting experience.<sup>12–14</sup> Compared with traditional rehabilitation methods, VR technology has shown to be unique in customising personalised treatment plans and enhancing patient engagement and motivation for rehabilitation.<sup>15–17</sup> Moreover, VR can track patients' rehabilitation performance and progress in real time, providing real-time data support for treatment decision-making. Although VR technology has been widely applied in cognitive training and emotional regulation for brain injury rehabilitation, and its overall efficacy has garnered attention, existing studies still show discrepancies in the evaluation of its effects across functional dimensions (such as cognitive function, depressive symptoms, and self-efficacy).<sup>18–20</sup> The current literature primarily focuses on the impact of VR on improving motor function recovery in patients with brain injuries.<sup>21</sup> However, studies have also demonstrated that VR technology plays a significant role in enhancing cognitive, emotional, and social functions. These studies indicate that VR devices employ advanced technologies capable of inducing comprehensive changes in cognitive, motor, and psychological domains. By creating a simulated environment, they can partially restore these functions and behaviors, as well as activities of daily living.<sup>22,23</sup> In clinical applications, the level of immersion in VR systems is a critical factor influencing intervention outcomes.<sup>24</sup> Virtual environments delivered via computer screens or mobile devices are easily accessible but offer lower immersion. Large projection screens or cave automatic virtual environment (CAVE) systems provide higher immersion, yet still fall short of full immersion. The use of head-mounted displays (HMDs) and motion-tracking devices delivers the strongest sense of immersion and interactivity. Fully immersive VR systems typically yield more significant improvements in patient rehabilitation outcomes compared to semi-immersive and non-immersive systems. This may be attributed to the fact that fully immersive systems more effectively activate the brain's multi-sensory integration mechanisms, thereby enhancing neuroplasticity and rehabilitation efficacy.<sup>25</sup>

Therefore, this study aims to systematically synthesize existing research evidence on the effects of VR interventions on cognition, mood (particularly depression), and self-efficacy in patients with brain injuries through a meta-analysis. Furthermore, it seeks to explore the relationship between intervention modalities (such as immersion level) and outcomes, thereby providing evidence-based medical support for the application of VR in brain injury rehabilitation.

## Methods

### Literature Search Strategy

Adhering strictly to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines,<sup>26</sup> the systematic review protocol was registered with PROSPERO (CRD420251074636). In order to comprehensively grasp the application and utility of virtual reality in brain injury rehabilitation therapy, we adopt a systematic literature

search strategy. Firstly, searches were conducted in major academic databases at home and abroad, including PubMed, Web of Science, Wiley Library and OVID. Secondly, keywords were selected around three core concepts: VR, brain injury and Rehabilitation. The search formula was constructed using Boolean operators to combine these keywords and terms: (“virtual reality” OR “augmented reality” OR VR) AND (“brain injury” OR “traumatic brain injury” OR “neurological injury” OR “cerebral injury” OR “brain damage” OR “stroke” OR “cerebrovascular accident”) AND (rehabilitation OR therapy OR treatment). The search period for each database was limited to 2005–18 January 2024, and the search language was English only. As far as applicable, the review was conducted according to the PRISMA guideline.<sup>26</sup>

## Inclusion and Exclusion Criteria

### Inclusion Criteria

- (1) Study types: Randomized controlled trials (RCTs), prospective or retrospective cohort studies, case - control studies, etc.
- (2) Study population: Patients with brain injury, including those with traumatic brain injury (TBI) and sequelae of cerebral vascular accidents (eg, strokes and aneurysm ruptures).
- (3) Interventions: Rehabilitative treatments using virtual reality technology.
- (4) Outcome indicators: Montreal Cognitive Assessment (MoCA), Frontal Assessment Battery (FAB), WEIGL Test, Trail Making Test – Form B - A (TMT - BA) (the result of TMT - BA was calculated as the time difference between TMT - B and TMT - A), and self - efficacy scores.

These scales are recommended by multiple consensus guidelines on brain injury rehabilitation for assessing cognitive and emotional functional recovery.<sup>27,28</sup> They demonstrate good sensitivity and specificity for detecting cognitive deficits, executive dysfunction, and depressive symptoms in patients with TBI and stroke.<sup>29</sup> Moreover, at least two of these scales were reported in over 90% of the studies included in our analysis,<sup>27,28,30–35</sup> indicating high data completeness that facilitates meta-analytic integration.

### Exclusion Criteria

- (1) Non - experimental studies (reviews, case reports, opinion articles, systematic reviews).
- (2) Repetitively published studies or those with duplicated data (only the most comprehensive or most recent one is included).
- (3) Studies with obvious methodological flaws or inappropriate statistical treatment.
- (4) Studies where the study population does not meet the definition of brain injury.

## Literature Screening and Data Extraction

The process of literature screening and data extraction in this study strictly followed a set process to ensure the quality and reliability of the Meta-analysis. Firstly, during the initial screening, two researchers independently excluded literature that was not relevant to the study topic based on the title and abstract, with the aim of narrowing down the scope of the study and focusing on potentially relevant studies. Subsequently, the initially screened literature was read in its entirety and more rigorously screened based on predetermined inclusion and exclusion criteria, with any doubtful literature being added to the discussion by a third researcher to decide whether or not to include it in the final analyses. For the screened and included literature, we extracted key information and data in detail, including study design, sample size, participant characteristics (eg, age, gender), details of the interventions and outcome assessment indicators, etc., which were independently performed by two researchers and cross-checked to ensure the accuracy and completeness of the data.

## Quality Assessment of Literature

The types of literature included in this paper included RCTs and case-control studies. The quality assessment of RCTs was conducted using the Cochrane Collaboration’s risk of bias tool, which encompasses multiple domains: random sequence generation, allocation concealment, blinding of participants and personnel, completeness of outcome data,

selective outcome reporting, and likelihood of other biases. Each domain was evaluated and categorized as “low risk”, “high risk”, or “unclear”. If at least four key domains (including random sequence generation, allocation concealment, blinding, completeness of outcome data) are rated as “low risk”, the study is considered to be of moderate or higher quality and meets the inclusion criteria. Quality assessment of the case-control studies was undertaken using the Newcastle-Ottawa Scale (NOS), an assessment tool that scores for the key areas of case selection, selection of comparison groups, and identification of exposure factors. The scoring for each domain is based on a set of predefined criteria, with a maximum total score of nine points. A score of  $\geq 6$  is considered indicative of high-quality research. The two researchers conducted the literature quality assessment separately, and in the event of disagreement on the assessment results, consensus was reached through discussion or consultation with third-party experts.

## Statistical Analysis

All statistical analyses were performed using RevMan 5.4 software (Cochrane Collaboration). For continuous variables (eg, MoCA, FAB scores), the mean difference (MD) with 95% confidence intervals (95% CI) was used as the effect measure. Study heterogeneity was evaluated using the following metrics: (1)  $I^2$  statistic: Quantifies heterogeneity magnitude ( $I^2 < 50\%$  = low heterogeneity;  $I^2 \geq 50\%$  = substantial heterogeneity); (2)  $\chi^2$ -test (Chi-square) with degrees of freedom (df): Assesses statistical significance of heterogeneity ( $p < 0.10$  indicates significant between-study heterogeneity); (3) Tau<sup>2</sup>: Estimates the variance of true effect sizes across studies in random-effects models. Based on the  $I^2$  results: (1) A fixed-effect model was applied when  $I^2 < 50\%$ ; (2) A random-effects model was used when  $I^2 \geq 50\%$ . The Z-value tested overall effect significance ( $|Z| > 1.96$  indicates  $p < 0.05$ ). Publication bias was assessed via funnel plot asymmetry, and sensitivity analysis was conducted using the leave-one-out method to evaluate the influence of individual studies. A two-sided p-value  $< 0.05$  was considered statistically significant.

## Results

### Results of Literature Search

The study selection process followed the PRISMA guidelines. A total of 1998 relevant articles were initially identified through the search. Following the removal of 286 duplicate records, the remaining 1712 entries underwent preliminary screening. After rigorous evaluation of abstracts, 1649 records were excluded, leaving 63 articles that qualified for full-text review. The literature that met the inclusion criteria was read and assessed in full, and 54 pieces of literature that did not meet the criteria were excluded, and nine pieces of literature were finally determined to be included in this Meta-analysis, covering seven RCTs and two case-control studies. The screening process is shown in [Figure 1](#).

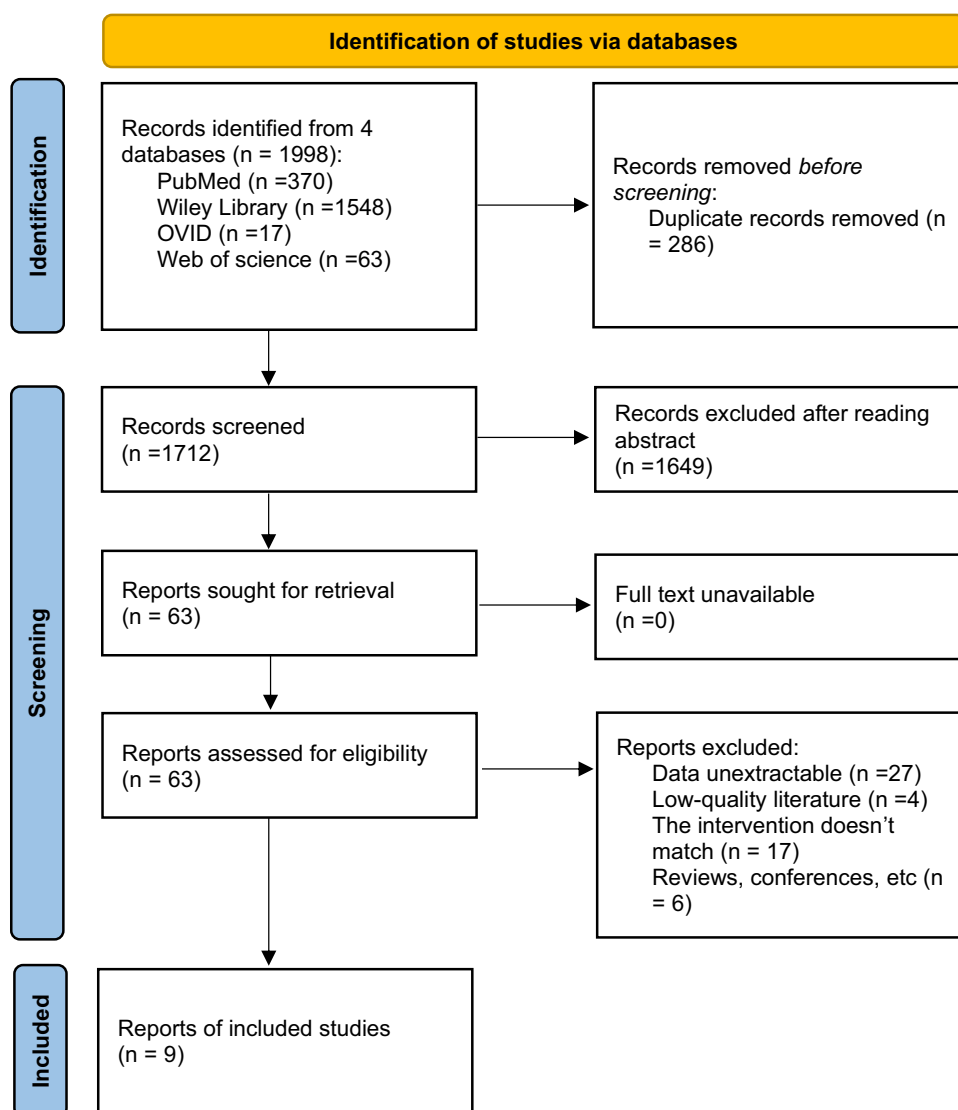
### Basic Characteristics of Included Studies and Evaluation of Literature Quality

The basic characteristics of the literature included in the Meta-analysis of this study cover a wide range of aspects such as study design, sample size, participant characteristics, interventions, and primary outcomes. The literature was mainly focused on RCTs and case-control studies, mostly RCTs, with the geographical area of the studies spanning several countries and regions, with a preponderance of studies in Italy, as shown in [Table 1](#). For the seven RCTs literature most of the studies were of relatively high quality, as shown in [Figure 2](#). The two case-control studies had NOS scale scores of  $>6$ . The nine included studies met the quality requirements of the present paper.

### Meta-Analysis Results

#### MOCA

In this section of the meta-analysis, we synthesized data from seven studies examining the effects of virtual reality interventions on MoCA scores in patients with brain injury, which is used to assess overall cognitive function following brain injury. The analysis revealed that the experimental group showed a significant improvement in MoCA scores compared to the control group, with a MD of 2.41 points (95% CI: 1.56–3.26,  $Z = 5.53$ ,  $P < 0.00001$ ). In addition, heterogeneity analysis revealed little difference between studies ( $I^2 = 0\%$ ), allowing us to ensure consistency of results with a fixed-effects model, as shown in [Figure 3](#). These findings highlight the effectiveness of virtual reality in brain



**Figure 1** Literature screening flowchart. OVID refers specifically to the OVID MEDLINE database.

injury rehabilitation therapy, especially in cognitive function improvement, and provide a solid evidence base for its further exploration in clinical applications.

### FAB

In this section of the meta-analysis, three studies were included to evaluate the effect of virtual reality intervention on improving the FAB scores in patients with brain injury, which is used to assess prefrontal executive functions. Data from a total of 88 patients in the experimental group versus 88 patients in the control group showed a statistically significant improvement in FAB scores in the experimental group compared to the control group, with a MD of 5.55 points and a 95% CI ranging from 2.35 to 8.74, as shown in [Figure 4](#). Despite the presence of a high degree of between-study heterogeneity ( $I^2 = 74\%$ ), the overall effect was still significant ( $Z = 3.40$ ,  $P = 0.0007$ ), which further confirms the value of virtual reality interventions in brain injury rehabilitation.

### WEIGL

In this section of the meta-analysis, by evaluating the WEIGL score for identifying categorization disorders caused by frontal lobe injuries, it was confirmed that virtual reality intervention can significantly improve cognitive function in

**Table 1** General Information on the Included Literature

Author	Year	Type of Study	Region	Sample Size		Age (Years)		Sex Ratio (Male/Female)		Interventions		The Goal of The Intervention	Rehabilitation Context	Session Frequency / Total Duration
				Experimental Group	Control Group	Experimental Group	Control Group	Experimental Group	Control Group	Experimental Group	Control Group			
Choi <sup>20</sup>	2021	RCT	Korea	40	38	3-6	4-7	19/21	19/19	Virtual reality intervention	Conventional treatment	Upper limb functional improvement in children with acquired brain injury	The VR rehabilitation system incorporates motion-enabled games using wearable inertial sensors to facilitate wrist and forearm joint mobilization	5 sessions/week × 5 weeks (30 min/session)
De Luca <sup>7</sup>	2023	RCT	Italy	10	10	46.2 ± 14.9	43.1 ± 17.9	5/5	4/6	Virtual Reality Cognitive Rehabilitation	Traditional cognitive training	Executive function and anxiety-depression symptoms in traumatic brain injury patients	Underwent VR-based rehabilitation training	3 sessions/week × 8 weeks (60 min/session)
De Luca <sup>36</sup>	2022	RCT	Italy	15	15	44.6 ± 14.44	42.53 ± 17.95	7/8	7/8	Non-immersive virtual reality	Traditional cognitive training	Attention and executive function	Custom-developed PC games built on Unity3D 5.5.2 platform	3 sessions/week × 4 weeks
De Luca <sup>8</sup>	2019	RCT	Italy	50	50	38.7±9.3	41.1 ±10.8	29/21	26/24	Semi-immersive virtual reality	Traditional cognitive training	Cognitive rehabilitation in TBI	Semi-immersive VR system	3 sessions/week × 8 weeks (60 min/session)
Jacoby <sup>14</sup>	2013	RCT	Israel	6	6	27.83±12.06	30.67 ±13.13	4/2	4/2	Virtual reality intervention	Conventional treatment	Executive function (planning/control)	Lokomat robotic exoskeleton with virtual scenario integration	2 sessions/week × 5 weeks (45 min/session)
Maggio <sup>15</sup>	2020	Case-control	Italy	28	28	47.6±12.4	47.6 ±12.3	18/10	18/10	Virtual reality intervention	Non-virtual reality intervention	Cognitive function (executive + attention)	Balance platform coupled with interactive visual biofeedback system	5 sessions/week × 8 weeks (60 min/session)

Man <sup>16</sup>	2013	Case-control	United States	20	20	/	/	/	/	Artificial Intelligence 3D Virtual Reality	Traditional intervention	Occupational problem-solving skills	Virtual supermarket shopping task; Training program formulation and execution	2–3 sessions/week × 6 weeks
Rogers <sup>18</sup>	2019	RCT	Australia	10	11	64.3±17.4	64.6 ±12.0	6/4	5/6	Elemental Virtual Rehabilitation	Conventional treatment	Integrated motor-cognitive function	AI-powered virtual workplace scenarios; 3D problem-solving simulations	2 sessions/week × 6 weeks
Tramontano <sup>19</sup>	2022	RCT	Italy	15	15	34.7 ± 12.8	36.8 ± 12.9	7/8	12/3	Virtual reality intervention	Conventional treatment	Dual-task training for gait coordination and cognition	Element VR system implementing context-embedded task-oriented training	Weekly

**Abbreviations:** RCT, randomized controlled trial; TBI, Traumatic Brain Injury.

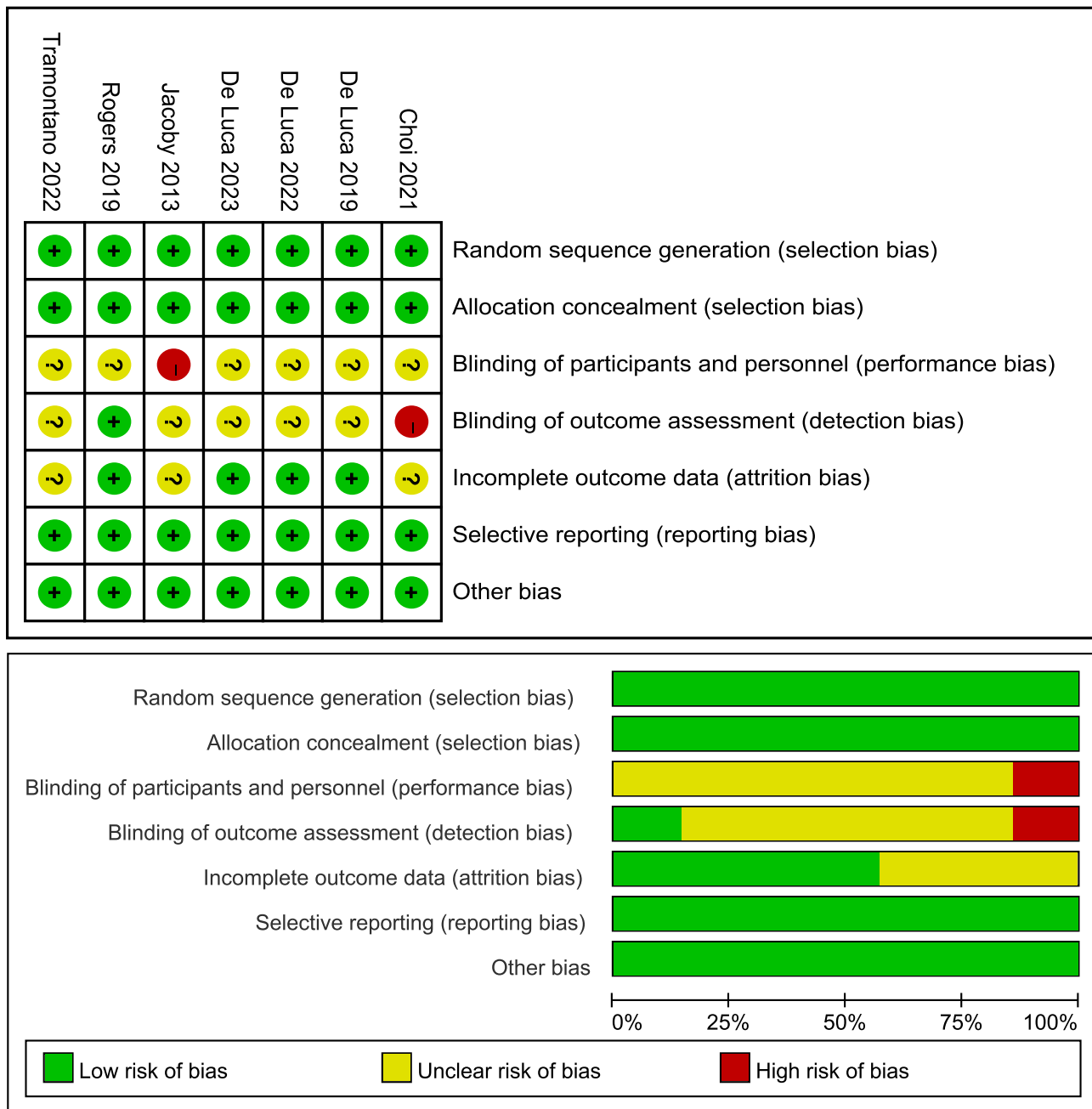
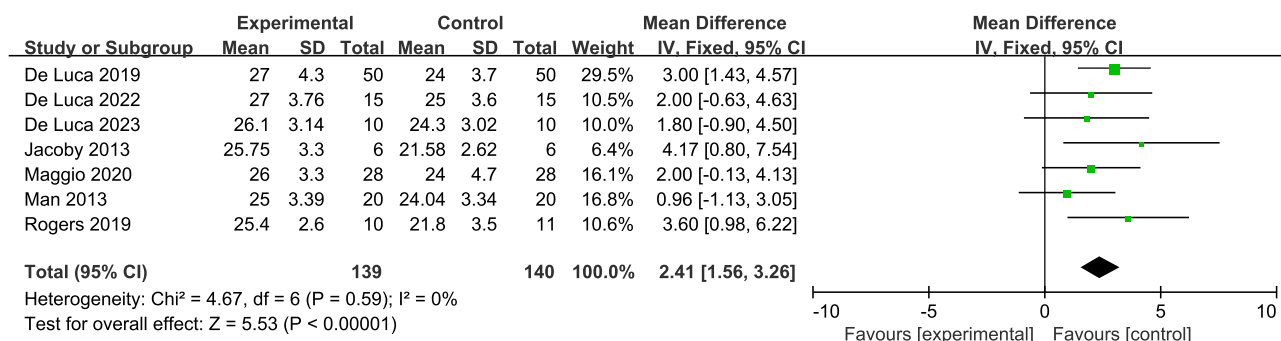


Figure 2 Evaluation of the quality of RCT literature. RCTs, randomized controlled trials.

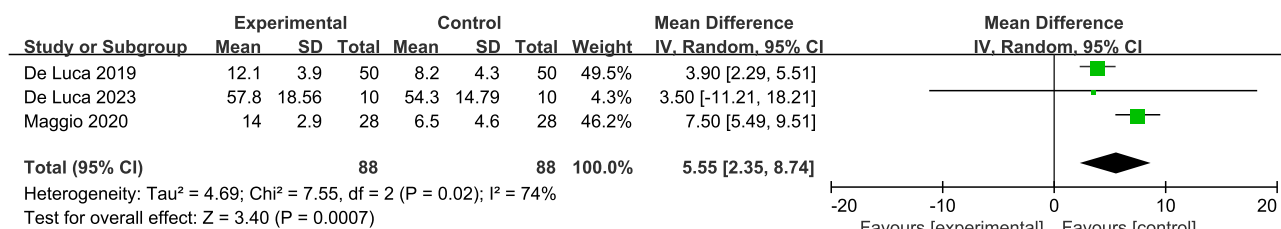
patients with brain injuries. The three studies with a total of 176 participants showed a statistically significant improvement in WEIGL scores in the experimental group compared to the control group, with a MD of 2.39 points (95% CI: 1.71 to 3.07) and an overall effect Z-value of 6.87 ( $p < 0.00001$ ), as shown in Figure 5. The between-study heterogeneity was found to be relatively low ( $I^2 = 37\%$ ), indicating statistically robust evidence supporting the cognitive rehabilitation efficacy of virtual reality-based interventions.

TMT-BA

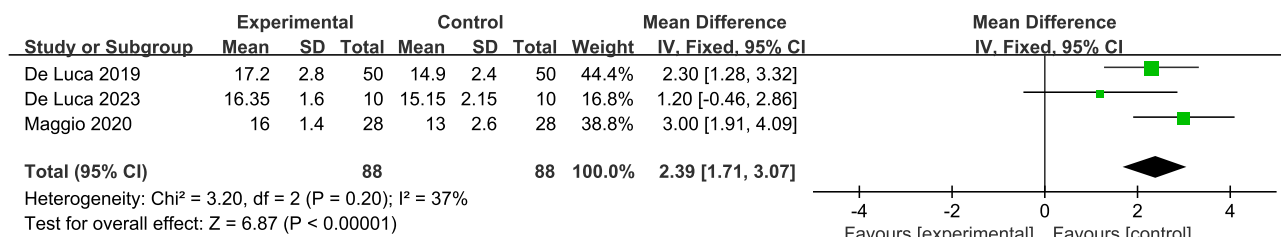
In this section of the analysis, we utilized the B-A time difference from the TMT-BA as the primary evaluation metric. This difference is obtained by subtracting the time taken to complete TMT-A from the time required for TMT-B, primarily reflecting cognitive flexibility, attention switching, and executive function. The analysis included four studies



**Figure 3** Forest plot of MoCA scores between the two groups.  
**Abbreviations:** CI, confidence intervals; SD, standard deviation; IV, instrumental variable.

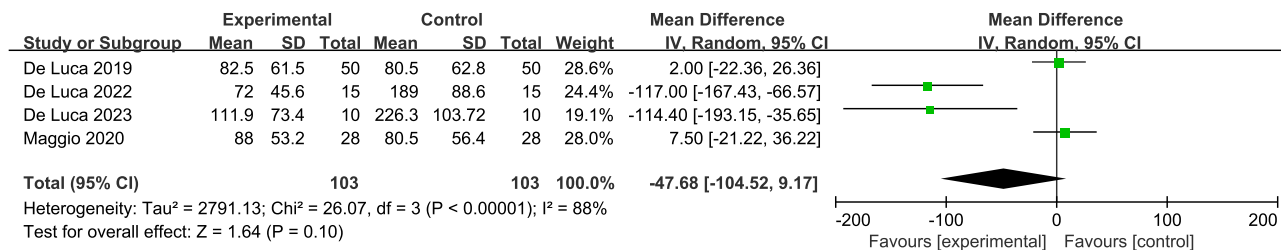


**Figure 4** Forest plot of FAB scores between the two groups.  
**Abbreviations:** CI, confidence intervals; SD, standard deviation; IV, instrumental variable.



**Figure 5** Forest plot of WEIGL scores between the two groups.  
**Abbreviations:** CI, confidence intervals; SD, standard deviation; IV, instrumental variable.

with a total of 206 participants (103 in the experimental group and 103 in the control group). Although the test of overall effect size was not significant (Z = 1.64, P = 0.10), the combined data revealed a MD in TMT-BA scores of -47.68 seconds (95% CI: -104.52 to 9.17) in the experimental group, suggesting that the virtual reality intervention may have a positive effect on reducing the time to complete the task. However, heterogeneity analysis revealed extremely high between-study variation (I<sup>2</sup> = 88%, p < 0.00001), as shown in Figure 6, implying significant differences between the results of these studies.



**Figure 6** Forest plot of TMT-BA scores between the two groups.  
**Abbreviations:** CI, confidence intervals; SD, standard deviation; IV, instrumental variable.

### HRS-D

In this part of the Meta-analysis, we assessed the effect of a virtual reality intervention on HRS-D scores, a scale used to rate the severity of depressive symptoms. The analyses involved four studies containing 171 participants each in the experimental and control groups. The results showed that the virtual reality intervention group showed a statistically significant reduction in HRS-D scores compared to the control group, with a MD of -3.36 points (95% CI: -6.29 to -0.42) and a Z-score of 2.24 ( $p = 0.02$ ), indicating an improvement in mild to moderate depressive symptoms. The high degree of between-study heterogeneity ( $I^2 = 89\%$ ,  $P < 0.00001$ ) suggests significant differences between outcomes, as shown in Figure 7, which may reflect the diversity of experimental designs, participant characteristics, or intervention modalities. Nonetheless, this analysis supports the potential effectiveness of virtual reality interventions in alleviating depressive symptoms in brain-injured patients.

### Self-Efficacy Scores

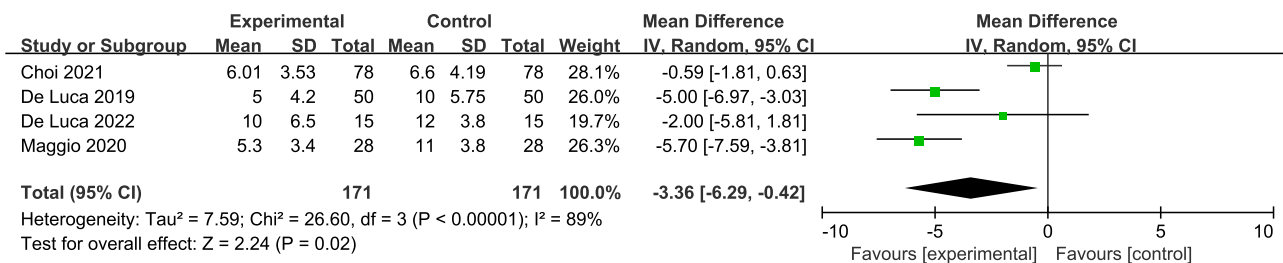
In this section of the meta-analysis, the impact of virtual reality intervention on self-efficacy scores was examined. Self-efficacy scores are commonly used to measure an individual’s confidence in their ability to successfully complete tasks. Two studies with a total of 70 participants (35 in the experimental group and 35 in the control group) were included. The combined results showed that despite some positive upward trend, the difference between the experimental and control groups on self-efficacy scores was not significant, with a MD of 3.17 points, a 95% CI of -4.72 to 11.05, and a Z-value of 0.79 ( $p = 0.43$ ). In addition, heterogeneity between these studies was low ( $I^2 = 0\%$ ,  $P = 0.44$ ), suggesting good consistency of results across studies, as shown in Figure 8. This finding suggests a limited impact of virtual reality interventions on improving self-efficacy in patients with brain injury, based on the current evidence base.

### Publication Bias Test

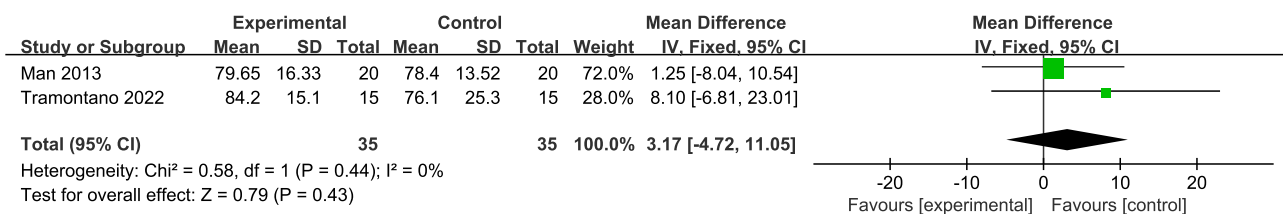
To assess the possible publication bias in this Meta-analysis, we used funnel plots as a visual detection tool. It was found that the distribution of studies presented in the funnel plot was relatively symmetrical, suggesting that there was no obvious publication bias, as shown in Figure 9.

### Sensitivity Analyses

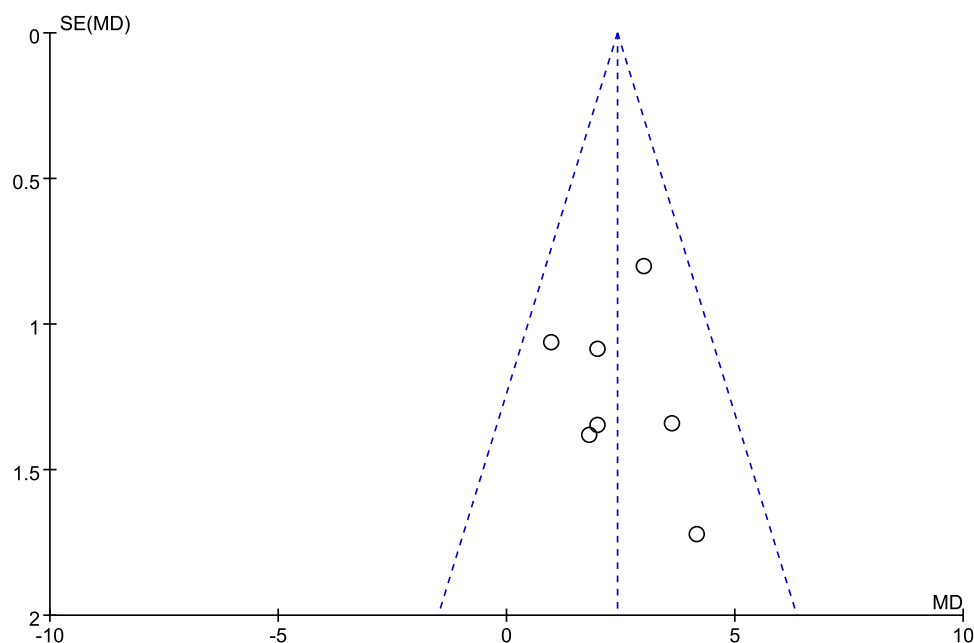
In this study, the results of our sensitivity analyses showed that although the removal of some studies resulted in changes in the effect sizes, the overall combined effect sizes and associated findings remained stable, indicating that the results of our Meta-analyses have a high degree of confidence.



**Figure 7** Forest plot of HRS-D scores between the two groups.  
**Abbreviations:** CI, confidence intervals; SD, standard deviation; IV, instrumental variable.



**Figure 8** Forest plot of self-efficacy scores between the two groups.  
**Abbreviations:** CI, confidence intervals; SD, standard deviation; IV, instrumental variable.



**Figure 9** Funnel plot test (MoCA as an example).

**Abbreviations:** MD, mean difference; SE(MD), standard error of the mean difference.

## Discussion

This meta-analysis systematically evaluates the intervention effects of VR technology in the rehabilitation of brain injuries, encompassing multiple dimensions such as cognitive function, self-efficacy, and emotional state. The study included a total of 9 literature sources meeting quality standards. The results demonstrated that VR interventions showed statistically significant improvements in scores on cognitive assessment scales such as MoCA, FAB, and WEIGL, as well as exhibited certain efficacy in alleviating depressive symptoms (indicated by reduced HRS-D scores). However, the outcomes in improving self-efficacy and the TMT-BA test were not significant.

VR intervention can significantly improve cognitive function in patients with brain injury, particularly in MoCA and FAB scores.<sup>8,12–15</sup> This may be due to the fact that VR technology provides a multi-sensory, interactive environment that enhances neuroplasticity and thus promotes recovery of cognitive function.<sup>1,37</sup> In addition, VR interventions have shown positive effects on alleviating depressive symptoms, which may be related to the immersive experience provided by VR, which can help patients to divert their attention from the traditional rehabilitation environment and reduce anxiety and depression.<sup>38–40</sup> However, although some studies have noted that by completing tasks in virtual environments, patients are able to obtain immediate feedback and a sense of achievement, which can help to enhance self-efficacy, our results did not show a significant positive effect, which may be due to the fact that the enhancement of self-efficacy requires longer interventions and more supportive social interactions,<sup>41–43</sup> which may have not yet been adequately realised.

The potential mechanisms by which VR interventions can improve functioning in brain-injured patients may involve several aspects; firstly, by providing a simulated reality, VR technology can stimulate the sensory and motor systems of the patient and facilitate the functional reconstruction of damaged areas in the brain.<sup>23,44</sup> Second, task-oriented training in VR environments can enhance neuroplasticity in the brain and help improve cognitive function.<sup>6,7</sup> In addition, gamification elements in VR can increase patient engagement and motivation, which can help adherence to the long-term rehabilitation process.<sup>34</sup> Moreover, among high-risk populations such as military personnel and participants in contact sports (eg, football, boxing, ice hockey), who frequently experience mild to moderate TBI, the demand for rehabilitation has garnered increasing attention.<sup>45</sup> Studies have shown that military personnel often suffer from post-traumatic stress disorder, cognitive decline, and emotional disturbances. Due to its controllable, customizable, and highly immersive features, VR systems have been applied in military rehabilitation for battlefield scenario simulations, attention training, and stress response modulation, demonstrating preliminary positive outcomes.

Similarly, professional athletes, who are prone to chronic traumatic encephalopathy due to repetitive head impacts, have seen VR technology integrated into early screening, cognitive assessment, and rehabilitation training protocols. This suggests that future research should focus on the differentiated application value of VR technology in populations with mild to moderate repetitive brain injuries and develop tailored intervention strategies based on their injury characteristics.

Here are the limitations of this study: First, the number of included studies is relatively limited, with some outcome measures (eg, self-efficacy) supported by data from only two studies, resulting in low statistical power and limiting the robustness and interpretability of the findings. Second, there is substantial heterogeneity among the studies, not only in terms of sample characteristics, injury types, and rehabilitation stages but also in the significant variations in parameters such as the types of VR systems, intervention content, frequency, and duration, which introduces some bias in the integration of results. Additionally, most studies did not adequately match or adjust for baseline characteristics between the intervention and control groups, and some studies lacked sufficient reporting of methodological details (eg, randomization procedures, blinding protocols, handling of missing data), compromising the comparability of overall study quality. Furthermore, there is currently a lack of long-term follow-up data, leaving the sustained effects and long-term rehabilitation outcomes of VR interventions unclear, which hinders the assessment of their sustainability and dynamic value across different rehabilitation stages. Moreover, some studies failed to report intervention adherence, acceptability, or potential adverse effects, creating gaps in the evaluation of VR interventions' feasibility and safety. Individual factors (eg, motivation levels, baseline cognitive status, adaptability to virtual environments) were also insufficiently controlled in most studies, which may further influence the interpretation of intervention effects. Finally, as a neuropsychological instrument assessing executive function, TMT exhibits substantial variability in performance outcomes. This variability is influenced by multiple factors, including individual differences (eg, age, baseline health status, severity of brain injury), testing conditions (eg, use of the non-dominant hand), and temporal factors (eg, testing sequence, participant familiarity with the task).<sup>35–37</sup>

In conclusion, although the findings of this study demonstrate the positive effects of VR technology in improving cognitive function and alleviating depressive symptoms in patients with brain injuries, there remain limitations in identifying the optimal system type, adapting to population characteristics, and matching rehabilitation stages. Future research should focus on standardized interventions, individualized assessments, and cross-stage longitudinal tracking to establish a more robust evidence base for the precise application of VR technology in brain injury rehabilitation.

## Data Sharing Statement

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

## Ethics Statement

As this study involves the summary and analysis of other studies, it does not involve medical ethics approval or patient-informed consent.

## Funding

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## Disclosure

The authors have no conflicts of interest to declare.

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