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Submitted to: Journal of Medical Internet Research
on: March 10, 2025

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Abstract

Background: In recent years, digital technologies have shown possibilities for improving cognitive function after stroke, but their effectiveness and treatment options vary, the optimal treatment remains unclear, and the current evidence is somewhat contradictory.

Objective: To evaluate the efficacy of various digital interventions in improving post-stroke cognitive function and provide evidence-based support for clinical decision-making.

Methods: This study adhered to the PRISMA guidelines for systematic review. We conducted searches in PubMed, Web of Science, Cochrane Library, Scopus, EMBASE, and CNKI databases from inception to January 2025. Outcomes included the Mini-Mental State Examination (MMSE) and Montreal Cognitive Assessment (MoCA). Randomized controlled trials (RCTs) were included.

Results: A total of 2,128 articles were retrieved, with 27 meeting the inclusion criteria. Compared to conventional rehabilitation or care, computer-assisted cognitive therapy (CACT) demonstrated significant superiority in MoCA scores (MD=2.36, 95% CI=1.45 to 3.27; SUCRA=83.2%); while cognitive training (CCT) demonstrated no statistical difference (MD=0.28, 95% CI=?0.81 to 1.37). For MMSE scores, robot-assisted therapy (RAT) ranked highest in efficacy (MD=5.77, 95% CI=3.47–8.08; SUCRA=99%); whereas both virtual reality (VR) (MD=0.69, 95% CI=?0.93 to 2.31) and CCT (MD=0.78, 95% CI=?1.19 to 2.75) showed no significant improvement.

Conclusions: Digital therapies effectively improve cognitive function in post-stroke patients. CACT exhibited superior efficacy in MoCA (which emphasizes executive function), while RAT ranked highest in MMSE (which focuses on basic cognition), suggesting distinct domain-specific effects. However, caution is warranted due to heterogeneity, risk of bias, and limited sample sizes in the included studies. Future research should focus on optimizing intervention protocols, integrating neuroregulatory or traditional Chinese rehabilitation techniques, and exploring cost-effective strategies for clinical implementation. Clinical Trial: CRD420251006601

(JMIR Preprints 10/03/2025:73687)
DOI: https://doi.org/10.2196/preprints.73687

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Original Manuscript

Digital therapies for post-stroke cognitive impairment: the first network meta-analysis comparing virtual reality, computer-assisted, and robotic interventions

Abstract

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To evaluate the efficacy of various digital interventions in improving post-stroke cognitive function and provide evidence-based support for clinical decision-making.

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Keywords: Stroke, cognitive impairment, virtual reality, computer-assisted therapy, robotics, cognitive training.

Introduction

Post-stroke cognitive impairment (PSCI) is a debilitating complication that affects functional recovery and quality of life in stroke survivors, with a prevalence exceeding 70% [1]. Cognitive deficits typically span multiple domains [2], including attention, memory, executive function, and spatial orientation. These deficits not only compromise patients' independence in daily activities but also contribute to psychological comorbidities through impaired self-efficacy such as depression and anxiety [3]. Left untreated, PSCI may progress to dementia [4]. Conventional cognitive rehabilitation methods (e.g., paper-based exercises, occupational therapy) remain widely used in clinical practice. However, their efficacy is constrained by standardization deficiencies, low personalization, and repetitive task paradigms lacking ecological validity. These challenges are particularly pronounced in resource-constrained healthcare settings, where long-term accessibility is hindered by workforce shortages and inequitable resource allocation.

The rapid advancement of digital technologies offers novel avenues for post-stroke cognitive rehabilitation. Virtual reality (VR) leverages immersive environments to integrate multisensory stimulation with task-oriented training[5], demonstrating unique advantages in enhancing visuospatial and executive functions[6]. Key components of VR, such as multimodal feedback (visual, auditory, and tactile), create comprehensive human-machine interactions that promote neuroplasticity[7]. Computer-assisted cognitive therapy (CACT), driven by intelligent algorithms and interactive modules, enables personalized training with dynamic difficulty adjustments, showing significant potential in improving memory, attention, and information-processing speed[8]. Adaptive learning systems, a cornerstone of CACT, optimize task content and feedback mechanisms based on real-time performance data, forming closed-loop cognitive reinforcement pathways[9]. This precisely targeted intervention model not only enhances training efficiency but also facilitates the reorganization and compensation of functional brain networks through neurofeedback technology, thereby providing an evidence-based strategy to remodel impaired cognitive pathways[10]. In addition, with the continuous development of artificial intelligence, AI-based cognitive intervention robots have been continuously applied to clinical practice[11]. It integrates the patient's behavioural patterns through multimodal interaction and big data analysis, which not only enhances the fun and engagement of rehabilitation training, but also provides the possibility of developing accurate rehabilitation programs[12].

However, there are significant contradictions in the available evidence: some studies concluded that VR is superior to conventional methods in spatial navigation training, and a meta-analysis by LIN[13]demonstrated that although the cognitive improvement effect was relatively low, the comparison with conventional therapies was still significant. While some studies showed no significant effect of VR in the area of cognitive improvement, for example, a study by ZHANG[14], which summarised 23 RCTs by meta-analysis, found that VR had a significant effect on executive and visuospatial functions in stroke patients, whereas the improvement in overall cognitive function did not show statistically significant differences. CACT may be advantageous in terms of improvements in executive and memory functions, but its significance compared with other digital therapies has been less well studied. In addition, there are issues such as the efficacy association between intervention dose, type of technique and cognitive improvement remains unclear. R is currently often used in the treatment of the motor system [15][16], and less research has been conducted in the cognitive domain.

Current systematic evaluations and meta-analyses[14][17][18]have mostly focussed on a single digital technology versus traditional rehabilitation, and have lacked direct efficacy comparisons of different interventions (e.g., VR vs CACT vs CCT) .

This network meta-analysis (NMA) addresses these gaps by:

(1) Quantifying the relative efficacy of different digital interventions in improving PSCI;

(2)Identifying optimal intervention strategies for specific cognitive domains (e.g., MoCA for executive function vs. MMSE for global cognition);

(3)Evaluating clinical feasibility and guiding future research directions for technology integration and protocol optimization.

Methods

Protocol and Registration

This study is a systematic review and network meta-analysis. The protocol was registered on PROSPERO (CRD420251006601) and adheres to the guidelines outlined in the Cochrane Handbook for Systematic Reviews of Interventions. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines were rigorously followed to ensure methodological transparency and reporting quality.

Data Sources and Search Strategy

Six databases—PubMed, Web of Science, Cochrane Library, Scopus, EMBASE, and CNKI—were systematically searched from their inception to January 2025. Two authors independently developed the search strategy using Medical Subject Headings (MeSH) terms and free-text keywords related to stroke, virtual reality (VR), computer-assisted cognitive therapy (CACT), robot-assisted therapy (R), and rehabilitation. No language or publication year restrictions were applied. A full search strategy that provides access to PubMed and the Cochrane Library, including MeSH terms and keyword combinations, is provided in Multimedia Appendix 1.

Eligibility Criteria

Two authors independently screened and selected studies based on predefined inclusion and exclusion criteria. Discrepancies were resolved through discussion or consultation with a third reviewer. Detailed records of study selection, including methodological quality assessment and data extraction, were maintained throughout the process.

Inclusion Criteria

Studies were included if they met all the following criteria:

(1)Adult patients (>18 years) clinically diagnosed with stroke and exhibiting post-stroke cognitive impairment.(2)Experimental groups receiving digital therapies, including virtual reality (VR), computer-assisted cognitive therapy (CACT), robot-assisted therapy (R), or computerized cognitive training (CCT).(3)Comparator groups receiving conventional cognitive rehabilitation (e.g., paper-and-pencil tasks, occupational therapy , or usual care).(4)Cognitive improvement measured using the Montreal Cognitive Assessment (MoCA) or Mini-Mental State Examination (MMSE).(5)Randomized controlled trials (RCTs) published in peer-reviewed journals.

Exclusion Criteria

Studies were excluded if they met any of the following criteria:

(1) Patients in a comatose state or unable to participate in cognitive interventions. (2)Unavailability of raw data for effect size calculation.(3)Interventions deviating from predefined digital or conventional therapies (e.g., pharmacological interventions).(4)Outcomes reported in non-quantifiable formats (e.g., qualitative descriptions).(5)Conference abstracts, case reports, or non-RCT study designs.

Data Extraction and Quality Assessment

Data Extraction

Eligible studies were independently reviewed and extracted by two authors, with discrepancies resolved through consultation with a third reviewer. The following data were systematically collected: Study title, publication year, and authors. Participant characteristics□Intervention details□Outcome measures □Quality Assessment.

The methodological quality of included studies was evaluated using the revised Cochrane Risk of Bias tool. Five domains were assessed: Risk of bias in randomization □Risk of bias in intervention allocation□Risk of bias due to missing data □Risk of bias in outcome measurement□Risk of selective reporting bias .Studies were classified as:

Low risk: All domains rated "low risk." High risk: At least one domain rated "high risk."

Some concerns: Remaining cases not meeting the above criteria.

Data Analysis

We conducted a network meta-analysis (NMA) using the “netmeta” and “gemtc” packages in R software. Treatment effects were estimated using mean differences (MD) with 95% confidence intervals (CI).

Two models (consistency and inconsistency) were compared based on Deviance Information

Criterion (DIC) values. If the DIC difference between models exceeded 5, the inconsistency model was applied; otherwise, the consistency model was retained.

Heterogeneity was assessed using the I^2 statistic, interpreted as follows: $I^2 \leq 25\%$: Low heterogeneity;25% < $I^2 \leq 50\%$: Moderate heterogeneity; $I^2 > 75\%$: High heterogeneity. Egger's test was used to evaluate publication bias.

A random-effects model was applied to account for between-study heterogeneity.

Sensitivity analyses were performed by excluding outliers when high heterogeneity ($I^2 > 75\%$) was detected.

Forest plots were generated to display effect sizes for interventions versus conventional rehabilitation. Network plots illustrated connectivity between interventions. Surface Under the Cumulative Ranking Curve (SUCRA) values were calculated to rank intervention efficacy, with higher values indicating superior effectiveness.

Pairwise comparisons between interventions were summarized in league tables, highlighting statistically significant differences (95% CI excluding zero).

Convergence and Consistency Checks

Convergence diagnostics (trace plots and density plots) were evaluated after 50,000 iterations.Node-splitting analysis assessed local inconsistency ($P < 0.05$ indicating significant inconsistency).

Robustness and Statistical Validation

To ensure the reliability of the findings, we rigorously validated the convergence of the network meta-analysis (NMA) by examining trace plots and density plots for stability. Global and local inconsistencies were assessed using the node-splitting method. A significance threshold of $P < 0.05$ was applied to identify inconsistencies between direct and indirect evidence, prompting the use of an inconsistency model to resolve discrepancies. Conversely, $P \geq 0.05$ indicated consistency, allowing the application of a consistency model for final analysis.

Publication bias was evaluated using funnel plots and Egger's test, while sensitivity and subgroup analyses were conducted to identify sources of heterogeneity (e.g., intervention protocols, population characteristics) and confirm result robustness.

Evidence Quality Assessment

The evidence quality for each outcome was systematically evaluated using the GRADE framework. If significant deficiencies were identified in domains such as risk of bias, heterogeneity, indirectness, imprecision, or publication bias, the evidence quality was downgraded from high to lower levels (e.g., moderate, low, or very low) accordingly.

Results

A total of 2,128 articles were retrieved from six databases: PubMed (n=226), Web of Science (n=470), Cochrane Library (n=374), Scopus (n=165), EMBASE (n=725), and CNKI (n=168). After removing 682 duplicates, 1,446 articles underwent title/abstract screening, with 1,250 excluded for irrelevance. Full-text review of 196 articles yielded 27[19][45] eligible randomized controlled trials (RCTs) (Figure 1).

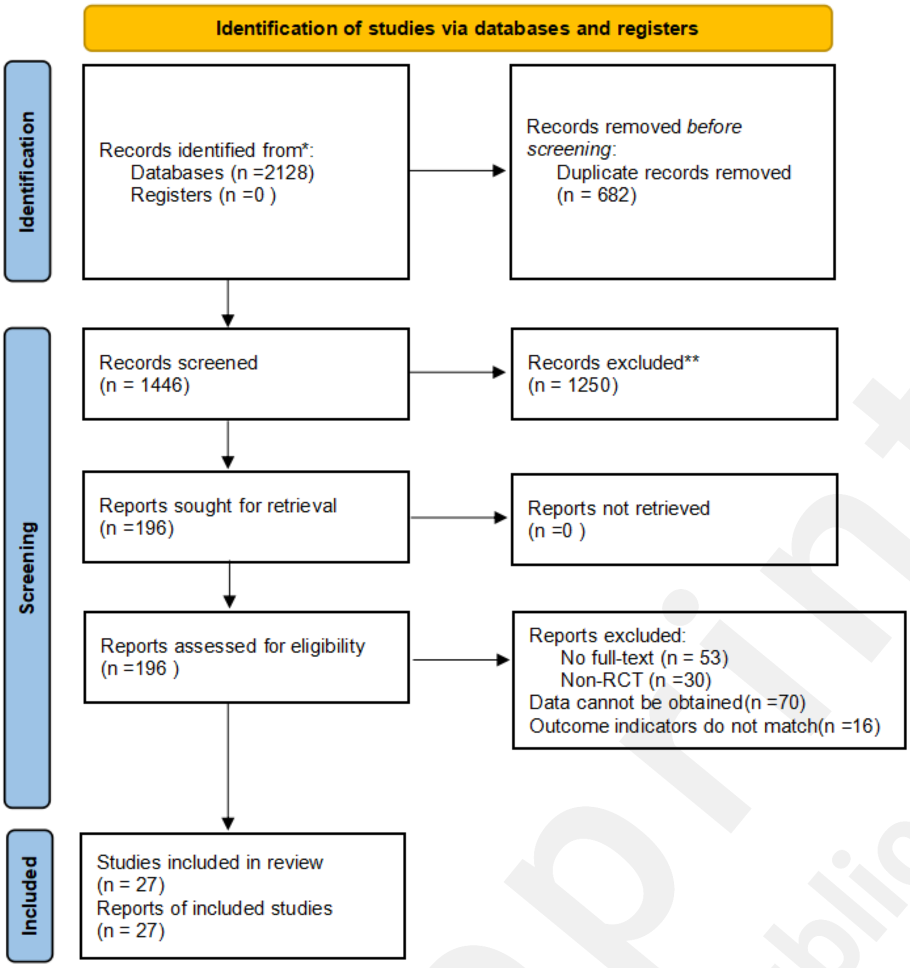

Figure 1 Flowchart of the study selection process.

Study Characteristics

A total of 27 studies with 1517 patients were included in the article, involving five different interventions, including virtual reality technology, computer-assisted therapy, robot-assisted therapy, cognitive training, and conventional rehabilitation. There were 12 studies involving virtual reality technology, 13 studies involving computer-assisted therapy, 4 studies involving robot-assisted therapy, and 8 studies involving cognitive training. The main characteristics of the included studies are shown in the table(Table 1).

Table 1 Characteristics of the Included Literature

study		disease duration	age	intervention	Intervention system or intervention modality	sample size	time	Measuring instrument
Faria 2020	T	45,93±43,56	59,14±11,81	VR	Reh@Cityv2.0	14	2Y	MOCA
	C	21,33±12,88	65,00±6,20	CCT	Paper-and-pencilintervention	18	2Y	
Faria 2018	T	24.9±20.3	57.1±11.0	VR	Reh@Task	12	1M	MOCA
	C	41.1±41.0	68.9±9.8	C	Vocational and writing training	12	1M	
Faria 2016	T	7±11.25	58±3.83	VR	Reh@City	9	4W	MMSE
	C	4±3.25	53±5.75	CCT	Cognitive training for time matching	9	4W	
Baltaduoniene 2019	T1	NOR	73.67±10,10	VR	SeeMeR BrontesProcessing	40	32D	MOCA MMSE
	T2	NOR	73.67±10,10	CACT	Fundamentals, memorization, problem solving, visual-spatial	41	32D	
	C	NOR	74.33±10.27	CCT	OT	40	32D	
Rogers 2019	T	22.8±14.8	64.3±17.4	VR	Elements mandates	10	4W	MOCA
	C	30.0±15.9	64.6±12.0	C	OT and PT	11	4W	
Kim BR	T	18.2±11.3	66.5±11.0	VR	IREX systems	15	4W	MMSE

2011	C	24.0±31.1	62.0±15.8	CACT	ComCog	13	4W	
Oh YB 2019	T	NOR	57.4±12.2	VR	Joystim	17	6W	MOCA MMSE
	C	NOR	52.6±10.7	C	OT	14	6W	
Ozen S 2021	T	151.8 ± 98.4	62.00±13.12	CACT	Rejoyce	15	20D	MOCA MMSE
	C	145.8 ± 86.1	62.00±13.12	C	OT	15	20D	
Soni AK 2025	T	NOR	51.8±6.25	CACT	NOR	25	4W	MOCA
	C	NOR	49.4±6.38	C	Paper and pencil based home training tasks	25	4W	
Marcela 2023	T	126±15.58	59.36	VR	OculusQuest2	25	4W	MOCA
	C	128±14.63	59.36	C		25	4W	
Akinci M 2024	T	74.18±33.77	59.18±8.89	VR	Lokomat	17	6W	MOCA
	C	66.71±34.13	59.12±13.22	CCT	Paper and pencil based training tasks	17	6W	
CaiJiang 2016	T	40,56±18,88	56,18 ± 11,86	CACT	RehaCom	51	3W	MOCA MMSE
	C	40.27±19.17	59.56 ± 10.10	C	Traditional rehabilitation	49	3W	
Wilson 2021	T	137.5±152.4	69.9±13.8	VR	Elements	10	8W	MOCA
	C	107.4±56.4	77.3±8.9	C	GRASP	7	8W	
Sahel Taravati 2021	T	10.94±8.02	50.94±17.20	R	Reo Go-Motor rehabilitation system	17	4W	MOCA
	C	12.65±8.42	55.75±11.61	C	Routine rehabilitation training	20	4W	
Adomaviien 2019	T	8.69±4.27	66±2.37	VR	Kinect OR Armeo	25	10D	MMSE
	C		62±1.33	C	NOR	25	10D	
Liu 2018	T	NOR	61.50±12.34	CACT	NOR	62	4W	MOCA
	C	NOR	62.35±10.34	C	NOR	66	4W	
Luca 2017	T	3±1(M)	43.9 ± 16.6	CACT	Istitutodi Ricercae Curaa Carattere Scientifico Neurolesi	20	8W	MMSE
	C	4±1(M)	42.1 ± 17.7	C	Traditional rehabilitation	15	8W	
Zucchella 2014	T	NOR	64±13.33	CACT	Unapalestraperlamente	42	4W	MMSE
	C	NOR	70±10.37	C	Routine rehabilitation training	45	4W	
Choi 2014	T	20.2±14.1	64.3±10.3	VR	business game		4W	MMSE
	C	23.67±20.7	64.7±11.3	C	OT		4W	
MENG 2022	T	8.38±2.05(W)	56.25±5.38	CACT	DKYYZ	40	3M	MMSE
	C	8.8±2.63(W)	57.4±6.04	CCT	NOR	40	3M	
LUO 2020	T1	NOR	NOR	CACT	CAARS	30	12W	MOCA
	T2	NOR	NOR	CCT	Artificial Cognitive Function Training	30	12W	
	C	NOR	NOR	C	NOR	30	12W	
Li ZAHNG 2020	T	3.2± 4.7(Y)	71.5±5.3	CACT	NOR	37	6W	MMSE
	C	3.5±4.3(Y)	71.6±5.7	CCT	Routine rehabilitation training	37	6W	
ZAHNG 2020	T	NOR	60.72±0.88	CACT	NOR	30	NOR	MOCA
	C	NOR	59.62±0.85	C	Routine rehabilitation training	30	NOR	
SU 2022	T	27.13±3.88	64.97±4.88	R	Upper Extremity Rehabilitation Robotic Training	30	4W	MOCA MMSE
	C	26.73±4.08	65.53±5.46	CCT	Routine rehabilitation training	30	4W	
XU 2023	T	2.61±1.32(M)	51.66±7.15	R	ReFle×100	32	3M	MMSE
	C	3.09±1.21(M)	52.94±6.27	C	Schuell stimulation	32	3M	
LU 2022	T	5.12±0.65	58.65±2.16	R	Lokomat Gait Assessment and Training and Integrated Upper Limb Training	48	1M	MOCA
	C	5.01±0.63	58.61±2.13	C	Traditional rehabilitation	48	1M	
YAO 2021	T	6.2±0.9(M)	68.6±6.2	CACT	Computerized Cognitive Function Systems Training	40	3W	MOCA MMSE
	C	5.9±1.5(M)	67.9±6.5	C	Routine rehabilitation training	40	3W	

Abbreviations: CACT, Computer-assisted cognitive therapy; VR, Virtual reality; R, robot-assisted therapy; CCT, cognitive training; MOCA, Montreal Cognitive Assessment Scale；MMSE, Minimum

Mental State Examination

Risk of Bias

Twenty-seven randomized controlled trials (RCTs) were included in the analysis. Based on the revised Cochrane Risk of Bias tool, 7 studies were rated as high risk, 6 as low risk, and the remaining 14 as moderate risk (some concerns). Analysis revealed that some studies exhibited deficiencies in blinding and allocation concealment, which may introduce bias into the outcomes. However, outcome measurement and reporting generally demonstrated low risk of bias across all studies. A detailed risk of bias assessment is presented in Figure 2.

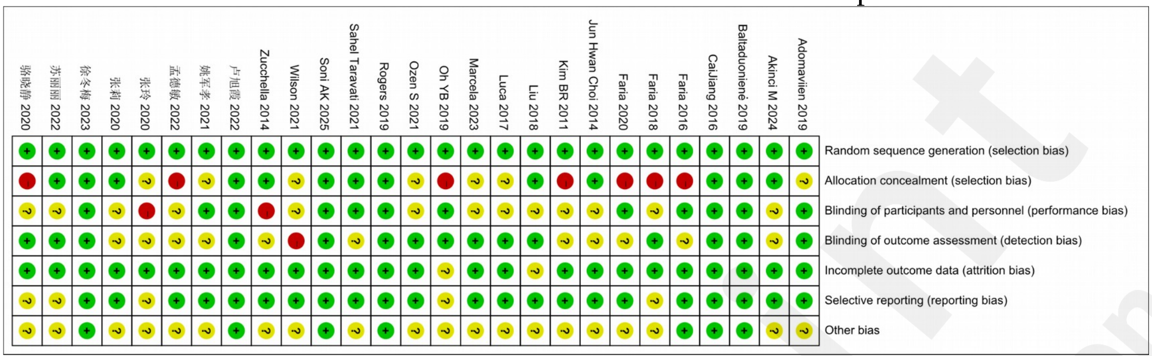

Figure 2 Risk-of-bias summary.

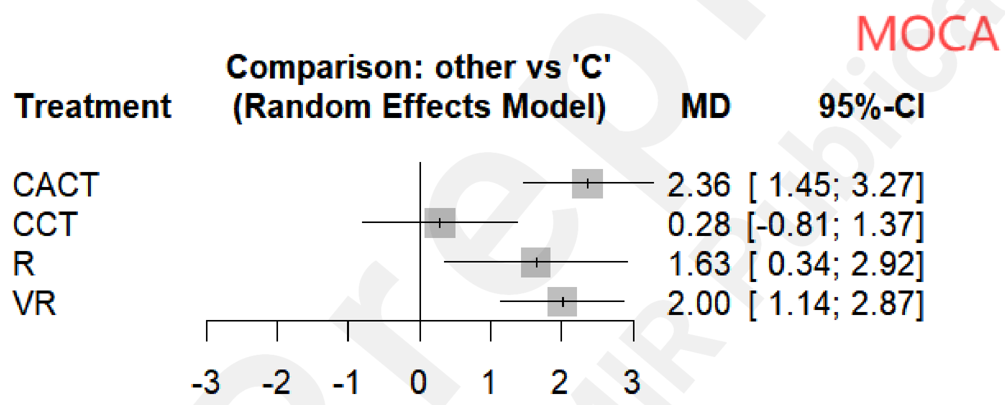

Figure 3 Forest plot for MOCA

Abbreviations: CACT, Computer-assisted cognitive therapy; VR, Virtual reality; R, robot-assisted therapy; CCT, cognitive training

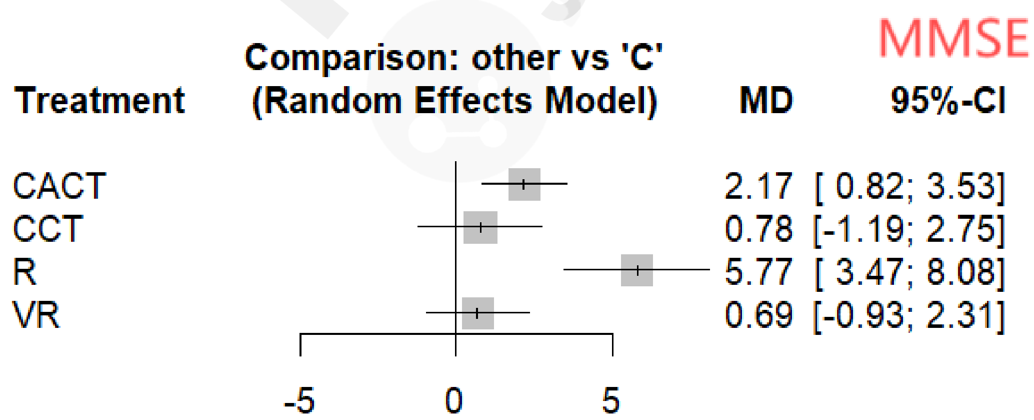

Figure 4 Forest plot for MMSE

Abbreviations: CACT, Computer-assisted cognitive therapy; VR, Virtual reality; R, robot-assisted therapy; CCT, cognitive training

Meta-Analysis

The analysis included 27 randomized controlled trials (RCTs) involving 1,517 patients with post-stroke cognitive impairment. Key findings are summarized below:In terms of improving MOCA scores, compared to interventions in conventional rehabilitation, CACT (6 items, involving 207 patients, mean difference (MD) = 2.36, 95% Cl = 1.45-3.27),VR (9 items, involving 204 patients, mean difference (MD) = 2.00, 95% Cl = 1.14-2.87), and R (3 items, involving 95 patients that Mean Difference (MD) = 1.63, 95% Cl = 0.34-2.92) showed significant differences and were most likely to improve patients' cognitive function. In contrast, the CCT (5 items, involving 143 patients, mean difference (MD) = 0.28, 95% Cl = -0.81-1.37) did not show a significant difference. In terms of improving MMSE scores, R (3 items, involving 79 patients, mean difference (MD)=5.77, 95% Cl=3.47-8.08), CACT (9 items, involving 299 patients, mean difference (MD)=2.17, 95% Cl=0.82-3.53) significantly improved patients' cognitive functioning in comparison to the conventional rehabilitation interventions, while VR (6 items, involving 95 patients, mean difference (MD) = 0.69, 95% Cl = -0.93-2.31) and CCT (5 items, involving 134 patients, mean difference (MD) = 0.78, 95% Cl = -1.19-2.75) did not show significant differences. Although VR did not have a significant effect on MMSE (MD=0.69,95% CI=-0.93-2.31), its potential to improve patient engagement and adherence warrants further investigation. For a forest-specific map, see Figure 3、Figure 4

Net meta-analysis

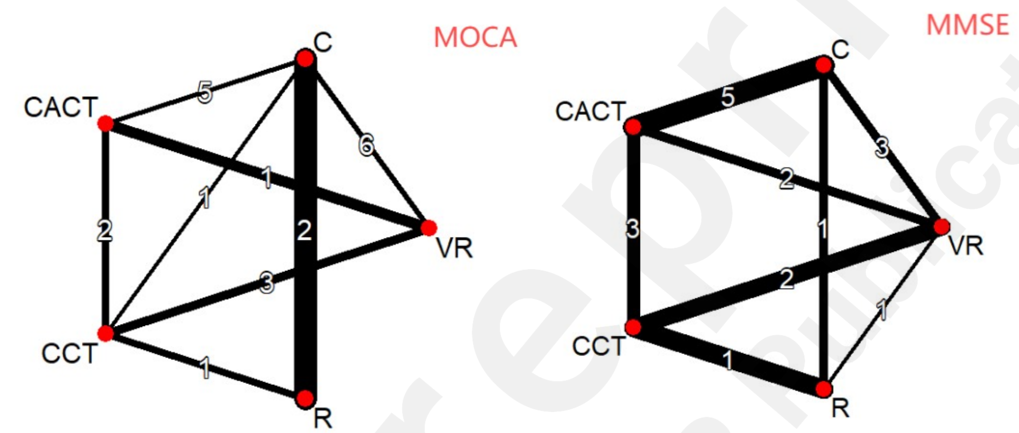

Figure 5 Network evidence diagram of included studies
Abbreviations: CACT, Computer-assisted cognitive therapy; VR, Virtual reality; R, robot-assisted therapy; CCT, cognitive training

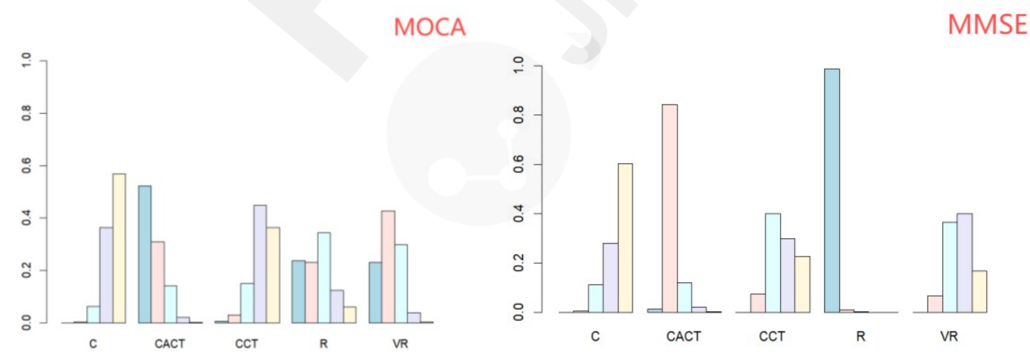

Figure 6 Incorporation of research stacking charts
Abbreviations: CACT, Computer-assisted cognitive therapy; VR, Virtual reality; R, robot-assisted therapy; CCT, cognitive training

Previous literature suggests that SUCRA values >70% are considered to indicate high grade efficacy (Salanti et al., 2011). According to the Sucra ranking scale, CACT (MD=2.36, 95% Cl=1.45-3.27, SUCRA=83.2%) ranked first among the MOCA scores as the most effective method to improve patients' cognitive functioning, followed by VR (70.1%) and R (61.3%). The specific rankings were CACT > VR > R > CCT > C. A completely different ranking was obtained in the MMSE scores, with R (MD = 5.77, 95% Cl = 3.47-8.08, SUCRA = 99%) ranking first, followed by CACT (71.2%), and the VR intervention did not show a significant difference. Its specific ranking was R > CACT > CCT > VR > C. See stacking diagram for details(Figure 6)

According to the league table(Table 2、Table 3), in the MOCA score CACT vs C: effect size -2.38 (95% CI: -4.13, -0.63), CACT was significantly better than C. VR vs C: effect size -1.90 (95% CI: -3.51, -0.27), VR was significantly superior to C. And effect size -1.63 (95% CI: -4.20, 0.94) for R vs C, a non-significant difference (CI contains 0). Comparisons between other interventions (e.g., VR vs CACT, R vs CCT) did not show statistical differences. In MMSE scores CACT vs C: effect size -2.17 (95% CI: -3.87, -0.43), suggesting that CACT was significantly better than conventional therapy.

R vs C: effect size -5.71 (95% CI: -8.56, -2.74), with R significantly better than C. R vs CACT: effect size -3.54 (95% CI: -6.52, -0.48) suggesting that R may be superior to CACT. R vs CCT: effect size -5.01 (95% CI: -7.99, -2.02), with R significantly superior to CCT. VR vs R: effect size 5.03 (95% CI: 2.05, 7.91), with VR significantly superior to R. None of the differences between VR,CCT, and C were statistically significant (CI contains 0).

Table 2 league table for the MOCA

MOCA

C	C				
CACT	*-2.38 (-4.13, -0.63)*	CACT			
CCT	-0.28 (-2.39, 1.83)	2.09(-0.23, 4.44)	CCT		
R	-1.63 (-4.20, 0.94)	0.74 (-2.26, 3.76)	-1.35 (-4.20, 1.50)	R	
VR	*-1.9 (-3.51, -0.27)*	0.46(-1.65, 2.62)	-1.63 (-3.65, 0.43)	-0.28 (-3.14, 2.62)	VR

Abbreviations: CACT, Computer-assisted cognitive therapy; VR, Virtual reality; R, robot-assisted therapy; CCT, cognitive training

Table 3 league table for the MMSE

MMSE

C	C				
CACT	*-2.17 (-3.87, -0.43)*	CACT			
CCT	-0.71 (-3.13, 1.85)	1.45 (-0.68, 3.71)	CCT		
R	*-5.71(-8.56, -2.74)*	*-3.54 (-6.52, -0.48)*	-5.01(-7.99, -2.02)	R	
VR	-0.68 (-2.69, 1.32)	1.48 (-0.64, 3.57)	0.03 (-2.50, 2.41)	*5.03(2.05, 7.91)*	VR

Abbreviations: CACT, Computer-assisted cognitive therapy; VR, Virtual reality; R, robot-assisted therapy; CCT, cognitive training

Convergence Diagnostics

After 50,000 iterations, the convergence of the network meta-analysis models was validated as follows:

MoCA Scores: CACT and VR demonstrated stable trace plots and unimodal density distributions compared to conventional therapy (C), indicating robust convergence. R showed minor fluctuations in trace plots and slightly wider density distributions, suggesting potential instability. However, subsequent validation confirmed model stability. The heterogeneity parameter (I^2) exhibited a right-skewed density distribution with a peak near 0.3, indicating moderate consistency across studies.

MMSE Scores: R achieved excellent convergence, with highly stable trace plots and sharply peaked density distributions. CCT vs. C comparisons revealed mild autocorrelation in trace plots and broader density distributions, likely due to small sample biases. Heterogeneity (I^2) displayed a density peak near 0.5, suggesting moderate heterogeneity attributable to protocol variations or population differences. See Multimedia Appendix 2.

Sensitivity Analysis

To assess the robustness of the findings, We applied stata 18.0 to perform leave-one-out sensitivity analysis by sequentially excluding each included RCT. The results demonstrated that the heterogeneity estimates (I^2 values) remained consistent with the primary analysis, with no single study significantly altering the overall effect sizes or confidence intervals. This confirms the stability and reliability of the pooled results.Through our analyses we found that there is a great deal of variation in the experimental design and application systems of most digital therapies, which may make this one of the main reasons for the high level of heterogeneity. See Multimedia Appendix 3

Inconsistency Test and Publication Bias

Node-splitting analysis revealed no significant inconsistency between direct and indirect evidence across the network ($P > .05$ for all comparisons), confirming the stability of the consistency model. See Multimedia Appendix 4

Funnel plots for MoCA and MMSE scores exhibited symmetrical distributions, suggesting no substantial publication bias. This was further supported by Egger's test results ($P = .601$ for MoCA; $P = .255$ for MMSE). Specific data are shown in Figure 7Figure 8

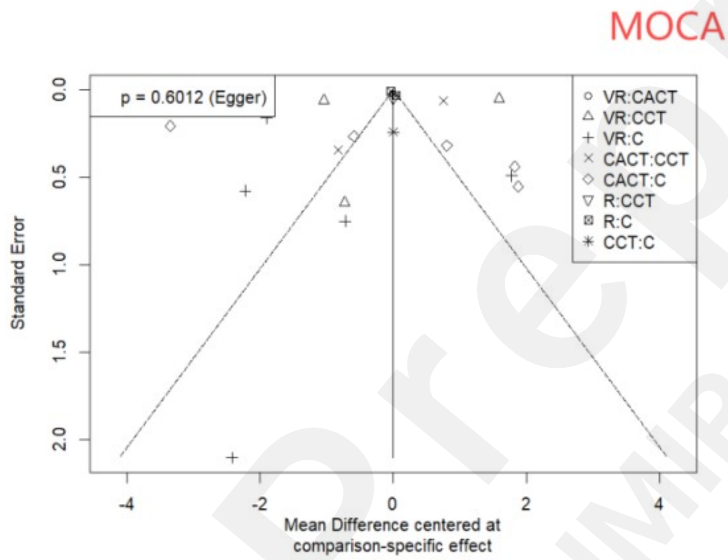

Figure 7 Funnel chart of the inclusion literature on MOCA

Abbreviations: CACT, Computer-assisted cognitive therapy; VR, Virtual reality; R, robot-assisted therapy; CCT, cognitive training

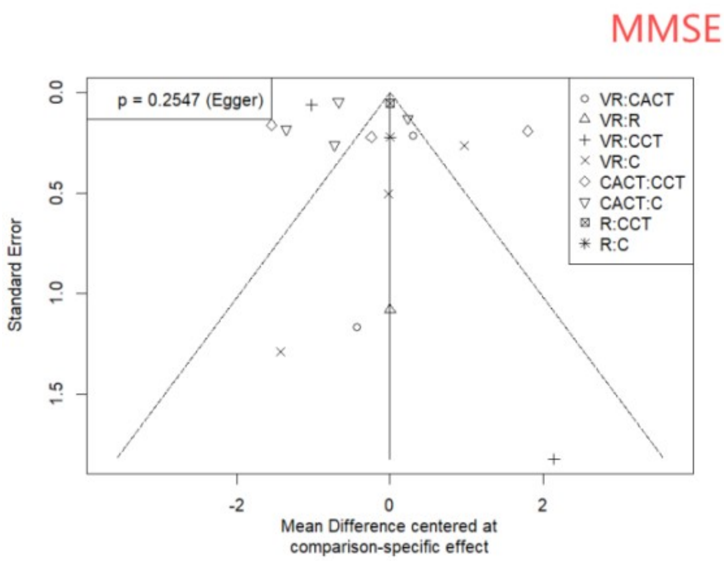

Figure 8 Funnel chart of the inclusion literature on MMSE
Abbreviations: CACT, Computer-assisted cognitive therapy; VR, Virtual reality; R, robot-assisted therapy; CCT, cognitive training

Evaluation of the quality of research evidence
The quality of evidence was evaluated by applying the GRADE method, and the quality of evidence was all rated as low. The main reasons for this were the presence of biased variability, imprecision and incoherence within the studies. Study bias was mainly due to the significant effect of high risk of bias studies on network estimates in all comparisons. Imprecision was due to insufficient data to demonstrate a conclusive effect and the fact that most comparisons were outside the 95 per cent Cl equivalence region.

Discussion

Post-stroke cognitive impairment, is a complex condition of impaired cognitive functioning that occurs after stroke[46]. It usually manifests as inattention, memory loss, slow reaction time, speech-language impairment, prosopagnosia, prosopagnosia, and so on[47], which causes great obstacles to the patient's participation in daily life and social activities[48].With the emergence of digital technologies such as computer-assisted therapy, virtual reality, and tele-intervention, new directions have been brought to the assessment and treatment of cognitive impairment after stroke. Digital technologies promote neuroplasticity and functional reorganisation by simulating real-life scenarios, delivering multimodal stimuli and high-intensity repetitive training [49].In addition, digital technology can quantitatively record patient training data (e.g. reaction time, error rate), providing an objective basis for dynamic assessment and programme optimisation[50], which is more standardised and scalable than traditional training methods.
To the best of our knowledge, this study is the first net meta-analysis that simultaneously evaluates virtual reality, computer-assisted, and robot-assisted, and includes 27 studies involving 1517 patients, aiming to assess the impact of different digital therapies on patients with post-stroke cognitive dysfunction and to rank them appropriately according to their efficacy.
For MOCA scores
The results showed that for the five digital therapies mentioned above, CACT had the highest SUCRA ranking (83.2%) in terms of MOCA improvement, suggesting that it may be the best digital therapy for enhancing executive function, possibly because it can target activation of the prefrontal network. XIAO [51] showed that CACT was superior to VR in MOCA scores, with significant improvement in cognitive functions, similar to the results of this study. However, CACT therapy did

not demonstrate a significant advantage in MMSE scores. The present study included more RCTs, which demonstrated that CACT has a non-negligible effect on MMSE scores through direct and indirect evidence. The main reasons why CACT can effectively improve cognitive function in stroke patients are explained as follows: CACT relies on multimedia technology, and stimulates neurons in the brain through repetitive and targeted cognitive training tasks, promoting neuroplasticity and neural network reorganization[52]. It can enhance patients' concentration on cognitive training through dynamic visual effects and different interactive tasks, and this multisensory stimulation training can activate multiple brain regions such as prefrontal and parietal lobes[53] ,improving patients' attention and executive ability. A study by LIN [54]found that CACT significantly improved patients' hippocampal functional linkages with the frontal and left parietal lobes through resting-state functional magnetic resonance imaging, and that improved hippocampal and frontal lobe functioning facilitated the recovery of patients' short-term memory and executive functioning. Bernini[55] found significant improvements in the overall cognitive, executive and attentional aspects of patients who underwent CACT by comparing them with traditional paper-and-pencil training. These studies once again demonstrate the reliability of the results of the present meta-analysis. Secondly, through the application of computers, the difficulty of the task can be personalised and real-time feedback can be provided.[56] By pinpointing the areas of cognitive deficits and quantitatively recording the training data of the patients, the efficiency of the training can be effectively improved, which can help to formulate a more effective assessment and intervention plan[57].

For the MMSE score

The results showed that for the five therapies mentioned above, robot-assisted (R) ranked first in SUCRA, indicating that R has the best efficacy in improving post-stroke cognitive impairment in MMSE scores.

Robotics technology can be used to capture real-time motor imagery or visually evoked EEG signals[58], translate the patient's active cognitive intent into action commands from the robot, and have the robot assist the patient in performing the corresponding activities. This training mode can form a closed-loop stimulation of 'intention-action-feedback'[59], through which the training of closed-loop stimulation can activate key brain regions such as the primary motor cortex, hippocampus, and prefrontal lobe of the patient, and promote the patient's memory and overall cognitive function improvement [60].

The study included two different outcome metrics, which were analysed and found to have different conclusions for the two outcome metrics. CACT was the best intervention in MOCA, whereas R was more effective in MMSE, which may be due to the fact that MOCA covers visuospatial and abstract thinking dimensions and focuses more on the improvement of executive ability, while CACT improves the executive function mainly by activating the prefrontal network[61], so MOCA is more sensitive to the therapeutic effect of CACT. MMSE, on the other hand, focuses more on basic cognitive functions and may underestimate the improvement of executive function and information processing ability in CACT[62][63], resulting in the effect of CACT being masked.

The effectiveness of VR for cognitive function has been controversial. The present study found that VR therapy demonstrated significant benefits in MOCA, whereas it had little efficacy in MMSE. Some studies[64][65]have pointed out that VR is currently focused on the improvement of motor function, and there are fewer studies on cognitive function, which makes it difficult to provide a reliable evidence-based basis. A study by Wiley [66] showed that the improvement of cognitive function by VR was not significantly different from that of the control group, and it only improved the patients' initiative and sense of experience in rehabilitation. The study by [67]also supported Wiley's view. However, this study found that the effect of VR on cognitive improvement in MOCA score was very significant. For this discrepancy, we believe that the main reason is that the domain of cognition is very complex, for the current research, there is not yet a system that really focuses on cognitive rehabilitation, and most of the cognitive systems need to rely on the intervention of the motor system to complete the task, so the intervention and assessment of cognition is not accurate.

Secondly, cognition consists of several aspects, such as memory, executive ability, etc[68]. Only by corresponding to specific areas can a certain cognitive function be effectively improved. Perhaps a VR system that truly focuses on cognitive rehabilitation can change the controversial situation of VR for improving cognition.

Implications for clinical practice and future research

Limitations

This study provides valuable insights in assessing the efficacy of digital therapies for post-stroke cognitive impairment, but there are some limitations. First, there is some risk of bias in the included studies, especially in terms of blinded implementation and allocation concealment, which may have an impact on the accuracy of the results. Second, although we verified the stability of the results through sensitivity analyses, heterogeneity between studies remained high, which may be due to differences in interventions, assessment methods, and patient characteristics. In addition, this study mainly focused on the short-term treatment effect and lacked long-term follow-up data to comprehensively assess the long-term efficacy of digital therapies and the long-term prognosis of patients.

Directions for future research

Given these limitations, future research should focus on the following areas. First, it is crucial to conduct long-term follow-up studies. This will help to gain insights into the long-term effects of digital therapies on patients with post-stroke cognitive impairment, and assess their lasting effects in delaying cognitive decline, improving quality of life, and promoting social regression. Secondly, future studies should further optimise the intervention protocols, including clarifying the optimal intervention dose, frequency and duration of different digital therapies, as well as exploring the basis for the development of individualised treatment plans. In addition, combining neuromodulation techniques or traditional rehabilitation means, such as transcranial magnetic stimulation and acupuncture, with digital therapies for synergistic application may bring more significant rehabilitation benefits to patients, which is worth exploring in depth. Finally, from the perspective of technological development, with the continuous advancement of artificial intelligence, virtual reality and other technologies, how to ensure that digital therapies maintain their therapeutic effects in long-term applications through continuous technological updates and optimisation is also an important research direction. This includes the development of smarter adaptive training systems, more immersive virtual reality scenarios, and more accurate tools for monitoring and analysing patient data, etc., in order to further enhance the effectiveness and feasibility of digital therapies in the field of post-stroke cognitive rehabilitation.

Conclusion

Overall, digital therapies provide scientific and personalised solutions for post-stroke cognitive rehabilitation, with CACT and R dominating in executive function and overall cognitive improvement, respectively. However, its optimal intervention model needs to be further validated by high-quality RCTs (e.g., expanded sample size, standardised intervention protocols) and interdisciplinary technology integration. Clinical applications need to weigh efficacy, safety (e.g., device dependence), and cost-effectiveness to promote the implementation of precision rehabilitation strategies.

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Supplementary Files

Multimedia Appendixes

Search Strategy.
URL: http://asset.jmir.pub/assets/c2db5e0f9ccd42360fa6c91ae6b900f3.doc

Convergence Diagnostics.
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