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A systematic review on the use of virtual reality in post-stroke patients: exploring when modalities make the difference in executive and motor recovery

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Background: Virtual reality (VR) has emerged as a promising tool in post-stroke neurorehabilitation, offering immersive and interactive environments capable of enhancing motor and executive function recovery through mechanisms of neuroplasticity. Although various VR modalities—immersive (I), semi-immersive (SI), non-immersive (NI), and mixed (MXD)—have been applied, their relative effectiveness remains unclear.

Objective: This systematic review aimed to evaluate the efficacy of different VR modalities in improving motor or executive functions in post-stroke patients and to explore how the stroke phase and the type of VR system used influence treatment outcomes.

Methods: A comprehensive literature search was conducted across PubMed, Embase, Scopus, and the Cochrane Library, resulting in 46 eligible peer-reviewed studies published between 2014 and 2024. These studies included randomized controlled trials, quasi-experimental designs, and observational studies, with an average sample size of approximately 35 participants. The inclusion criteria focused on studies utilizing VR as a therapeutic modality for motor or executive function recovery in post-stroke populations.

Results: Forty-six studies met the inclusion criteria. Overall, VR interventions yielded positive motor outcomes in 76.3% of cases, with semi-immersive VR (SI-VR) achieving the highest proportion of significant improvements (88.24%), followed by non-immersive VR (NI-VR) (66.67%) and immersive VR (I-VR) (50%). Only 13% of studies assessed executive functions, but SI-VR and I-VR modalities showed more consistent benefits than NI-VR. No statistically significant associations were found between VR typology, the stroke phase (chronic vs. subacute), and motor outcome efficacy.

Conclusion: VR is an effective and versatile adjunct to conventional stroke rehabilitation, with SI-VR showing the most consistent motor benefits and immersive systems offering additional cognitive engagement. The lack of significant differences by stroke phase suggests that VR can be applied across

recovery stages. Future research should address the underrepresentation of executive function outcomes and directly compare modalities in well-powered trials.

KEYWORDS

stroke, virtual reality, neurorehabilitation, executive functions, motor recovery, neuroplasticity

1 Introduction

Acquired brain injury is the second most common cause of death (62.2%) and the third most common cause of death and disability combined; survivors often suffer severe motor and cognitive impairments that greatly reduce their own and their families' quality of life (GBD 2019 Stroke Collaborators, 2021).

In these patients, cognitive and motor rehabilitation treatments aim to stimulate neuroplasticity and support the reorganization of damaged brain areas (Einstad et al., 2021).

In recent years, virtual reality (VR) has gained growing interest due to its capacity to deliver engaging, adaptive, and task-oriented environments that simulate real-world scenarios while ensuring patient safety (Masseti et al., 2018). VR enhances motivation, provides real-time feedback, and allows for the repetition of exercises in a controlled setting, which are key factors in effective neurorehabilitation (Rizzo and Koenig, 2017). Depending on the level of immersion, VR environments can be categorized into immersive (I), semi-immersive (SI), non-immersive (NI), or mixed (MXD) reality systems. Immersive VR (I-VR) uses head-mounted displays to fully surround users with a virtual environment, enhancing the presence but sometimes causing side effects such as nausea or disorientation ("VR sickness") due to sensory conflict between the visual input and signals from the vestibular system (Chang et al., 2020). Roussou et al. (2024) showed that I-VR is safe and usable when basic measures are taken to reduce adverse effects and help users adapt. Semi-immersive VR (SI-VR) allows interaction via screens or robotic interfaces while maintaining partial contact with the real world (Fernández-Vázquez et al., 2022). Non-immersive VR (NI-VR) typically involves standard displays such as TVs or monitors and basic input devices, whereas mixed reality overlays virtual elements onto physical environments, creating hybrid scenarios (Howard, 2017).

Clinically, VR has demonstrated promising effects in post-stroke rehabilitation for both motor and executive function recovery, including improvements in upper and lower limb coordination, strength, and range of motion, enhanced attention, processing speed, and cognitive flexibility (Maier et al., 2019).

Motor and executive functions are closely linked following a stroke, as goal-directed movements require planning, decision-making, and attentional control (Schaefer and Schumacher, 2009). Stroke often affects networks involving both motor and prefrontal regions, leading to concurrent deficits; thus, evaluating these domains together offers a more complete view of recovery and potential cross-domain rehabilitation effects (Cramer et al., 2011). This systematic review aims to bridge this gap by reviewing studies focused on the impact of VR rehabilitative treatments, across all modalities—immersive, semi-immersive, non-immersive, and mixed reality—on both motor and executive functions (or one of them) in post-stroke patients. A secondary objective is to

demonstrate the benefits of this innovative therapeutic strategy and its potential role in advancing neurorehabilitation.

2 Materials and methods

We conducted this systematic review to explore the existing evidence on innovative rehabilitation for improving motor and cognitive outcomes in post-stroke patients. This review was registered with a DOI ([osf.io/fy3mw](https://doi.org/10.3389/fy3mw)) on the Open Science Framework (OSF).

2.1 Search strategy

A review of currently published studies was performed in the following databases: PubMed, Embase, Scopus, and the Cochrane Library. The following search string was used: (((neurorehabilitation [Title/Abstract]) AND (virtual reality [Title/Abstract])) AND (executive functions [Title/Abstract])) OR (motor impairment [Title/Abstract])). All the articles were published between 2014 and 2024.

2.2 Study selection

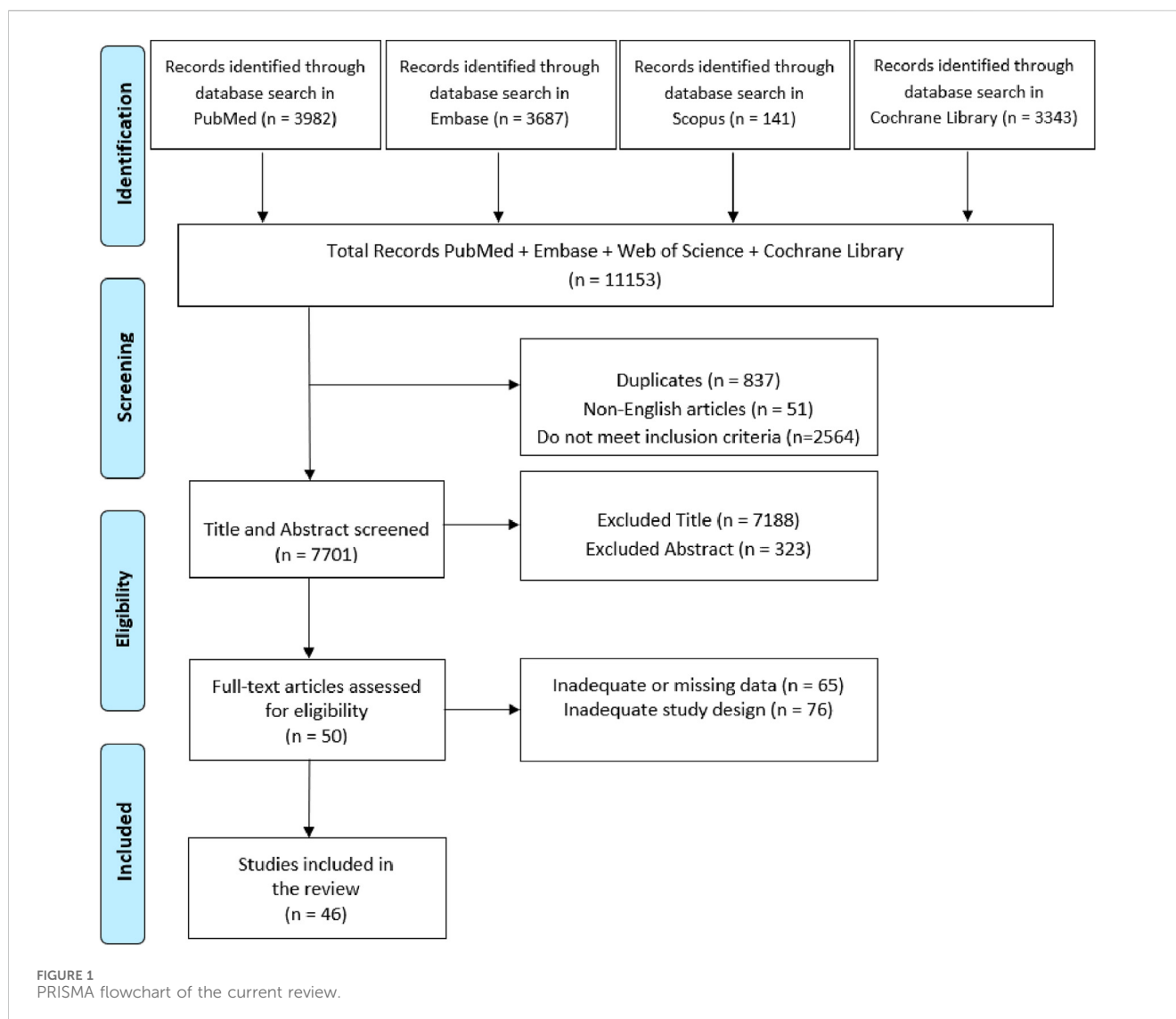
To minimize bias and ensure a rigorous selection process, three investigators (C.A., D.C., and G.G.) independently reviewed and extracted data from the studies. Full-text articles deemed suitable for the study were then read by these researchers, and any discrepancy in selection was resolved through collaborative discussion, with consultation from a fourth researcher (R.S.C). This multistep approach ensured that at least three research workers independently assessed each article. In cases of persistent disagreement, the final decision involved all authors.

2.3 Inclusion criteria

A study was included if it described or investigated patients with acquired brain injuries who were treated with innovative cognitive or motor rehabilitation approaches. To ensure consistency and quality, only articles written in English and published in peer-reviewed journals were included.

2.4 Exclusion criteria

A study was excluded if it described theoretical models, methodological approaches, algorithms, and basic technical descriptions, along with (i) animal studies, (ii) conference proceedings or reviews, and (iii) studies involving other neurological patients.



2.5 Risk of bias within individual studies

The risk of bias was assessed considering five domains: (i) bias due to the randomization process, (ii) bias due to deviations from the intended interventions, (iii) bias due to missing outcome data, (iv) bias due to the risk of bias in the measurement of post-exposure outcomes, and (v) bias due to the risk of bias in the selection of the reported outcome. A detailed summary of the risk of bias is available in Appendix 1.

3 Results

3.1 Synthesis of evidence

The initial search resulted in 11,153 studies from different databases, such as PubMed, Embase, Scopus, and the Cochrane Library. After screening the titles, abstracts, and full texts of articles against the inclusion and exclusion criteria, 46 studies (Duret et al., 2015; Brunner et al., 2017; Mazzoleni et al., 2018; Mekbib et al., 2021; Zhang et al., 2023; Dahdah et al., 2017; Torrisi et al., 2021; Lam

et al., 2022; Gerardin et al., 2022; Valdés and Van der Loos, 2018; Noveletto et al., 2020; Manuli et al., 2020; Norouzi-Gheidari et al., 2020; Johnson et al., 2018; Luo et al., 2023; Schuster-Amft et al., 2018; Colomer et al., 2016; Yuan et al., 2021; Llorens et al., 2021; Paquin et al., 2015; Aşkın et al., 2018; Yao et al., 2020; Saposnik et al., 2016; Kong et al., 2016; Taravati et al., 2022; Jung et al., 2017; Thielbar et al., 2020; Aprile et al., 2021; Patel et al., 2019; Şenocak et al., 2023; Mazzoleni et al., 2014; Rong et al., 2021; Lu et al., 2020; Maistrello et al., 2021; Mugler et al., 2019; Saleh et al., 2017; Ranzani et al., 2020; Sip et al., 2023; Kim et al., 2017; Sale et al., 2014; Lee, 2019; Adams et al., 2023; Abd El-Kafy et al., 2022; Yeh et al., 2017; Thielbar et al., 2014; Palermo et al., 2018) were identified as eligible for this systematic review. The details of the search process are shown in Figure 1.

3.2 Description of studies and VR technologies

All studies included in this systematic review were published in English between 2014 and 2024. The main features of the used

VR tasks and technologies are summarized in [Supplementary Table S1](#).

Out of the 46 studies reviewed, over two-thirds used robotic devices, either to actively assist limb movement or to provide haptic and motor feedback. Many studies also used assistive elements, such as arm supports, smart gloves or handlebars, designed to facilitate motion or reduce the need for compensatory strategies.

The equipment ranged from head-mounted displays (HMDs) (Mekbib et al., 2021; Dahdah et al., 2017) to robotic exoskeletons (Manuli et al., 2020; Saposnik et al., 2016; Taravati et al., 2022; Rong et al., 2021) and glove-based systems (Jung et al., 2017; Adams et al., 2023; Brunner et al., 2017). Some studies utilized sensor-based tracking systems, such as Kinect sensors (Valdés and Van der Loos, 2018; Aşkın et al., 2018), camera setups (Sip et al., 2023) or motion-tracking gloves (Paquin et al., 2015; Jung et al., 2017; Yeh et al., 2017). Non-robotic equipment was often paired with commercial gaming platforms, particularly the Nintendo Wii (Paquin et al., 2015; Saposnik et al., 2016; Kong et al., 2016) and the Xbox Kinect (Paquin et al., 2015; Saposnik et al., 2016; Kong et al., 2016). These platforms provided cost-effective, engaging environments but generally lacked mechanical assistance.

The software used varied widely: commercial platforms (e.g., WiiMote, Unity3D, and VRRS Evo) (Paquin et al., 2015; Kong et al., 2016; Maistrello et al., 2021), custom-built or proprietary software [such as tyroS with Amadeo (Paquin et al., 2015; Kong et al., 2016; Maistrello et al., 2021), REA software Axinesis with REAplan® (Paquin et al., 2015; Kong et al., 2016; Maistrello et al., 2021) or InMotion Solution Designer (Duret et al., 2015; Mazzoleni et al., 2018)], and hybrid systems, such as those integrated brain-computer interface (BCI) components with functional electrical stimulation (FES) and VR (Zhang et al., 2023; Johnson et al., 2018). Some systems included multimodal inputs, such as EMG signals (Zhang et al., 2023; Johnson et al., 2018), EEG (Zhang et al., 2023; Johnson et al., 2018) or force feedback (Zhang et al., 2023; Johnson et al., 2018), emphasizing motor control precision and adaptability.

All outcomes were measured at baseline and at the end of all interventions. Cognitive outcomes were assessed using the Montreal Cognitive Assessment (MoCA) in five studies (Manuli et al., 2020; Torrisi et al., 2021; Gerardin et al., 2022; Yuan et al., 2021; Taravati et al., 2022). Three studies (Torrisi et al., 2021; Manuli et al., 2020; Ranzani et al., 2020) used the Frontal Assessment Battery (FAB) to evaluate EF. Three studies (Yuan et al., 2021; Schuster-Amft et al., 2018; Ranzani et al., 2020) assessed the cognitive outcomes by the mini-mental state examination. One study (Manuli et al., 2020) used the Trial Making Test (TMT). Two studies (Torrisi et al., 2021; Yuan et al., 2021) used the digit span test. In one study (Torrisi et al., 2021), the attentive matrices test (AMT) was used. Instead, the Rey–Osterrieth complex figure (ROCF) was used to assess cognitive outcomes in one study (Torrisi et al., 2021). Finally, one study (Dahdah et al., 2017) used the Automated Neuropsychological Assessment Metrics (ANAM), in which a Go/No-Go task and the Stroop test are involved as EF outcomes.

Regarding the motor outcomes, the Fugl-Meyer Assessment (FMA) was used in 27 studies (Mekbib et al., 2021; Zhang et al., 2023; Lam et al., 2022; Valdés and Van der Loos, 2018; Noveletto et al., 2020; Norouzi-Gheidari et al., 2020; Luo et al., 2023; Llorens et al., 2021; Aşkın et al., 2018; Yao et al., 2020; Kong et al., 2016;

Thielbar et al., 2020; Aprile et al., 2021; Patel et al., 2019; Şenocak et al., 2023; Mazzoleni et al., 2014; Rong et al., 2021; Maistrello et al., 2021; Mugler et al., 2019; Sip et al., 2023; Kim et al., 2017; Sale et al., 2014; Lee, 2019; Adams et al., 2023; Yeh et al., 2017; Thielbar et al., 2014; Mazzoleni et al., 2018). The Wolf Motor Function Test (WMFT) was used by seven studies (Luo et al., 2023; Patel et al., 2019; Şenocak et al., 2023; Mugler et al., 2019; Kim et al., 2017; Adams et al., 2023; Yeh et al., 2017). The Action Research Arm Test (ARAT) was used in five studies (Lam et al., 2022; Yao et al., 2020; Abd El-Kafy et al., 2022; Thielbar et al., 2014; Brunner et al., 2017). Four studies (Mekbib et al., 2021; Yao et al., 2020; Lu et al., 2020; Palermo et al., 2018) used the Barthel Index to assess motor outcome, whereas two studies (Aprile et al., 2021; Rong et al., 2021) used the modified Barthel Index (mBI). Two studies (Adams et al., 2023; Yeh et al., 2017) evaluated the motor outcomes using the Box and Block Test (BBT), and six studies (Saposnik et al., 2016; Kong et al., 2016; Taravati et al., 2022; Palermo et al., 2018; Brunner et al., 2017; Rong et al., 2021) used the Functional Independence Measure. In two studies (Paquin et al., 2015; Saleh et al., 2017), the motor outcome measure used was the Jebsen Hand Function Test (JHFT). Finally, in one study (Şenocak et al., 2023), the Trunk Impairment Scale was used. Moreover, in this case, all outcomes were assessed at baseline and at the end of treatment.

3.3 Description of VR interventions and recipients

The number of participants across the studies varied considerably, ranging from a minimum of three patients (Johnson et al., 2018) to a maximum of 141 patients (Saposnik et al., 2016), with an average sample size of approximately 36 participants per study (Table 1).

According to the post-stroke timeframe proposed by Bernhardt et al. (2017), the majority of studies involved individuals in the chronic stage; a total of 25 studies focused on chronic patients (Torrisi et al., 2021; Gerardin et al., 2022; Valdés and Van der Loos, 2018; Noveletto et al., 2020; Manuli et al., 2020; Norouzi-Gheidari et al., 2020; Johnson et al., 2018; Luo et al., 2023; Schuster-Amft et al., 2018; Colomer et al., 2016; Llorens et al., 2021; Paquin et al., 2015; Aşkın et al., 2018; Thielbar et al., 2020; Lu et al., 2020; Maistrello et al., 2021; Mugler et al., 2019; Saleh et al., 2017; Sip et al., 2023; Kim et al., 2017; Sale et al., 2014; Adams et al., 2023; Abd El-Kafy et al., 2022; Yeh et al., 2017; Thielbar et al., 2014). Fifteen studies included individuals in the subacute phase (Mekbib et al., 2021; Zhang et al., 2023; Lam et al., 2022; Yuan et al., 2021; Saposnik et al., 2016; Kong et al., 2016; Jung et al., 2017; Aprile et al., 2021; Patel et al., 2019; Şenocak et al., 2023; Rong et al., 2021; Ranzani et al., 2020; Palermo et al., 2018; Duret et al., 2015; Brunner et al., 2017), whereas four studies involved mixed chronic/subacute samples (Yao et al., 2020; Taravati et al., 2022; Mazzoleni et al., 2014; Mazzoleni et al., 2018). Only two studies did not specify the stroke phase of the participants (Dahdah et al., 2017; Lee, 2019).

In terms of the type of VR used, 21 studies used NI-VR systems (Zhang et al., 2023; Lam et al., 2022; Gerardin et al., 2022; Valdés and Van der Loos, 2018; Johnson et al., 2018; Luo et al., 2023; Paquin et al., 2015; Aşkın et al., 2018; Saposnik et al., 2016; Kong et al., 2016;

TABLE 1 Summary of patients' characteristics, VR features, and outcomes of the studies included in the research.

Study	Sample size	Stroke phase	VR typology	Duration	Frequency	Total number of sessions	EF/MOT improvement	Significant outcome	Significance
Maistrello et al. (2021)	50	C	NI	4 w	5 se/w	20	n.a./+*	MAS/FMA-UE/RPS	p < 0.001
Aşkın et al. (2018)	40	C	NI	4 w	5 se/w	20	n.a./+*	FMA/BBT	p < 0.05
Mugler et al. (2019)	32	C	NI	6 w	6 se	6	n.a./-	FMA/WMFT/MASA	p = 0.15
Kim et al. (2017)	30	C	NI	4 w	3 se/w	12	n.a./+	FMA/WMFT	p = 0.461
Lu et al. (2020)	26	C	NI	6 w	4 se/w	24	n.a./-	BI	p = 0.606
Gerardin et al. (2022)	24	C	NI	3 d	1 se/d	3	n.a./+*	FMA-UE/BBT	p = 0.0003
Luo et al. (2023)	17	C	NI	3 m	n.s	n.s	n.a./+*	FMA-UE	p = 0.045
Valdés and Van der Loos (2018)	14	C	NI	1 d	n.s	1	n.a./+	FMA/trunk rotation	p > 0.05
Paquin et al. (2015)	10	C	NI	8 w	2 se/w	16	n.a./+*	JHFT/BBT/NHPT/SIS	p = 0.03; p = 0.03; p = 0.01; p = 0.009
Johnson et al. (2018)	3	C	NI	6 w	3/w	18	n.a./+*	BBT	p < 0.01
Colomer et al. (2016)	30	C	MXD	2 m	3 se/w	24	n.a./+*	WMFT/BBT	p < 0.01
Manuli et al. (2020)	90	C	SI	8 w	5 se/w	40	+*/n.a	EF (FAB; TMT)	p < 0.001
Schuster-Amft et al. (2018)	54	C	SI	4 w	4 se/w	16	n.a./+*	BBT	p = 0.08
Torrisi et al. (2021)	48	C	SI	8 w	5 se/w	40	+*/+*	EF/FMA-UE	p = 0.04; p = 0.028
Abd El-Kafy et al. (2022)	40	C	SI	12 w	3 se/w	36	n.a./+*	ARAT/WMFT/MAS/AROM	p = 0.0001; p = 0.0001; p = 0.0314; p = 0.0152
Llorens et al. (2021)	29	C	SI	2 m	1 se/w	4	n.a./+*	FMA/WMFT	p = 0.043
Adams et al. (2023)	21	C	SI	8 w	4 se/w	32	n.a./+*	FM-UE/WMFT	p = 0.002
Thielbar et al. (2020)	20	C	SI	4 w	2/w	8	n.a./+*	FMA-UE	p = 0.006
Saleh et al. (2017)	19	C	SI	2 w	4/w	8	n.a./+*	JTHFT	p = 0.03; p = 0.048
Yeh et al. (2017)	16	C	SI	8 w	3 se/w	24	n.a./+*	FMA/WMFT	p < 0.01
Thielbar et al. (2014)	14	C	SI	6 w	3 se/w	18	n.a./+*	ARAT	p = 0.022
Sale et al. (2014)	14	C	SI	4 w	5 se/w	20	n.a./+*	FMA	p < 0.01
Noveletto et al. (2020)	11	C	SI	10 w	2 se/w	20	n.a./+*	FMA-LE/TUG	p < 0.001
Norouzi-Gheidari et al. (2020)	4	C	SI	1 m	10 se/m	10	n.a./+	FMA-UE	p > 0.05

(Continued on following page)

TABLE 1 (Continued) Summary of patients' characteristics, VR features, and outcomes of the studies included in the research.

Study	Sample size	Stroke phase	VR typology	Duration	Frequency	Total number of sessions	EF/MOT improvement	Significant outcome	Significance
Sip et al. (2023)	20	C	I	3 w	n.s	n.s	n.a./+*	FMA-UE/SF-36	p = 0.009; p = 0.001 (EG) p = 0.019; p = 0.022 (CG)
Taravati et al. (2022)	37	S/C	NI	4 w	5 se/w	20	+*/+*	FMA/MOCA	p > 0.05; p = 0.025
Mazzoleni et al. (2014)	25	S/C	NI	6 w	5 se/w	30	n.a./+*	FM (S); MSS-SE (C)	p < 0.05 (S); p < 0.001 (C)
Yao et al. (2020)	40	S/C	SI	2 w	5 se/w	19	n.a./+*	FM-UE; ARAT; BI	p < 0.05; p = 0.003; p = 0.026; p = 0.043
Mazzoleni et al. (2018)	40	S/C	SI	6 w	5 se/w	30	n.a./+*	FM/MAS	p < 0.001; p = 0.002 (C); p < 0.001; p = 0.063 (S)
Saposnik et al. (2016)	141	S	NI	2 w	10 se	10	n.a./+	WMFT/BBT/SIS	p = 0.70
Kong et al. (2016)	105	S	NI	3 w	4 se/w	12	n.a./+	FMA/ARAT/SIS	p = 0.15
Lam et al. (2022)	83	S	NI	8 w	2 se/w	16	n.a./+*	FMA-UE/ARAT	p = 0.001
Aprile et al. (2021)	51	S	NI	6 w	5 se/w	30	n.a./+*	mBI index/FMA-UE	p = 0.006; p = 0.037
Şenocak et al. (2023)	41	S	NI	6 w	5 se/w	30	+	FMA-UE/WMFT	p = 0.556
Rong et al. (2021)	40	S	NI	4 w	5 se/w	20	n.a./+*	FMA-UL/FIM	p = 0.048
Zhang et al. (2023)	33	S	NI	1 m	18 se	18	n.a./+*	FMA-UE	p = 0.027
Ranzani et al. (2020)	33	S	NI	4 w	15 se	15	+/+	FAB/FMA-UE	p = 0.7079; p = 0.529
Duret et al. (2015)	25	S	NI	8 w	4 se/w	32	n.a./+*	FMA	p = 0.002
Brunner et al. (2017)	120	S	SI	4 w	5 se/w	20	n.a./+	ARAT/BBT	p = 0.234
Yuan et al. (2021)	30	S	SI	2 w	6 se/w	12	+/+*	FMA-L/MMSE	p = 0.022
Jung et al. (2017)	13	S	SI	3 w	5 se/w	15	n.a./+*	WMFT	p = 0.046
Patel et al. (2019)	13	S	SI	1 w	8 se/w	8	n.a./+*	FMA-UE/wrist AROM	p = 0.024; p = 0.019
Palermo et al. (2018)	10	S	SI	5 w	4 se/w	20	n.a./+*	FIM/BI/FAT/FMA	p = 0.005
Mekbib et al. (2021)	23	S	I	2 w	4 se/w	8	n.a./+*	FMA-UE/BI	p = 0.0001; p = 0.003
Lee (2019)	42	n.s	SI	6 w	5 se/w	30	n.a./+*	FMA-LE	p < 0.05
Dahdah et al. (2017)	15	n.s	I	4 w	2 se/w	8	+ */n.a	EF, information processing	p = 0.0408; <0.0001

Legend: NI, non-immersive; SI, semi-immersive; I, immersive; d, day; w, week; m, month; n.s., not specified; c, chronic; s, subacute; EF, executive function; MOT, motor function; n.a., not assessed; +*, significant improvement; +, improvement; −, no change; FMA-UE, Fugl-Meyer assessment for upper extremity; BI, Barthel Index; BBT, Box and Block Test; WMFT, Wolf Motor Function Test; FAB, Frontal Assessment Battery; TMT, Trial Making Test; ARAT, Action Research Arm Test; MAS, Modified Ashworth Scale; AROM, active range of motion; JHFT, Jebsen Hand Function Test; NHPT, Nine-Hole Peg Test; SIS, Stroke Impact Scale; MoCA, Montreal Cognitive Assessment; MSS-SE, shoulder and elbow section of motor status scale; JTHFT, Jebsen–Taylor hand function test; FMA, Fugl-Meyer assessment; FMA-LE, Fugl-Meyer Assessment Lower Extremity; TUG, timed up and go test; MMSE, mini-mental state examination; FIM, functional independence measure; FAT, Frenchay Arm Test; SF-36, 36-Item Short Form Survey. Articles were grouped according to the patients' stroke temporal phase (chronic, subacute or not specified) and listed in descending order by both the sample size and VR typology used (non-immersive, semi-immersive, and immersive) at the time of the last clinical assessment/observation.

Taravati et al., 2022; Aprile et al., 2021; Şenocak et al., 2023; Mazzoleni et al., 2014; Rong et al., 2021; Lu et al., 2020; Maistrello et al., 2021; Mugler et al., 2019; Ranzani et al., 2020; Kim et al., 2017; Duret et al., 2015), and another 21 studies used SI-VR systems (Torrise et al., 2021; Noveletto et al., 2020; Manuli et al., 2020; Norouzi-Gheidari et al., 2020; Schuster-Amft et al., 2018; Yuan et al., 2021; Llorens et al., 2021; Yao et al., 2020; Jung et al., 2017; Thielbar et al., 2020; Patel et al., 2019; Saleh et al., 2017; Sale et al., 2014; Lee, 2019; Adams et al., 2023; Abd El-Kafy et al., 2022; Yeh et al., 2017; Thielbar et al., 2014; Palermo et al., 2018; Brunner et al., 2017; Mazzoleni et al., 2018). Only one study used an MXD approach (Colomer et al., 2016), whereas three studies implemented I-VR systems (Mekbib et al., 2021; Dahdah et al., 2017; Sip et al., 2023). Treatment duration ranged from a minimum of 1 day (Zhang et al., 2023; Johnson et al., 2018) to a maximum of 3 months (Zhang et al., 2023; Johnson et al., 2018). The total number of VR training sessions ranged from a single session (Zhang et al., 2023; Johnson et al., 2018) to a maximum of 40 sessions (Torrise et al., 2021; Manuli et al., 2020), whereas the frequency varied between a minimum of one session per week (Torrise et al., 2021; Manuli et al., 2020) to a maximum of daily sessions (i.e., one session per day in consecutive days) (Torrise et al., 2021; Manuli et al., 2020).

Regarding outcome assessment for executive function (EF) and motor functions (MOTs), only 6 out of 46 studies assessed executive functioning, whereas 44 studies evaluated motor outcomes. Of the studies assessing executive function, four studies reported statistically significant improvements (+) (Dahdah et al., 2017; Torrise et al., 2021; Manuli et al., 2020; Taravati et al., 2022) and two observed a nonsignificant trend toward improvement (+) (Yuan et al., 2021; Ranzani et al., 2020), with no study reporting null effects (–); the remaining 40 studies did not assess EF at all (n.a.) (Mekbib et al., 2021; Zhang et al., 2023; Lam et al., 2022; Gerardin et al., 2022; Valdés and Van der Loos, 2018; Noveletto et al., 2020; Norouzi-Gheidari et al., 2020; Johnson et al., 2018; Luo et al., 2023; Schuster-Amft et al., 2018; Colomer et al., 2016; Llorens et al., 2021; Paquin et al., 2015; Aşkın et al., 2018; Yao et al., 2020; Saposnik et al., 2016; Kong et al., 2016; Jung et al., 2017; Thielbar et al., 2020; Aprile et al., 2021; Patel et al., 2019; Şenocak et al., 2023; Mazzoleni et al., 2014; Rong et al., 2021; Lu et al., 2020; Maistrello et al., 2021; Mugler et al., 2019; Saleh et al., 2017; Sip et al., 2023; Kim et al., 2017; Sale et al., 2014; Lee, 2019; Adams et al., 2023; Abd El-Kafy et al., 2022; Yeh et al., 2017; Thielbar et al., 2014; Palermo et al., 2018; Duret et al., 2015; Brunner et al., 2017; Mazzoleni et al., 2018). Considering motor function, 34 studies reported statistically significant improvements (+) (Mekbib et al., 2021; Zhang et al., 2023; Torrise et al., 2021; Lam et al., 2022; Gerardin et al., 2022; Noveletto et al., 2020; Johnson et al., 2018; Luo et al., 2023; Schuster-Amft et al., 2018; Colomer et al., 2016; Yuan et al., 2021; Llorens et al., 2021; Paquin et al., 2015; Aşkın et al., 2018; Yao et al., 2020; Taravati et al., 2022; Jung et al., 2017; Thielbar et al., 2020; Aprile et al., 2021; Patel et al., 2019; Mazzoleni et al., 2014; Rong et al., 2021; Maistrello et al., 2021; Saleh et al., 2017; Sip et al., 2023; Sale et al., 2014; Lee, 2019; Adams et al., 2023; Abd El-Kafy et al., 2022; Yeh et al., 2017; Thielbar et al., 2014; Palermo et al., 2018; Duret et al., 2015; Mazzoleni et al., 2018), 8 studies observed only a nonsignificant improvement trend (+) (Saposnik et al., 2016; Kong et al., 2016; Şenocak et al., 2023; Ranzani et al., 2020; Kim et al., 2017; Brunner et al., 2017; Valdés and Van der Loos et al., 2018; Norouzi-

Gheidari et al., 2020), and two studies reported no change (–) (Lu et al., 2020; Mugler et al., 2019); only two studies did not assess motor outcomes (n.a.) (Dahdah et al., 2017; Manuli et al., 2020).

In terms of intervention strategies, the duration of treatment ranged from a minimum of a single session (Valdés and Van der Loos, 2018) to a maximum of 12 weeks (Abd El-Kafy et al., 2022). The mean duration of treatment was 5.3 weeks.

All the interventions involved virtual reality devices in different modalities. In particular, five studies (Mekbib et al., 2021; Dahdah et al., 2017; Sip et al., 2023; Lee, 2019; Palermo et al., 2018) involved patients undergoing rehabilitation treatment in an immersive virtual reality environment. Sixteen studies (Manuli et al., 2020; Norouzi-Gheidari et al., 2020; Schuster-Amft et al., 2018; Yuan et al., 2021; Llorens et al., 2021; Yao et al., 2020; Jung et al., 2017; Thielbar et al., 2020; Patel et al., 2019; Sale et al., 2014; Adams et al., 2023; Abd El-Kafy et al., 2022; Yeh et al., 2017; Thielbar et al., 2014; Brunner et al., 2017; Mazzoleni et al., 2018) based their rehabilitation interventions on sessions of semi-immersive virtual reality. However, 24 studies (Zhang et al., 2023; Torrise et al., 2021; Lam et al., 2022; Gerardin et al., 2022; Valdés and Van der Loos, 2018; Noveletto et al., 2020; Johnson et al., 2018; Luo et al., 2023; Paquin et al., 2015; Aşkın et al., 2018; Saposnik et al., 2016; Kong et al., 2016; Taravati et al., 2022; Aprile et al., 2021; Şenocak et al., 2023; Mazzoleni et al., 2014; Rong et al., 2021; Lu et al., 2020; Maistrello et al., 2021; Mugler et al., 2019; Saleh et al., 2017; Ranzani et al., 2020; Kim et al., 2017; Duret et al., 2015) based the treatment on a non-immersive virtual reality modality. Finally, one study (Colomer et al., 2016) used a treatment in mixed virtual reality.

To explore potential associations between treatment efficacy and key clinical and technological factors, we conducted chi-square tests of independence. In particular, we examined whether the distribution of motor outcomes [categorized as statistically significant improvement (+*), nonsignificant positive trend (+) or no improvement (–)] varied according to the type of VR applied (non-immersive, semi-immersive, immersive or mixed) and the stroke phase (chronic vs subacute). Motor function outcomes were selected for analysis due to their consistent reporting across studies. The chi-square analysis revealed no statistically significant association between VR typology and motor treatment outcomes [$\chi^2(6) = 5.98$; $p = 0.425$]. Similarly, no significant association was found between the stroke phase and motor outcomes [$\chi^2(2) = 5.46$; $p = 0.486$]. These results suggest that, based on the available data, the efficacy of VR interventions on motor function does not appear to be significantly influenced by either stroke chronicity or the level of immersion of the VR system used.

4 Discussion

4.1 Mechanistic differences across VR modalities

Generally, our findings confirm that VR interventions improve both motor and executive functions in post-stroke rehabilitation, with varying efficacy depending on the degree of immersion. However, as only four studies used I-VR (Mekbib et al., 2021; Dahdah et al., 2017; Sip et al., 2023) or only one use the MXD-VR modality (Colomer et al., 2016), a real comparison was possible

only between SI-VR and NI-VR. In particular, SI-VR demonstrated superior motor outcomes (88.24% positive results) compared to NI-VR (66.67%). Although I-VR is typically delivered through head-mounted displays that enhance sensorimotor engagement and presence (Patsaki et al., 2022; Laver et al., 2017), SI systems use large screens or projection setups, and by balancing realism and comfort, they often achieve high adherence and motor outcomes comparable to immersive setups (Hao et al., 2024). The advantages of SI-VR may derive from tasks such as grasping tasks, which improve upper limb movements and cerebral connectivity (Llorens et al., 2021; Yao et al., 2020; Jung et al., 2017; Saleh et al., 2017; Adams et al., 2023; Brunner et al., 2017; Cano-de-la-Cuerda et al., 2015; Laver et al., 2015), along with mirror tasks (Sip et al., 2023), throwing tasks (Mekbib et al., 2021), and hitting or cycling tasks for the lower limbs (Noveletto et al., 2020; Lee, 2019). On the other hand, NI-VR, including BCI-based motor imagery (Zhang et al., 2023) and gaming consoles such as Xbox (Aşkın et al., 2018; Thielbar et al., 2020) and Nintendo Wii (Sapounik et al., 2016; Kong et al., 2016), shows lower efficacy than SI-VR. Nevertheless, NI-VR shows good motor gains, particularly in upper limb recovery, making it preferable to conventional rehabilitation, possibly due to its precise motion tracking and accessible design (Zhang et al., 2025; Molier et al., 2010).

Post-stroke EF impairments (planning, attention, and inhibition) can benefit from VR's real-world-like challenges (Makmee and Wongupparaj, 2022), enhancing cognitive flexibility and engagement. I-VR and SI-VR modalities lead to significant improvement in the majority of cases (Dahdah et al., 2017; Torrisi et al., 2021; Manuli et al., 2020), with only one study showing just a positive, nonsignificant trend improvement (Yuan et al., 2021). On the other hand, both studies using the NI-VR modality showed nonsignificant improvements (Taravati et al., 2022; Ranzani et al., 2020).

For both motor and executive functions, each VR modality offers unique advantages. I-VR may better stimulate visuospatial and body representation networks, whereas NI-VR systems increase usability and training frequency (Weiss et al., 2004). The current results align with previous reviews, showing that VR, across modalities, supports motor recovery and, to a lesser extent, cognitive improvement post-stroke (Cano-de-la-Cuerda et al., 2015; Lohse et al., 2014). Patsaki et al. (2022) emphasized I-VR's sensory richness, whereas Zhang et al. (2025) and Molier et al. (2010) highlighted the effectiveness of NI-VR systems, particularly when tasks are gamified and adaptive. Hao et al. (2024) found no consistent superiority of any single modality, suggesting that contextual and patient-related factors such as tolerance, stage of recovery, and resource availability are critical in modality selection. However, considering the significant fine mobility improvements reported by the only study involving a mixed VR modality (Colomer et al., 2016), the comparative efficacy with single-modality treatments (I, SI, and NI) remains an open question.

4.2 Neurophysiological correlates, stroke phase, and VR treatment response

VR promotes neuroplasticity through repetitive, task-specific, multisensory stimulation that engages both motor and cognitive

networks (Laver et al., 2015). Functional neuroimaging studies demonstrate that VR tasks can induce neural reorganization, increase cortical excitability, strengthen sensorimotor connectivity, and enhance activity in prefrontal areas during cognitive-motor tasks (Calabrò et al., 2017; Shin et al., 2016; Feitosa et al., 2022). I-VR and SI-VR may more strongly activate visuospatial integration areas, whereas NI-VR can still promote significant reorganization when the feedback is salient and tasks are motivating (Mirelman et al., 2011). These mechanisms likely underlie the dual-domain benefits observed in our review. Our stratified analysis showed VR to be effective in both chronic and subacute phases, with no significant differences in motor outcomes by the stroke stage. However, a study suggested that the subacute stage may offer heightened neuroplastic potential, allowing faster gains in some cases (Hao et al., 2024). Chronic patients, nevertheless, can achieve meaningful improvements when therapy remains intensive and engaging (Patsaki et al., 2022; Laver et al., 2017). The adaptability of VR tasks makes them suitable across recovery stages, with adjustments in difficulty, duration, and feedback tailored to each phase.

4.3 Clinical implications and recommendations

The results of this review highlight the value of VR as an adjunct to conventional rehabilitation for post-stroke patients, yet they also suggest that its effectiveness depends on patient-related factors that should be carefully considered in clinical practice. The stroke stage appears to play an important role. Although our analysis did not identify statistically significant differences in outcomes between subacute and chronic patients, existing evidence suggests that the subacute phase may represent a window of heightened neuroplastic potential in which VR interventions could accelerate functional recovery (Peng et al., 2021). At the same time, patients in the chronic stage are not excluded from potential benefits. Intensive and engaging VR protocols support meaningful gains even several months or years after stroke, indicating that treatment is delivered with sufficient frequency and challenge (Laver et al., 2017). Another determinant of treatment success is the severity of motor impairment. Patients with mild-to-moderate deficits often respond well to non-immersive or semi-immersive VR environments, including commercial gaming platforms or home-based telerehabilitation programs, which combine accessibility with strong motivational components. In contrast, individuals with more severe impairments may require robotic-assisted or sensor-based VR systems that provide physical support, multimodal feedback, and a higher level of guidance to facilitate active participation (Aprile et al., 2021; Mazzoleni et al., 2018). In this sense, tailoring the level of technological assistance to the patient's motor profile is crucial to maximizing engagement and avoiding frustration. Cognitive status also influences the suitability of different VR modalities. Immersive systems, which demand sustained attention and tolerance of sensory load, may be more appropriate for patients with preserved cognitive and perceptual abilities, whereas simpler non-immersive setups may better serve individuals with cognitive impairments or limited tolerance. Motivation and adherence emerge as additional key factors as

VR's capacity to provide real-time feedback, gamified challenges, and socially meaningful tasks can reinforce patient engagement and ultimately promote functional recovery (Proffitt and Lange, 2015).

From a clinical perspective, these findings suggest that VR cannot be applied indiscriminately but should instead be integrated into individualized rehabilitation plans. Subacute patients with moderate deficits may benefit from early exposure to semi-immersive or non-immersive VR to capitalize on neuroplasticity, whereas chronic patients with severe impairments may still achieve progress when supported by robotic VR systems. Immersive VR may be reserved for those able to tolerate and benefit from enriched environments, whereas home-based VR represents a promising solution for maintaining therapy intensity after discharge, indicating that appropriate monitoring and safety protocols are ensured.

In conclusion, VR should be regarded not as a one-size-fits-all intervention but rather as a flexible therapeutic platform whose modality and intensity can be adapted to stroke stage, impairment severity, cognitive status, and contextual factors. By stratifying patients along these dimensions, clinicians can better determine who is most likely to benefit from VR-based rehabilitation, thereby optimizing outcomes and enhancing the translation of this technology into routine practice.

Author contributions

DC: Conceptualization, Methodology, Supervision, Writing - original draft, Writing - review and editing. CA: Data curation, Resources, Writing - original draft, Writing - review and editing. FC: Resources, Visualization, Writing - review and editing. GG: Data curation, Resources, Writing - review and editing. AG: Data curation, Validation, Writing - review and editing. MM: Supervision, Validation, Writing - review and editing. CR: Resources, Supervision, Writing - review and editing. AQ: Project administration, Resources, Writing - review and editing. FT: Data curation, Investigation, Methodology, Writing - review and editing. RC: Data curation, Supervision, Validation, Writing - review and editing.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/frvir.2025.1653968/full#supplementary-material>

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