Somma *et al. Journal of NeuroEngineering and Rehabilitation* (2026) 23:35
https://doi.org/10.1186/s12984-025-01839-x

Journal of NeuroEngineering
and Rehabilitation

REVIEW **Open Access**

Technologies for the three-dimensional assessment and treatment of unilateral spatial neglect in individuals with stroke: a systematic review

Daniele Somma[2,3], Alice Finocchi[1], Silvia Campagnini[1], Ester Marra[1*], Chiara Pedrini[1], Samuele Pinna[1], Maria Anna Szczepanska[1], Alessio Fasano[1], Francesca Cecchi[1,4], Egidio Falotico[2,3] and Andrea Mannini[1]

Abstract
Unilateral spatial neglect (USN) is a failure to respond or orient to stimuli in contralesional space, not explained by primary sensory or motor deficits. It affects up to two-thirds of right hemisphere stroke survivors and significantly impacts rehabilitation and functional outcomes. Recent advances in three-dimensional (3D) technologies, such as virtual reality (VR) and robotics, offer promising tools for assessment and treatment, providing realistic scenarios and precise clinical stimulation. This systematic review explores the current use of 3D technologies in USN, focusing on their features, level of development, and reported outcomes. A structured search of four databases using the PICO format identified 37 relevant studies out of 2891. The most frequently employed technologies were immersive and non-immersive VR, augmented and mixed reality, and robotics. However, these tools are still in early experimental phases. Among the studies, 15 addressed assessment, 17 focused on treatment, and 5 were technical in nature. Key challenges include methodological variability and the lack of standardized protocols. Due to the heterogeneity of technologies and outcomes, a meta-analysis was not feasible. Future studies should adopt rigorous designs to validate these approaches and support their integration into clinical practice.

Keywords 3D rehabilitation, Robotics, Stroke, Systematic review, Technology, Unilateral spatial neglect, Virtual reality, Wearable electronic devices

---

*Correspondence:
Ester Marra
emarra@dongnocchi.it
[1] IRCCS Fondazione Don Carlo Gnocchi ONLUS, Via di Scandicci 269, Firenze 50143, Italy
[2] The BioRobotics Institute, Scuola Superiore Sant'Anna, Pontedera, Italy
[3] Department of Excellence in Robotics and AI, Scuola Superiore Sant'Anna, Pisa, Italy
[4] Department of Experimental and Clinical Medicine, University of Florence, Firenze, Italy

Background

Stroke is a major cause of disability worldwide, with an estimated 15 million people affected annually [1]. Among the various neurological deficits that result from stroke, unilateral spatial neglect (USN) is a disorder of contralesional space awareness that negatively impacts prognostic recovery [2]. USN is a disabling condition that typically occurs after unilateral brain damage, particularly in the right hemisphere. It can result from various pathological conditions but is most commonly associated with cerebral infarction or hemorrhage, affecting up to two-thirds of survivors with acute right hemisphere stroke [2]. USN is defined as a failure to report, respond, or orient to stimuli in contralesional space after brain injury that is not explained by primary sensory or motor deficits [3, 4]. It may affect personal, peripersonal and/or extrapersonal space, and it may significantly impact rehabilitation efforts and functional recovery [5], resulting in diminished quality of life (QoL) [6]. Patients with USN frequently fail to notice or acknowledge items on their contralesional side (typically the left side for those with right hemisphere damage) and instead focus on items located on their ipsilesional side. This neglect can be so severe that individuals may remain unaware of large objects or even people in extrapersonal space [7]. USN may also affect or be confined to personal space, with patients failing to acknowledge their contralesional body parts during daily activities [6]. In some cases, patients exhibit "motor neglect", where they fail to use their contralesional limbs despite minimal or no weakness [8–10]. Some patients with USN also show anosognosia, a lack of awareness of their deficits, and may even fail to recognize or acknowledge their difficulties in perception or motor control [11]. Studies have shown that people with USN may experience more severe disability, slower recovery, and lower rates of return to independent living than people with stroke without USN [12, 13]. The QoL in stroke survivors is influenced by various factors, including the severity of physical and cognitive impairments, emotional well-being, and the ability to perform daily activities [14]. Many patients with USN following stroke improve within a few weeks, but some continue to show persistent neglect and are likely to require rehabilitation input [15].

While significant strides have been made in post-stroke rehabilitation, addressing complex deficits such as USN remains a challenge. USN is a multifaceted, heterogeneous condition that often requires long-term, targeted interventions to complement spontaneous recovery [16]. In current clinical practice, different members of the interdisciplinary rehabilitation team may adopt varied therapeutic approaches. Broadly, these can be grouped into three main families of strategies:

- *Restorative (or restitutive) strategies* aim to directly restore impaired brain functions by stimulating the affected spatial systems through visual, tactile, or auditory cues. These cues are progressively reduced and eliminated as recovery progresses [17].
- *Compensatory strategies* focus on adapting the environment or behavior to work around the impairment. This can include simplifying the visual field, providing external aids, or educating the patient and caregivers about safety and adaptation techniques. An example of treatment is the Visual scanning training [18].
- *Vicarious strategies* attempt to recruit alternative or adjacent brain networks that can take over some of the lost functions. This may involve engaging tasks designed to increase activation in spatial cognitive areas not directly damaged by the stroke, for example through a Non-invasive brain stimulation (rTMS / tDCS) [19].

In some cases, pharmacological treatments (e.g., stimulants to improve arousal) may be considered either restorative or compensatory, depending on the therapeutic goal [20, 21]. Despite the wide range of available interventions—from visual scanning training to non-invasive brain stimulation [15, 22] it remains unclear which combination of strategies is most effective. This uncertainty reflects the complex and dynamic nature of USN, as well as the variability in how it is assessed. Some methods target *body function impairments* using bottom-up tasks (e.g., line bisection), while others focus on *activity limitations* via top-down evaluations of real-world tasks. Similarly, treatment strategies differ in orientation, with bottom-up approaches (e.g., prism adaptation [23, 24]), stimulating sensory input, and top-down methods enhancing goal-directed behavior through feedback and task relevance.

Overall, traditional assessment and treatment methods predominantly rely on two-dimensional (2D) representations of space. These instruments have long been central to the clinical and theoretical understanding of USN, offering robust and widely validated measures of spatial attention. Yet, because they mainly operate within planar environments, they may only partially reflect the complexities of three-dimensional (3D) spatial interactions that are critical for real-world functioning. This limitation is particularly important given that USN manifests in both peripersonal and extrapersonal spaces, often extending beyond the 2D plane into the dynamic, 3D environments encountered in daily life [16]. In addition to their predominantly 2D nature, traditional USN interventions have other limitations: low ecological validity and poor generalization to real-world contexts, limited multisensory integration, short-lived effects, reduced motivational engagement, and poor protocol customization. These constraints justify the interest in neuroengineering technologies such as virtual reality and robotics, which are capable of offering immersive environments, multisensory feedback, and more ecological and adaptive training [25]. 3D technologies act through multisensory and motor engagement, fostering body–space integration. In personal neglect, body-centered or avatar-based feedback enhances awareness of the contralesional side; in peripersonal neglect, interactive 3D reaching tasks strengthen visuo-motor coupling and spatial attention within near space; in extrapersonal neglect, 3D navigation supports reconstruction of far-space representations. VR systems can integrate visual, motor, and attentional feedback, promoting spatial adaptation in contexts closer to real-world environments [25]. Overall, immersive environments promote spatial recalibration across domains more effectively than 2D methods. The main features of the technologies considered in this review (VR and robotics) were analyzed and reported (Table 2). Although 3D measures exist in literature [26], it remains a little-considered aspect in the evaluation of USN symptoms. Despite the existence of national guidelines [27] on conventional USN assessment and treatment, there is still no specific consensus on approaches, nor innovative technologies such as robotic rehabilitation or virtual reality (VR) considered. These emerging healthcare technologies are reshaping stroke management by offering personalized and engaging therapy modalities that leverage neural plasticity to enhance recovery [28]. Additionally, these technologies are more often embedded with wearable sensors, able to objectively assess high-resolution users' functionalities [29, 30]. As an example, VR provides promising alternatives for USN assessment and treatment by enabling precise control of visual stimuli (and in some cases auditory) in 3D environments, an advantage over traditional 2D tools [31]. Similarly, robot-assisted arm training (RAT), by offering repetitive movement of the upper limbs in multiple control modalities (e.g., assistive, assist-as-needed, resistive [32]), can generate motor stimuli for the USN treatment and assessment [33]. These technological advancements not only enhance motor recovery but also offer innovative solutions for addressing cognitive deficits [34], including USN [35]. By integrating immersive 3D environments and adaptive interventions, they hold the potential to improve the precision of assessments, the effectiveness of treatments, and consequently, patient recovery.

Within this framework, the objective of this systematic review is to analyze the state-of-the-art technologies for the 3D assessment and/or treatment of post-stroke survivors affected by USN. More specifically, details on the characteristics, level of readiness, and reference outcomes of these technologies will be investigated.

Methods

Study design

This systematic review has been performed following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [36]. The protocol was registered on PROSPERO (ID CRD42023464275).

Selection criteria

The selection criteria for this systematic review followed the Population, Intervention, Comparison, and Outcome (PICO) framework [37]. More specifically, the selection criteria were formulated as follows.

Population criteria

In this study, we included adult patients (age ≥ 18) affected by stroke and with USN of any kind. USN subtypes were defined across three categories:

- Spatial domains: Personal, peripersonal and extrapersonal space [38]. Personal neglect is defined as a lack of exploration or awareness of the side of the body opposite the brain lesion, as seen for example in dressing only one side of the body. Peripersonal neglect refers to neglect behaviors occurring within reaching distance (near space), such as failing to eat food on one half of a plate. Extrapersonal neglect refers to neglect behaviors occurring in far space, for instance inadvertently contacting obstacles like doorways when walking.
- Frames of reference [39]: Egocentric and allocentric neglect [40]. Egocentric neglect relates to a self-centered (viewer-centered) frame of reference, where stimuli on the contralesional side of space relative to the body are ignored. Allocentric neglect refers to a failure to attend to the contralesional side of individual objects, independent of their spatial location (object-centered or object-based frame).
- Sensory modalities: visual, tactile, and auditory neglect [38]. Visual neglect involves failure to attend to visual stimuli on the contralesional side, tactile neglect refers to reduced awareness of tactile stimuli on the contralesional side of the body, and auditory neglect to impaired perception or localization of sounds coming from the contralesional side.

Patients were included independently of the type of stroke, time post-onset, and side of the lesion. Additionally, no criteria were imposed on the presence and level of hemiplegia of the patients. In cases where no patient

Table 1 Search string for each database

Database	Search string
Pubmed	((stroke [Mesh] OR ((cerebr* OR brain OR intracran*) AND (ischem* OR hemorr* OR haemorr*))) AND (neglect OR hemispat* OR neglig* OR inatt* OR hemineg* OR visuosp* OR attent* OR visuopercept*)) AND ((technology [Mesh] OR technol* OR instrum* OR device) OR (exos* OR end-effector OR robot* OR suit OR robotics [Mesh] OR mechatron* OR electric*) OR (wearab* OR IMU OR acceleromet* OR inertial OR wearable electronic devices [Mesh] OR sens*) OR (reality AND(augmented OR virtual OR mixed)) OR virtual OR immersive OR VR OR virtual reality [Mesh] OR visor* OR visual stim* OR computer-assist* OR game* OR gami*) AND (3D OR ((three OR 3) AND dimension*) OR spat* OR space OR depth OR environment* OR stereo*)
Web of Science	TS=(((stroke OR ((cerebr* OR brain OR intracran*) AND (ischem* OR hemorr* OR haemorr*))) AND (neglect OR hemispat* OR neglig* OR inatt* OR hemineg* OR visuosp* OR attent* OR visuopercept*)) AND ((technology OR technol* OR instrum* OR device) OR (exos* OR end-effector OR robot* OR suit OR robotics OR mechatron* OR electric*) OR (wearab* OR IMU OR acceleromet* OR inertial OR wearable electronic devices OR sens*) OR (reality AND (augmented OR virtual OR mixed)) OR virtual OR immersive OR VR OR virtual reality OR visor* OR visual stim* OR computer-assist* OR game* OR gami*) AND (3D OR ((three OR 3) AND dimension*) OR spat* OR space OR depth OR environment* OR stereo*))
CENTRAL	(((stroke OR ((cerebr* OR brain OR intracran*) AND (ischem* OR hemorr* OR haemorr*))) AND (neglect OR hemispat* OR neglig* OR inatt* OR hemineg* OR visuosp* OR attent* OR visuopercept*)) AND ((technology OR technol* OR instrum* OR device) OR (exos* OR end-effector OR robot* OR suit OR robotics OR mechatron* OR electric*) OR (wearab* OR IMU OR acceleromet* OR inertial OR wearable electronic devices OR sens*) OR (reality AND(augmented OR virtual OR mixed)) OR virtual OR immersive OR VR OR virtual reality OR visor* OR visual stim* OR computer-assist* OR game* OR gami*) AND (3D OR ((three OR 3) AND dimension*) OR spat* OR space OR depth OR environment* OR stereo*))
Scopus	TITLE-ABS-KEY (((stroke OR ((cerebr* OR brain OR intracran*) AND (ischem* OR hemorr* OR haemorr*))) AND (neglect OR hemispat* OR neglig* OR inatt* OR hemineg* OR visuosp* OR attent* OR visuopercept*)) AND ((technology OR technol* OR instrum* OR device) OR (exos* OR end-effector OR robot* OR suit OR robotics OR mechatron* OR electric*) OR (wearab* OR IMU OR acceleromet* OR inertial OR wearable electronic devices OR sens*) OR (reality AND(augmented OR virtual OR mixed)) OR virtual OR immersive OR VR OR virtual reality OR visor* OR visual stim* OR computer-assist* OR game* OR gami*) AND (3D OR ((three OR 3) AND dimension*) OR spat* OR space OR depth OR environment* OR stereo*))

sample was included, eligibility criteria were based on the target population for which the technology was designed. Preliminary studies involving healthy participants were also included to explore feasibility and initial efficacy.

Intervention criteria

Any technology (exclusively electrical, electro-mechanical, or based on mechatronics) developed for assessment and/or treatment purposes, exploring space (three-dimensional – 3D), was included. Technologies were considered only when utilizing the 3D movement for the intervention or assessment. Regarding digital representation, 3D ones were included, with edge cases involving 3D representations displayed on planar screens. Technologies limited to neurophysiopathological assessment and/or stimulation (e.g., electroencephalography or electro-magnetic stimulations) were also excluded from the study to reduce the heterogeneity across technologies.

Comparison criteria

None or any comparison was included.

Outcome criteria

Any outcome measure was considered.

Type of studies

In this review, we considered only primary studies, excluding reviews, overviews, study protocols, and abstract proceedings. Additionally, no restriction was applied on the publication date of the studies; however, only studies in English and with available full text were screened.

Search method for the identification of the studies

The search was conducted on the 18th of September 2023 on four different databases, namely CENTRAL, PubMed, Web of Science, and Scopus.

The search string was designed following the PICO framework [37], utilizing keywords such as "Stroke", "Technology", "Robotics", "Wearable electronic devices", and "Virtual reality" (Table 1).

Once the records were retrieved from the databases, a check of duplicates and screening were performed on Covidence [41]. The screening was performed first at the title and abstract level, and subsequently at the full-text level. For the title and abstract screening, three couples of independent reviewers were involved, while during the full-text screening, only two couples of independent reviewers were involved. In both cases, in the presence of conflict over the inclusions, another reviewer was involved.

Data collection

The data extracted from the included studies concerned:

- Source of data: authors, study design, year of publication, DOI;
- Study population and intervention:
  - Participants' characteristics: number of participants, diagnosis, age, time from stroke, type of USN;
  - Methodology description: type of technology used, dose and frequency of the intervention (if present), readiness of technology;
  - Control description: presence and type of control treatment or assessment;
- Study outcomes and performances:
  - Outcome description: outcome type, measure, and timing;
  - Technology performance: type of analysis performed and results obtained.

Risk of bias assessment

Given the inclusion of both technologies for treatment and assessment of USN, a high heterogeneity of study designs was present among the included studies. For this reason, three different risk of bias (RoB) tools were used, depending on the design of the evaluated study; in particular:

- The Risk of Bias 2 (ROB2) [42] was used for Randomized Controlled Trials (RCTs);
- The Risk Of Bias In Non-randomized Studies - of Interventions (ROBINS-I) [43] was used for Non-Controlled (NCT) and Non-Randomized Controlled Trials (NRCT);
- The Risk Of Bias In Non-randomized Studies - of Exposures (ROBINS-E) [44] was used for observational studies;
- Technical studies (TS) were excluded from this analysis, as they did not include experiments on human data.

Data synthesis

To ensure clarity and coherence, the section of results is structured as follows. First, we provided a description of the study design, with a distinction between technical studies (TS) and clinical studies. TS were excluded from the analysis as they do not provide clinically relevant outcomes for the target population but were included in the systematic review for their methodological and technological contributions, which help contextualize findings and inform future clinical studies. Clinical studies are evaluated based on RoB, study population and interventions, and study outcomes and performances. The results are first presented as a whole to provide an overall view, followed by a distinction between studies focusing on assessment and those addressing treatment technologies.

Due to the heterogeneity of the selected studies, in terms of technologies used and outcomes assessed, a meta-analysis was not performed. Instead, a quality analysis, based on the data extracted from the systematic search, and a narrative synthesis of the selected papers were conducted. Studies were categorized and analyzed based on the technology employed, either for USN assessment or treatment. TS without patients were excluded from the analysis, since, while providing valuable insights into the technological readiness and potential applicability of 3D systems, these studies fall outside the scope of the present analysis.

Firstly, a clinical description of the population was provided, including a characterization of age, time since the event and type of stroke (acute, sub-acute and chronic), and details regarding the presence and characteristics of USN [38–40].

Then, the relationships between sample size, study design, and the use of treatment and assessment technologies in the included studies were examined. Analysis also examined the prevalence of technology macro-types, the use of robotics, wearable sensors, non-physiological stimulations, and the level of technological readiness (fully commercial, prototypical software integration of commercial devices, and fully prototype), as well as the degree of immersivity of VR utilized.

With regard to the outcomes, a classification was performed (Supplementary Table 1; Additional file 1) according to the International Classification of Functioning, Disability, and Health (ICF) framework [45]. For each outcome measure, the ICF classification was provided in terms of domains (e.g., b: "Body functions" - letter) and categories (e.g., b110: "Consciousness functions" - digits). Then, outcome measures were aligned with the major ICF domain (letter)-category (digit) pair (letter and first digit) to ensure a structured and consistent analysis.

Finally, we provided a description of the technology performances for all study types except for TS. In this part, the point of view of the analysis transitions from a study-specific perspective to an outcome-specific perspective, offering a detailed analysis of the data. Specifically, for studies involving assessment technologies, the examined performance metrics were those related to the analyzed psychometric properties. For the studies involving treatment technologies, performances were classified into three categories: descriptive analysis, usability analysis, and inferential and effect analysis. The first concerned the statistical description of the sample undergoing the intervention; the second involved the use of dedicated usability tools, and the third included correlations or associations between the technologies and the comparison of the effects of the intervention group with respect to a control. For both cases, a specification of the number of analyses, number of studies, and metrics used was also provided.

Results

Study design

In this study, a total number of 37 papers was included out of 2891 (Fig. 1). Among the eligible 197 papers, the main reason for exclusion was related to intervention (no technology [46, 47], neurophysiological [48, 49], only mechanical [50, 51], no 3D [52–54]).

Analysis included 15 assessment-focused papers [55–69] and 17 treatment-focused [70–86]. The remaining five studies were identified as TS [87–91]. With no temporal constraints applied to the string search, the included papers were published between 2004 and 2023, with a median publication year of 2018. For what concerns the study design, a variety of designs were observed among the selected studies. Most papers included in the analysis are either longitudinal studies focused on treatment or cross-sectional studies focused on assessment. Only Eskes et al. [71] is a cross-sectional study that focuses on the feasibility of functional electrical stimulation (FES), and this is therefore classified as a treatment-focused paper.

The majority were observational studies (ObS), totaling 15 papers [55–69]. These were followed by NCTs, which accounted for five studies [70–74]. RCTs and NRCTs both represented the smaller fractions, with a total of nine studies (five RCTs [75–79] and four NRCTs [80–83]). A minor subset of three papers employed a case study design with an intervention (CSInt: three studies [84–86]). Further information on each interventional study is available in Supplementary Table S2 (Additional file 2), which details the intervention protocols, outcome measures (and corresponding ICF domains), statistical methods, and main findings. Focusing on the five RCTs, we analyzed the differences in improvement between groups to determine the specific effect of technology-based interventions compared with conventional therapy. Regarding outcomes measured with clinical and functional scales, results were inconsistent across studies. Most trials that used the Catherine Bergego Scale (CBS) and the Modified Barthel Index reported no significant between-group differences [76–78], with the only exception of one study showing an effect on the CBS [79]. Other scales, such as the Fugl–Meyer Assessment for the Upper Extremity and the World Health Organization Disability Assessment Schedule, showed significant between-group effects difference in one study [76].

For performance-based paper-and-pencil measures, significant between-group differences in favor of the intervention group were more frequently reported. Improvements were found in tests of visual search and spatial exploration, including cancellation tasks (e.g., Star, Letter, and Bells Cancellation Tests) and the Behavioral Inattention Test [75, 76, 79], although no significant between-group difference was reported for the Star Cancellation Test in Shin et al. (2023). Results for the Line Bisection Test, which evaluates spatial bias rather than active visual search, were less consistent, showing no significant between-group differences in some studies [75, 79], but significant effects in others [77, 78].

Overall, the small number of RCTs and the heterogeneity of outcome measures make direct comparison difficult and prevent firm conclusions about the effectiveness of the interventions.

Technical studies

TS are characterized by a cross-sectional design and focus on assessment technologies. All the studies (5 in total) employed electrical technology and involved groups of healthy participants. Among these studies, 4 out of 5 employ completely immersive VR systems [88–91], 3 studies incorporate wearable sensors [87, 88, 90] and only 1 study involves the use of physiological stimulations [90].

Clinical studies

Risk of bias results

The analysis of the RoB contextualizes the reliability and validity of the results, offering insights into the included studies (Fig. 2). In this review, five RCTs were evaluated using ROB2, a tool designed to assess the RoB in randomized trials. A total of 12 non-randomized studies were assessed with the ROBINS-I, which is suited for studies evaluating interventions in non-randomized settings. The remaining 15 observational studies were evaluated using the ROBINS-E, a tool designed for non-interventional studies that explore associations between exposures and outcomes. Among the five RCTs assessed using the ROB2 tool, 3 (60%) were classified as having a "low" RoB [76–78], while two was classified as having a "moderate" RoB [75, 79]. For the studies with moderate risk, the main concerns were related to Domain 4 (bias in the measurement of the outcome). Regarding the 12 non-randomized studies evaluated with ROBINS-I, four (33.3%) studies were classified as having a "low" RoB [72, 80, 82, 84]. Eight (66.7%) were categorized as having a "moderate" RoB [70, 73, 74, 81, 83, 85, 86], primarily due to the lack of control for confounding factors, and bias in the selection of the reported results. Lastly, one work (8.33%) had a "high" overall RoB [71], largely due to insufficient control of confounders and potential measurement biases. Of the 15 observational studies assessed using the ROBINS-E tool, eight (53.3%) were classified as having a "moderate" RoB [57, 60–62, 66–69], while the remaining seven (46.7%) were classified as having a "low"

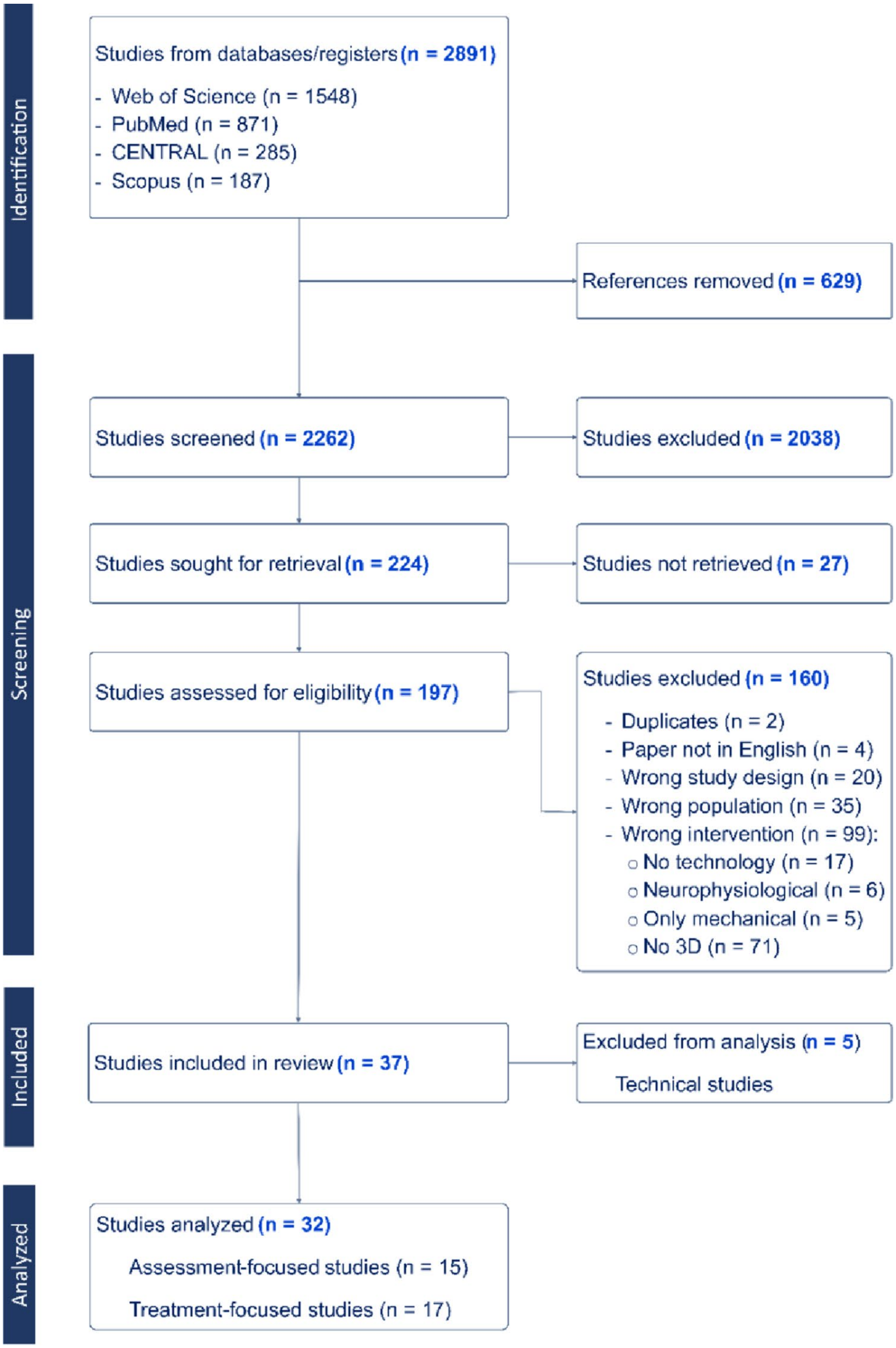

Fig. 1 PRISMA workflow diagram. *n* numerosity

RoB [55, 56, 58, 63–65]. For the studies with a moderate risk, the primary concerns were related to Domain 1 (bias due to confounding), Domain 6 (bias arising from measurement of the outcome), and Domain 7 (bias in the selection of reported results).

Study populations and interventions

All assessment studies included at least one cohort of participants, which could consist of patients, healthy individuals, or a mix of both. However, only five studies focused exclusively on cohorts of patients. Similarly, in treatment studies, an experimental group of patients was always included. In 11 studies, these groups consisted

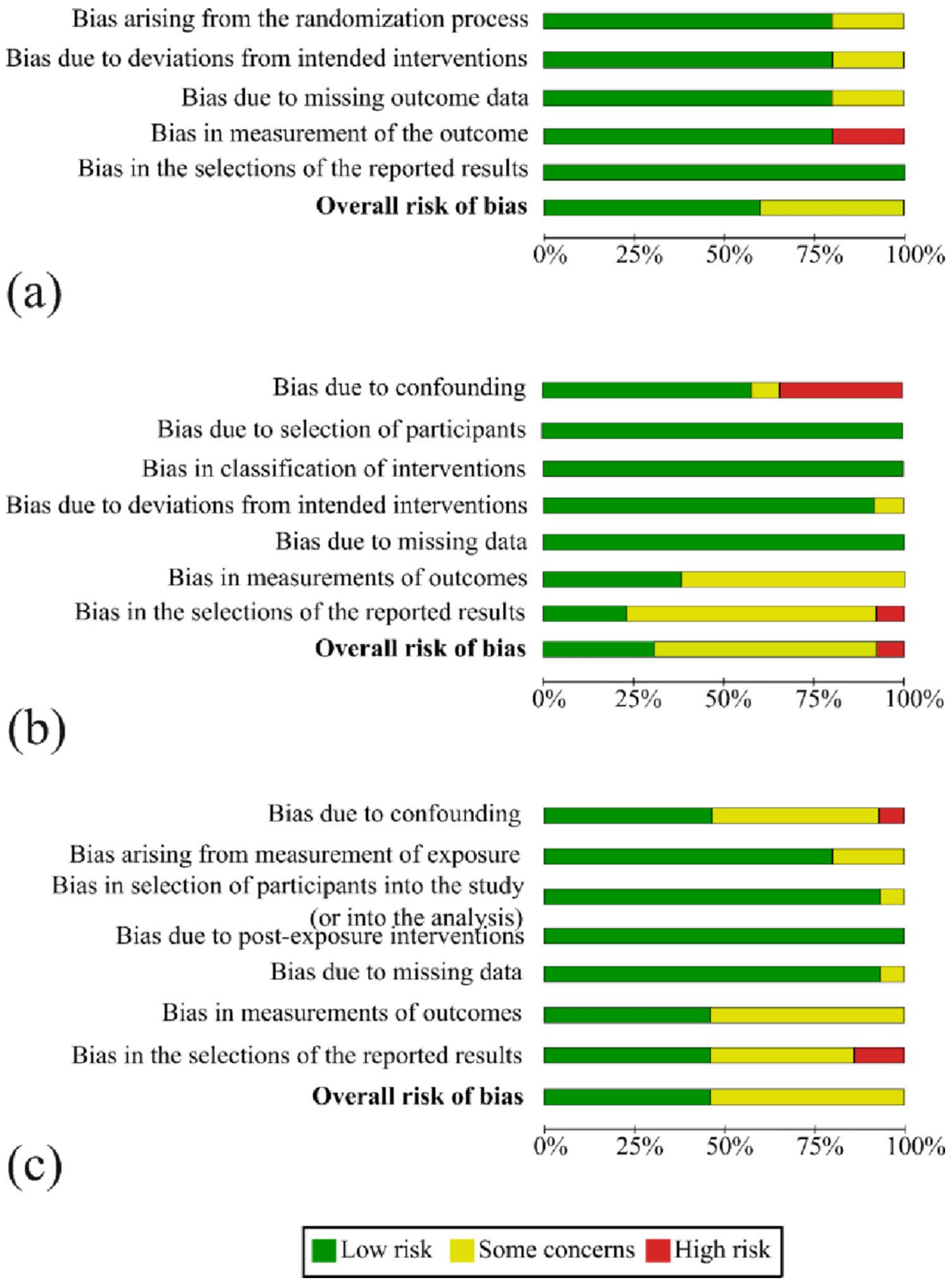

Fig. 2 Summary of the risk of bias (RoB) assessment across three different tools: **a** ROB2, **b** ROBIN-I, and **c** ROBIN-E. Each bar represents the RoB for specific domains within randomized trials (ROB2), non-randomized intervention studies (ROBIN-I), and non-randomized exposure studies (ROBIN-E). The color coding indicates the level of risk: green for low risk, yellow for some concerns, and red for high risk. The overall RoB for each tool is shown at the bottom of each section. *ROB2* Risk Of Bias 2, *ROBIN-E* The Risk Of Bias In Non-randomized Studies - of Exposures, *ROBIN-I* The Risk Of Bias In Non-randomized Studies - of Interventions

exclusively of patients, without the involvement of healthy participants. Studies without patients, involving only healthy control groups, were classified under the TS category. Enrolled cohorts ranged from 1 to 41 patients per study (Supplementary Table S3; Additional file 3). The median age [interquartile range (IQR)] for the group of patients in all studies is 60.0 [7.9].

Assessment studies have a population with a median age [IQR] of 60.1 [6.0], instead treatment studies have a median age [IQR] of 61.9 [13.1]. Regarding the time from the event, most papers considered chronic patients [55–58, 61, 62, 66, 69–72, 74, 79, 82]. Four assessment studies and three treatment studies did not report the stroke phase but instead provided only the timing after the stroke. Additionally, two papers from the last group did not report either the stroke phase nor the time from the event. Fordell et al. [60] reported assessments from 1 to 20 weeks post-stroke; Kim et al. [63] assessed patients with hemispatial USN at 3.9 ± 3.2 months and those without USN at 2.2 ± 1.7 months post-stroke; Ogourtsova et al. [67] assessed patients with USN at 1.6 ± 1.0 months and those without USN at 2.0 ± 2.1 months and Ulm et al. [68] between 2 weeks and over 3 months.

Concerning the treatment studies, Ansuini et al. [83] presented patients with a dorsal fronto-parietal lesion at 59 days post-stroke and patients with a ventral temporo-parietal group at 58 days; Shin et al. [78] included individuals with chronic stroke (12.0 ± 15.5 months after the stroke), and Stammler al. [75] included individuals at 138.4 ± 192.1 days post-stroke.

For what concerns the USN specification, few studies reported the type of USN observed in patients. Specifically, only 11 studies identified the type of neglect domains, with the majority of these papers focusing on the extrapersonal domain [62, 63, 71, 73, 75, 81] (two for assessment and four for treatment). The largest category within the frames of reference is the allocentric domain, with five papers employing treatment technology [70, 72, 74, 80, 81]. Finally, regarding the modalities of sensory neglect, the most studied category across the papers is the visual domain, with seven papers in total (five employing treatment technology [70, 80, 82–84] and two focused on assessment [55, 67]).

The analysis of the technologies revealed distinct trends in the types of technologies employed across the reviewed studies, with notable differences between treatment and assessment ones (Fig. 3). In general, only four studies employed electro-mechanical technologies [72, 73, 76, 82], each characterized by a longitudinal design and a treatment focus; however, all other studies relied on electrical technology. In particular, only Kang et al. [74] uses an electro-mechanical technology but without robotics. In general, robotics is rarely used, with only the end-effector being employed in two studies that use treatment technologies [72, 82]. Regarding technological readiness, the prototypical software integration of commercially available hardware solutions appears to be the most common solutions [57–63, 65, 68–71, 73, 75–77, 80, 83, 85, 86], both for assessment and treatment. The other works employs fully commercial devices [55, 56, 64, 66, 67, 72, 74, 78, 79, 81, 82, 84], both for assessment and treatment.

Physiological stimulations were used in a few studies and all of these focused on treatment [71, 72, 78]. Completely immersive and non-immersive VR were the most frequently employed types of virtual reality across both treatment and assessment studies. In contrast, other types of VR, such as augmented [57–59, 75] and mixed reality [83, 85], were used exclusively in treatment-focused studies. Details about technical solutions adopted in all analyzed studies are provided (Supplementary Table S4; Additional file 4), and a schematic representation illustrating the working principle of the different technologies is presented in Fig. 4.

Study outcomes and performances

All types of outcomes were included in the analysis, categorized based on the technology used for assessment and treatment. Specifically, the clinical or functional aspects of neglect addressed by each outcome were categorized into the domains b, d, and NoICF (Fig. 5). Then, a further itemization was performed within the b and d domains, dividing them into their main categories. For domain b, the categories included b1, b2, b7, and the combined categories b1-b2 and b1-b7. For domain d, the categories included d1, d2, d4, d5, and the combinations d1-d4 and d4-d5. In treatment studies, outcomes classified under the b domain accounted for 41.6%, whereas in assessment studies they represented 28.9%. In both cases,

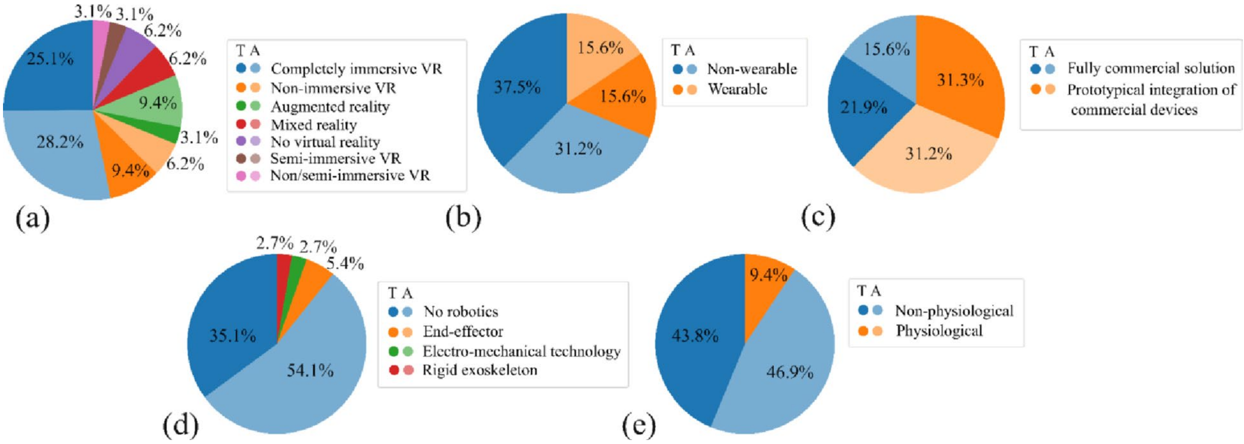

Fig. 3 Pie charts showing the distribution of technological characteristics in treatment and assessment studies. **a** virtual reality types; **b** sensors; **c** levels of technological readiness; **d** robotics; **e** stimulations. *A* Assessment, *T* Treatment, *VR* Virtualreality

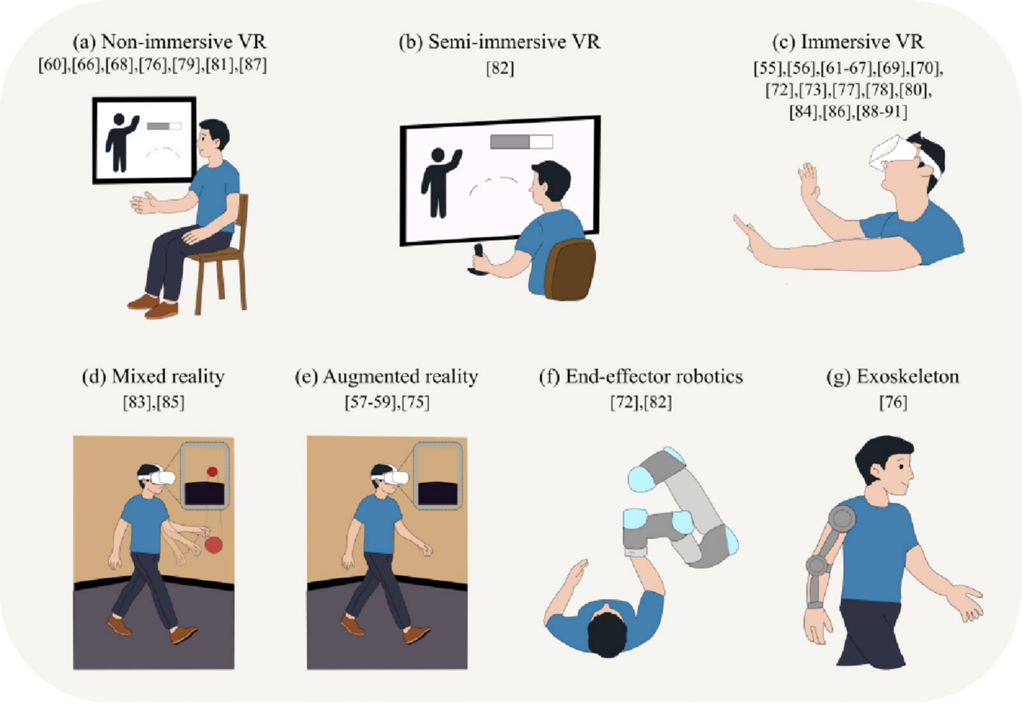

Fig. 4 Schematic representation of the components and working principles of technologies. Each panel represents the typical setup and mode of interaction for patients, with corresponding references to the studies included in the review: **a** non-immersive VR: screen-based tasks with limited interaction, **b** semi-immersive VR: projection or large-screen environments with interaction and sensory feedback, **c** immersive VR: head-mounted display for full 3D immersion, **d** mixed reality: combination of real and virtual stimuli, **e** augmented reality: real environment enhanced with digital cues, **f** end-effector robotics: robotic device guiding upper limb movements, and **g** exoskeleton-based systems: wearable robotic support for upper limb movements

the b domain was the most frequently represented. The domain d accounted for 24.9% overall, with a predominance of 13.9% observed in assessment-focused articles. In addition, 4.6% of the outcomes fell outside the ICF framework (usability, acceptability, not validated tools).

For the main categories within domain b, the most frequent is b1, primarily associated with treatment technologies (46.7%), followed by assessment technologies at 35.2%. In contrast, within domain d, nearly half of the outcomes fall under category d1, predominantly linked to assessment technologies (46.4%), followed by category d5 from treatment technologies (25.5%).

Detailed insights into the performance of the selected studies, organized by the types of analysis for treatment studies (Supplementary Table S5A; Additional file 5) and psychometric properties (only validity) for assessment studies (Supplementary Table S5B; Additional file 6) are available in supplementary materials.

Assessment studies (Supplementary Table S5B; Additional file 6) exclusively focused on evaluating the validity of the tools used. They examined construct, criterion, and face validity through a range of statistical methods, such as Analysis of variance (ANOVA) for construct validity, Bland-Altman plots for criterion validity—both concurrent and predictive—and usability or perception questionnaires for face validity. Treatment studies (Supplementary Table S5A; Additional file 5) employed pilot analyses, focusing on descriptive statistics (means, standard deviations), to assess sample characteristics and usability. Then, the inferential and effect analyses included statistical tests such as ANOVA, Wilcoxon, paired t-tests, and correlation measures, commonly reporting means, standard deviations, p-values, and effect sizes for pre- and post-treatment or interventional and control groups comparisons.

Discussion

This study examines the potential of 3D technologies to tackle USN, a condition that significantly impacts post-stroke recovery and QoL [2, 6]. Conventional 2D assessment methods remain effective and foundational; innovative approaches—such as robotic rehabilitation and virtual reality could play a complementary role by addressing aspects less readily captured in 2D tasks. These technologies have the potential to harness neural plasticity to enhance recovery [28]; in particular, VR provides promising alternatives for USN assessment and treatment by enabling precise control of visual stimuli (and in some cases auditory) in 3D environments, an advantage over traditional 2D tools [31]. Similarly, RAT, by offering repetitive movement of the upper limbs in multiple control modalities (e.g., assistive,

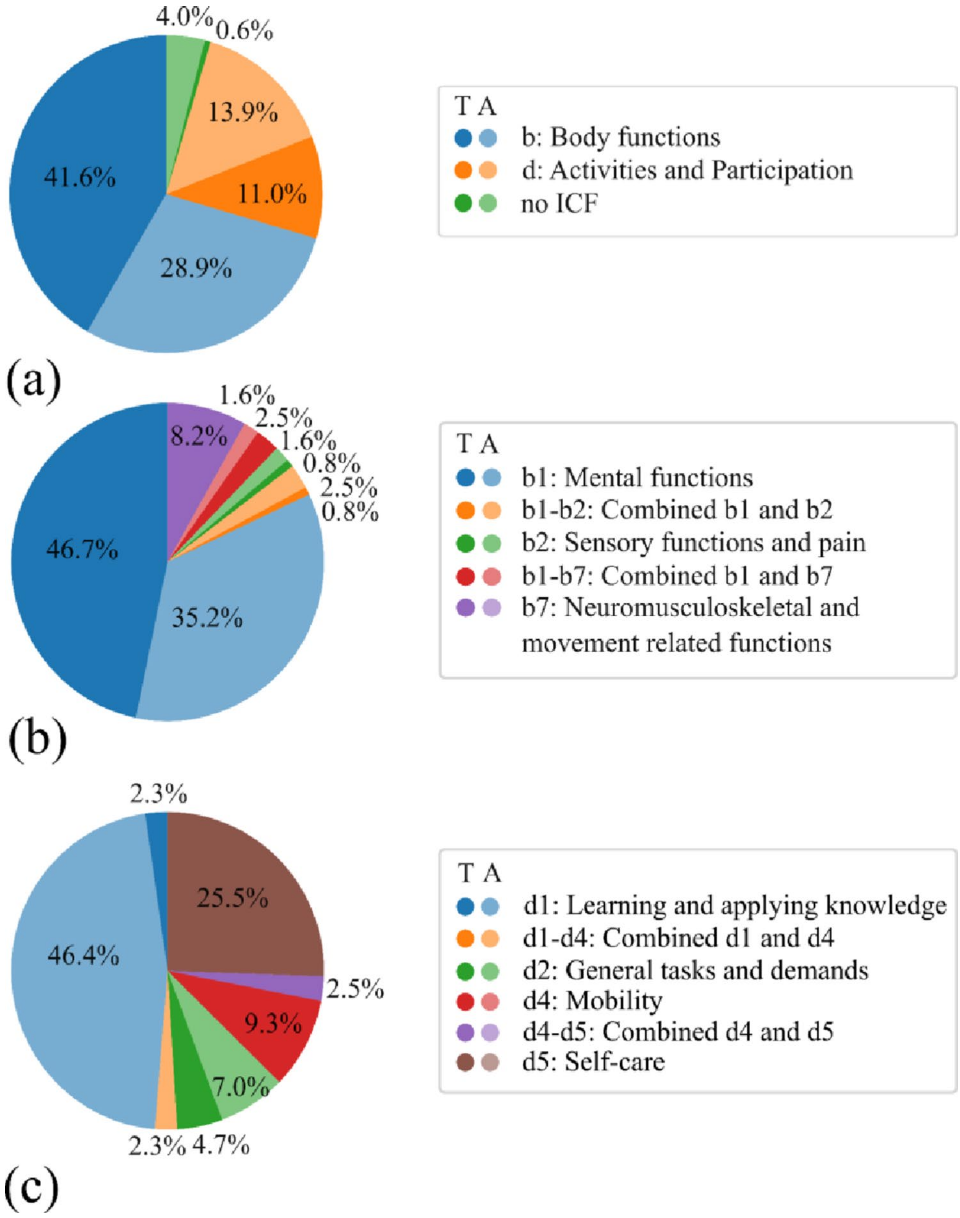

Fig. 5 Pie charts showing the distribution of International classification of functioning (ICF) domains and subcategories in treatment and assessment studies. **a** Overall distribution of the main ICF domains across all included studies. **b** Distribution of b domain. **c** Distribution of d domain. The values are expressed as percentages. *A* Assessment, *ICF* International classification of functioning, *T* Treatment

assist-as-needed, resistive), can generate motor stimuli for USN treatment and assessment [32, 33]; both classes of systems can be integrated with wearable sensors for high-resolution assessments [29] that may offer personalized and engaging approaches suited to the 3D nature of USN. At the neurophysiological level, immersive 3D paradigms may modulate attentional circuits (e.g., fronto-parietal dorsal/ventral attention networks) and facilitate interhemispheric plasticity through controlled visuomotor stimuli. The integration of sensorimotor feedback in 3D may engage multisensory convergence zones (e.g., posterior parietal cortex), thereby strengthening connections between sensory input and motor planning (sensorimotor integration) [92]. From a cognitive perspective, 3D interventions may enhance top-down spatial attention by promoting voluntary reorientation toward the contralesional side and reducing ipsilesional bias. Immersive and interactive tasks foster active sensorimotor integration, linking visual, proprioceptive, and motor inputs to rebuild coherent body–space representations [93]. These experiences also encourage adaptive learning through continuous feedback and increase body awareness via avatar-based or embodied feedback. Together, these mechanisms facilitate spatial recalibration and attentional redistribution in patients with USN [92]. This review emphasizes their ability to improve assessment precision and therapeutic outcomes [28, 31], and examines state-of-the-art 3D technologies for the assessment and treatment of post-stroke survivors with USN.

The heterogeneity in study designs reflects the different approaches used to investigate the 3D technologies for USN. About half of the clinical studies included are studies of intervention (17). Among the observational studies (focusing on neglect assessment, 15), 14 studies are cross-sectional. Only the study by Dvorkin et al. adopts 3D technologies in monitoring neglect in a follow-up study after 10 months on a reduced pool of two patients [58]. Although no quantitative analysis was conducted, this qualitative assessment of RoB allowed us to systematically appraise the methodological rigor of the included studies. This approach was consistent with the aims of our review, which focused on providing a comprehensive and descriptive synthesis of the available evidence rather than a meta-analytic evaluation. Through this qualitative approach, we were able to identify common methodological limitations and patterns across studies, which offered valuable insights into the strengths and weaknesses of current research in this field. At the same time, it is important to recognize that many of the studies included in this review were conceived as proof-of-concept investigations. These exploratory designs aim to demonstrate feasibility, usability, and the potential value of 3D technologies in neglect assessment and rehabilitation, rather than to provide definitive evidence of efficacy through RCT methodology. Such studies play a foundational role in innovation, generating preliminary data that inform and justify larger, controlled trials.

The analysis of the RoB revealed that controlled studies with high RoB primarily faced challenges in the domain of outcome measurement, due to non-blinded assessors or inconsistencies in evaluation protocols. These factors may impact the reliability and validity of the results, underscoring the importance of standardizing assessment procedures to minimize potential biases [94]. Non-controlled and observational studies exhibited variability in the RoB, particularly concerning confounding (Domain 1). As a result, observed differences in outcomes may reflect not the intervention itself but rather pre-existing participant characteristics, environmental factors, or other external influences. In non-controlled studies, the high level of confounding is largely attributed to small sample sizes (e.g., Chen et al. [70]). The lack of a control group further complicates the interpretation of improvements in spatial neglect, as it becomes unclear whether these improvements are due to the proposed technology or are influenced by factors such as spontaneous recovery, placebo effects, or concurrent rehabilitation activities. Another limitation of longitudinal studies lies in the long intervals between assessments, which may hinder the ability to directly link patient performance to the presence or severity of USN. Given that USN-related behaviors can fluctuate over short periods, delayed measurements may not accurately reflect the dynamic nature of the condition. In the study by Morse et al. [66], the authors highlight the potential for selection bias due to participant recruitment that may not be representative of the broader stroke survivor population. This could introduce confounding variables related to participant engagement and support, potentially affecting both their responses and the study outcomes. Additionally, in this observational study, the authors acknowledge the small sample size and lack of randomization as limitations that may impact the generalizability of their findings. Additionally, moderate risks were observed in the domain of outcome measurement, indicating that the reliability of the outcomes could be improved and some concerns were presented regarding selective reporting. This suggests that there may be variability in how results are selected or presented, raising questions about the completeness of reporting in the literature. Such factors could influence the interpretation of findings and underscore the need for more comprehensive reporting in future studies to provide a clearer and more balanced view of the evidence [95].

Nonetheless, shifting the focus to the specific technologies employed in the studies: VR technologies are the most used, while robotic approaches are comparatively less represented. Broeren et al. [82], Chen et al. [76], and Fordell et al. [72] were the only studies employing robotic technology, and its use was exclusively in treatment-focused applications. The results indicate that robotics is always accompanied by VR systems, such as non-immersive, semi-immersive, and completely immersive VR. Probably, the potential advantage or robotics compared to other tools, that is the ability to facilitate repetitive movements and allow actions assisted or against resistance, might not hold significant relevance for this specific application. In addition, an important advantage of robotic technologies is that they can enable people with stroke to respond with their contralesional hemiparetic arm. By facilitating the active use of both hands, robotic systems may therefore better support the recovery of functional skills required in daily activities. However, in terms of treatment technologies, robotics can certainly provide valuable insights and offer the opportunity to implement motor cues. The limited use of robotics in assessment technologies, although their technical complexity and patient experience are comparable to those of VR systems, may be attributed to factors such as greater mechanical complexity, higher costs and space requirements [96]. One of the main limitations of robotic systems lies in the restricted domains they can explore.

Broeren et al. [82] and Fordell et al. [72] proposed end-effector solutions for treating USN, while Chen et al. [76] utilized a rigid exoskeleton. All these technologies contribute to the motor rehabilitation of the upper limbs. However, the range of motion of these robotic systems constrains patient movement to their personal space, making it impossible to explore the potential benefits of robotic technologies in the extrapersonal space.

A key focus of this review is the assessment and rehabilitation of USN in 3D space, where the extrapersonal space plays a crucial role [55, 56, 60–69]. Although some studies in the literature have employed robotic systems for USN treatment, their contributions are largely limited to the planar case [97]. In this sense, the analysis of existing VR technologies for assessment and treatment for the USN appears to offer more information, as VR has been specifically developed to explore 3D tasks. Assessment tools for USN utilizing VR can provide multisensory cues, enable precise mapping of deficient spatial areas, and support a wide range of movement, from personal to extrapersonal space, and offer high accuracy and sensitivity. Regarding USN treatment, VR systems are significantly more intuitive for inexperienced users to learn and operate than robotic systems. Indeed, VR technologies provide patients with a variety of multisensory cues. For instance, VR headsets, being commercial systems, already include features that allow for the integration of these stimuli without the need for additional modifications. In contrast, the use of an end-effector robot primarily provides motor cues; incorporating other types of feedback (e.g., visual or auditory) would require adding external sensors and adapting the existing technology, thereby increasing costs and development time. On the other hand, the use of exoskeletons often requires a long training period for patients to become accustomed to the device, further complicating the process. Interestingly, the literature lacks examples of studies using robots other than exoskeletons or manipulators to assess or treat USN, such as humanoid robots or social robots. Examples involving humanoid or animaloid robots could offer valuable insights into this area [98].

In contrast, VR systems are often more accessible and user-friendly, facilitating their integration into rehabilitation programs either in person or by adopting a telerehabilitation system [99, 100]. The use of RAT in the 3D assessment and rehabilitation of USN remains limited, although several studies have demonstrated its potential to support movements constrained to a low-dimensional (2D) space with a limited degree of freedom [35]. While there are a greater number of VR tools available, a notable gap remains that is worthy of exploration: the effectiveness of motor cues in the rehabilitation of USN, a domain that virtual reality cannot address in the same way. Limb activation has been shown to reduce visuospatial deficits in patients with USN [97, 101–103]. Additionally, somatosensory activation of the contralateral side during limb activation has been demonstrated to facilitate the neural circuits underlying spatial representation, which may help in the rehabilitation of USN [71, 104]. Moreover, the possibility to deliver both assistive and resistive forces allows therapists to adapt the level of support or challenge to the patient's motor abilities, thereby promoting engagement of the affected limb while preventing compensatory strategies that may reinforce neglect. These features make robotics a powerful complement to VR in multimodal interventions: while VR environments primarily target attentional, perceptual, and cognitive components of neglect, robotics can simultaneously enhance motor rehabilitation and sensorimotor integration. From a practical standpoint, VR may be more suitable for patients with sufficient cognitive engagement, whereas robotics better serves those with marked motor impairment or reduced autonomy. Clinical integration should consider safety, cognitive load, and therapist supervision to tailor technology use to individual profiles [105].

Table 2 Comparison of main characteristics of the studies with robotics and VR

	General features	Assessment	Treatment
Robotics	- Underutilized - Always accompanied with a VR system - Longer patient training time - Hard to deploy at home		- Precise, repetitive motor training - Supports assisted/resistive movements - Adapt to degree of difficulty and patients' motor abilities
VR	- Widely adopted - Suitable for telerehabilitation and home use - Intuitive interface - Limited in providing motor cues - Less effective for tasks requiring force feedback or resistance	- Multisensory cues (e.g., visual, auditory) - Precise mapping of deficient areas - Wide movement range (from personal to extrapersonal space) - High accuracy and sensitivity	- It is possible to re-create links between the affected and the non-affected space in patients with neglect - Adapt to degree of difficulty and patients' cognitive abilities - Reproduction of the complexity of daily life scenarios

VR Virtual reality

To clarify the distinction between robotics and VR, the main characteristics of each are presented (Table 2).

Regarding the readiness, both treatment and assessment technologies display similar levels of maturity, with almost equal shares of fully commercial and prototypical software integration of commercial devices. This balance suggests that while a considerable portion of solutions has reached commercial availability, many are still in the prototypical phase, particularly where integration and customization are required for neglect treatment/assessment.

Wearable sensors were utilized in a moderate proportion of studies (31.2%), which reflects their growing relevance in clinical research as non-invasive tools that can support both assessment and treatment aims. Finally, the physiological stimulations are also underutilized and are found exclusively in the group of papers focusing on treatment technologies.

The analysis of outcomes categorized under the ICF framework [45] highlights expected trends while uncovering insights. Within the b domain, the majority of outcomes, over three-quarters, focus on mental functions (b1), reflecting the cognitive nature of USN, as expected. This pattern is consistent across both treatment and assessment technologies. Interestingly, a proportion of the outcomes address neuromusculoskeletal and movement-related functions (b7), exclusively within treatment-focused studies. This observation underscores the non-negligible impact of USN on motor behavior and supports the integration of robotic systems, targeting physical rehabilitation in neglect treatment. For the d domain, the emphasis on cognitive outcomes diminishes, with nearly half of the outcomes in this category focusing on learning and applying knowledge (d1), especially in assessment technologies. At the same time, a notable proportion of the outcomes target mobility (d4) and self-care (d5), reflecting their significance in treatment contexts. This shift from cognitive functional outcomes to outcomes regarding activities underlines the importance of addressing independence and mobility as primary USN treatment goals. These findings highlight the dual focus of current technologies in addressing the cognitive function and the activity dimensions of USN. While the predominance of cognitive outcomes aligns with the condition's characteristics, the inclusion of motor and functional outcomes, particularly in treatment studies, reflects a broader and more holistic approach to rehabilitation. This balance emphasizes the potential of innovative technologies, such as robotics and VR, to address the multifaceted challenges of USN.

The performance analysis provides insights on the tests and metrics used across the studies, categorized by treatment and assessment domains. For the assessment studies, the focus on psychometric validity reveals significant variability in approaches, especially in evaluating construct, criterion, and face validity [36, 106]. While construct validity often employs ANOVA to align with study designs [107], criterion validity relies on methods like Bland-Altman plots and regression models, though predictive validity has been examined in only one study. Additionally, face validity primarily uses usability metrics (e.g., SSQ), which emphasize descriptive statistics but provide limited insights into long-term measure stability [108]. Treatment studies predominantly use descriptive statistics to evaluate baseline information, usability and feasibility, rather than effectiveness, reflecting their exploratory nature (for pilot analysis). Conversely, inferential methods, such as ANOVA and non-parametric tests, allow to assess treatment effects, yet advanced statistical models like mixed-linear models are rarely utilized. Finally, studies focused on treatment typically adopted longitudinal designs to assess prolonged interventions and their effects on recovery. In contrast, assessment studies were predominantly cross-sectional, providing momentary evaluations of patient conditions. However, this reveals a gap in the exploration of psychometric properties—such as reliability, validity, and especially responsiveness—of the technological measures employed. Including designs that allow for the evaluation of responsiveness, for example through repeated measurements over time, could support the identification of minimal clinically important differences and strengthen the clinical relevance of assessment tools.

This review presents some limitations, mainly related to the broad focus of its scope. While this approach has led to some heterogeneity in the findings, limiting the ability to perform detailed quantitative analysis, it was intended to provide a comprehensive view of the current state-of-the-art. Although this may reduce the specificity of certain conclusions, it supports a more general understanding of the different methodologies and applications of 3D technologies for USN. Moreover, the high heterogeneity of the included studies posed additional challenges, limiting the possibility of quantitative synthesis and prompting a narrative approach instead. The scarcity of studies addressing psychometric properties beyond validity further complicates the ability to provide clear recommendations or evaluate the overall robustness of the proposed tools. Validity alone is not sufficient to establish the soundness of an assessment instrument.

Future research should prioritize the reliability of assessment technologies, and the clinical effects of treatment technologies, as well as integrate predictive models for personalized therapy.

Despite its limitations, this review highlights the potential of 3D technologies, such as VR, robotics, and wearable sensors, in addressing the complexities of USN. These tools offer innovative solutions for real-world 3D interactions and patient-centered care.

Conclusions

This systematic review highlights the growing potential of 3D technologies—including VR, robotics, and other advanced electro-mechanical systems—in the assessment and rehabilitation of post-stroke survivors with USN. Collectively, these approaches demonstrate a paradigm shift from traditional 2D clinical tools toward immersive, interactive, and ecologically valid environments that capture real-world spatial behaviors and enable the integration of cognitive and motor rehabilitation within a single framework.

Across the included studies, VR emerged as the most frequently employed technology, adopted for both assessment and treatment due to its accessibility, multisensory feedback, and adaptability to home or tele-rehabilitation settings. Robotic systems were less represented, mainly applied in treatment protocols, and primarily targeting upper-limb rehabilitation within personal or peripersonal space. Outcome analyses revealed a predominance of measures related to mental functions (ICF b1) in both treatment and assessment studies. Treatment-focused works also addressed motor (b7) and activity-related (d4, d5) outcomes, reflecting a gradual shift toward more holistic rehabilitation goals that integrate cognitive and functional recovery. However, the field remains characterized by methodological heterogeneity, small sample sizes, and limited psychometric validation, which constrain the comparability and generalizability of results.

From a clinical perspective, technology selection should be guided by patient characteristics and rehabilitation goals. VR-based approaches may be particularly beneficial for individuals with preserved cognitive capacity and attention, enabling engaging, feedback-rich, and potentially tele-rehabilitation-compatible interventions. Conversely, robotic-assisted systems may provide critical support for patients with more severe motor deficits or limited autonomy, allowing for safe, controlled, and quantifiable motor stimulation within both personal and peripersonal space. Effective implementation of these tools requires attention to patient safety, cognitive load, usability, and therapist supervision, ensuring that technological innovation translates into meaningful clinical outcomes.

From a research standpoint, most studies to date represent early-phase or proof-of-concept work, serving primarily to establish feasibility and preliminary efficacy. These foundational efforts are essential but must be followed by RCTs to establish standardized protocols, determine dose–response relationships, and evaluate long-term functional outcomes. Furthermore, there is a need to validate 3D spatial performance measures, and develop shared methodological frameworks that support comparability across studies.

Looking ahead, the field should prioritize standardization, cross-disciplinary collaboration, and the exploration of hybrid VR–robotic systems that can simultaneously target cognitive-perceptual and motor domains. The integration of adaptive algorithms, machine learning, and real-time biofeedback may further enable personalized, data-driven rehabilitation. Ultimately, by advancing methodological rigor and clinical translation, these technologies hold the promise to deliver more accurate assessments, individualized interventions, and sustainable rehabilitation solutions for individuals with USN, fostering their recovery, autonomy, and quality of life.

Abbreviations

2D	Two-dimensional
3D	Three dimensional
ANOVA	Analysis of variance
CBS	Catherine Bergego Scale
FES	Functional electrical stimulation
ICF	International Classification of Functioning, Disability, and Health
IQR	Interquartile range
NCT	Non-controlled trial
NRCT	Non-randomized controlled trial
ObS	Observational study
PICO	Population, Intervention, Comparison, Outcome
PRISMA	Preferred Reported Items for Systematic Reviews and Meta-analyses
QoL	Quality of life
RAT	Robot-assisted arm training
RCT	Randomized controlled trial
ROB2	Risk of Bias 2
ROBINS-E	Risk of Bias in Non-randomized Studies of Exposures
ROBINS-I	Risk of Bias in Non-randomized Studies of Interventions
RoB	Risk of Bias
SSQ	Simulator Sickness Questionnaire
SUS	System Usability Scale
TS	Technical study
USN	Unilateral spatial neglect
VR	Virtual reality

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12984-025-01839-x.

Supplementary Material 1

Supplementary Material 2

Supplementary Material 3

Supplementary Material 4

Supplementary Material 5

Supplementary Material 6

Acknowledgements

Not applicable.

Author contributions

AM, EF and FC were responsible for the conception and design of the study. DS, AFi, SC, AFa and SP performed screening. DS, AFi, MAS, SP and EM performed data extraction. AFi, DS, SC, EM, MAS and AFa drafted the manuscript. AFi, DS, SC, SP, AM, EM, EF, FC, MAS and CP critically revised the manuscript. All authors read and approved the final manuscript.

Funding

This work was funded by Ministero dell'Università e della Ricerca (Italian Ministry of University and Research) under the PNC - Piano Nazionale Complementare, FIT4MEDROB (PNC0000007) "Fit4MedRob- Fit for Medical Robotics" Project. Additionally, the study was funded by the Italian Ministry of Health under: the "Ricerca Corrente" program; the "Ricerca Finalizzata" program thorugh the project "Clinical validatiOn of an AI-based DEcision support system for Robotic upper limb rehabilitation in patients with Stroke, a CO-AIDER Study" (RF-2021-12375472) and under the frame of Transforming

Health and Care Systems, THCS, (NeuroRehab4EU, GA N° 101095654 of the EU Horizon Europe Research and Innovation Programme).

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 1 July 2025 / Accepted: 1 December 2025

References

1. Feigin VL, Forouzanfar MH, Krishnamurthi R, Mensah GA, Connor M, Bennett DA, et al. Global and regional burden of stroke during 1990–2010: findings from the global burden of disease study 2010. Lancet. 2014;383:245–55. https://doi.org/10.1016/S0140-6736(13)61953-4.
2. Halligan PW, Marshall JC. Spatial compression in visual neglect: A case study. Cortex. 1991;27:623–9. https://doi.org/10.1016/S0010-9452(13)80011-1.
3. Stone SP, Wilson B, Wroot A, Halligan PW, Lange LS, Marshall JC, et al. The assessment of visuo-spatial neglect after acute stroke. J Neurol Neurosurg Psychiatry. 1991;54:345–50. https://doi.org/10.1136/jnnp.54.4.345.
4. Jacobs S, Brozzoli C, Farnè A, Neglect. A multisensory deficit? Neuropsychologia. 2012;50:1029–44. https://doi.org/10.1016/j.neuropsychologia.2012.03.018.
5. Di Monaco M, Schintu S, Dotta M, Barba S, Tappero R, Gindri P. Severity of unilateral Spatial neglect is an independent predictor of functional outcome after acute inpatient rehabilitation in individuals with right hemispheric stroke. Arch Phys Med Rehabil. 2011;92:1250–6. https://doi.org/10.1016/j.apmr.2011.03.018.
6. Corbetta M, Kincade MJ, Lewis C, Snyder AZ, Sapir A. Neural basis and recovery of Spatial attention deficits in Spatial neglect. Nat Neurosci. 2005;8:1603–10. https://doi.org/10.1038/nn1574.
7. Pizzamiglio L, Cappa S, Vallar G, Zoccolotti P, Bottini G, Ciurlil P, et al. Visual neglect for Far and near Extra-Personal space in humans. Cortex. 1989;25:471–7. https://doi.org/10.1016/S0010-9452(89)80060-7.
8. Bisiach E, Perani D, Vallar G, Berti A. Unilateral neglect: personal and extra-personal. Neuropsychologia. 1986;24:759–67. https://doi.org/10.1016/0028-3932(86)90075-8.
9. Zoccolotti P, Judica A. Functional evaluation of Hemineglect by means of a semistructured scale: personal extrapersonal differentiation. Neuropsychol Rehabil. 1991;1:33–44. https://doi.org/10.1080/09602019108401378.
10. Beschin N, Robertson IH. Personal versus extrapersonal neglect: A group study of their dissociation using a reliable clinical test. Cortex. 1997;33:379–84. https://doi.org/10.1016/S0010-9452(08)70013-3.
11. Laplane D, Degos JD. Motor neglect. J Neurol Neurosurg Psychiatry. 1983;46(2):152–8. https://doi.org/10.1136/jnnp.46.2.152.
12. CogniReMo Study Group, Mancuso M, Iosa M, Abbruzzese L, Matano A, Coccia M, et al. The impact of cognitive function deficits and their recovery on functional outcome in subjects affected by ischemic subacute stroke: results from the Italian multicenter longitudinal study CogniReMo. Eur J Phys Rehabil Med. 2023;59. https://doi.org/10.23736/S1973-9087.23.07716-X.
13. Heilman KM, Watson RT. Neglect and related disorders. Semin Neurol. 2000;20(4):463–70. https://doi.org/10.1055/s-2000-13179.
14. Savini S, Alvaro R, Vellone E. Stroke impact scale: a specific instrument to assess the quality of life in stroke survivors. Int Nurs Perspect. 2010;10:13–20.
15. Parton P, Malhotra, Husain M. Hemispatial neglect. J Neurol Neurosurg Psychiatry. 2004;75(1):13–21.
16. Bonato M. Neglect, and extinction depend greatly on task demands: a review. Front Hum Neurosci. 2012;6. https://doi.org/10.3389/fnhum.2012.00195.
17. Rossetti Y, Rode G, Pisella L, Farné A, Li L, Boisson D, et al. Prism adaptation to a Rightward optical deviation rehabilitates left hemispatial neglect. Nature. 1998;395:166–9. https://doi.org/10.1038/25988.
18. Weinberg J, Diller L, Gordon WA, Gerstman LJ, Lieberman A, Lakin P, Hodges G, Ezrachi O. Visual scanning training effect on reading-related tasks in acquired right brain damage. Arch Phys Med Rehabil. 1977;58(11):479–86. PMID: 931586.
19. Cazzoli D, Muri RM, Schumacher R, Von Arx S, Chaves S, Gutbrod K, et al. Theta burst stimulation reduces disability during the activities of daily living in Spatial neglect. Brain. 2012;135:3426–39. https://doi.org/10.1093/brain/aws182.
20. Bergquist T, Sullan M, Alden E. Rehabilitation of neuropsychological deficits: the role of restorative approaches. In: Brown GG, Crosson B, Haaland KY, King TZ editors. *APA handbook of neuropsychology: Neuroscience and neuromethods*. Washington (DC): American Psychological Association; 2023. p. 335–355. https://doi.org/10.1037/0000308-016
21. Riestra AR, Barrett AM. Rehabilitation of spatial neglect. In: Handbook of Clinical Neurology. Vol. 110. Elsevier; 2013. pp 347–55. https://doi.org/10.1016/B978-0-444-52901-5.00029-0.
22. Priftis K, Passarini L, Pilosio C, Meneghello F, Pitteri M. Visual scanning training, limb activation treatment, and prism adaptation for rehabilitating left neglect: who is the winner? Front Hum Neurosci. 2013;7. https://doi.org/10.3389/fnhum.2013.00360.
23. Serino A, Bonifazi S, Pierfederici L, Làdavas E. Neglect treatment by Prism adaptation: what recovers and for how long. Neuropsychol Rehabil. 2007;17:657–87. https://doi.org/10.1080/09602010601052006.
24. Ten Brink AF, Visser-Meily JMA, Schut MJ, Kouwenhoven M, Eijsackers ALH, Nijboer TCW. Prism adaptation in rehabilitation? No additional effects of Prism adaptation on neglect recovery in the subacute phase poststroke: A randomized controlled trial. Neurorehabil Neural Repair. 2017;31:1017–28. https://doi.org/10.1177/1545968317744277.
25. Cavedoni S, Cipresso P, Mancuso V, Bruni F, Pedroli E. Virtual reality for the assessment and rehabilitation of neglect: where are we now? A 6-year review update. Virtual Real. 2022;26:1663–704. https://doi.org/10.1007/s10055-022-00648-0.
26. Kageyama S, Imagase M, Okubo M, Takayama Y. Neglect in three dimensions. Am J Occup Ther. 1994;48(3):206–10. https://doi.org/10.5014/ajot.48.3.206.
27. Istituto Superiore di Sanità. Diagnosi e riabilitazione dell'Eminegligenza Spaziale (neglect) nel paziente con ictus. ISS. https://www.iss.it/-/snlg-diagnosi-riabilitazione-eminegligenza-spaziale-in-pz-con-ictus.
28. Laver KE, Lange B, George S, Deutsch JE, Saposnik G, Crotty M. Virtual reality for stroke rehabilitation. Cochrane Stroke Group, editor. Cochrane Database Syst Rev. 2017;2018. https://doi.org/10.1002/14651858.CD008349.pub4.
29. Cui J, Yeh S-C, Lee S-H. Wearable sensors integrated with virtual reality: A Self-Guided healthcare system measuring shoulder joint mobility for frozen shoulder. J Healthc Eng. 2019;2019:1–6. https://doi.org/10.1155/2019/7681237.
30. Boukhennoufa I, Zhai X, Utti V, Jackson J, McDonald-Maier KD. Wearable sensors and machine learning in post-stroke rehabilitation assessment: A systematic review. Biomed Signal Process Control. 2022;71:103197. https://doi.org/10.1016/j.bspc.2021.103197.
31. Couyoumdjian A, Di Nocera F, Ferlazzo F. Functional representation of 3d space in endogenous attention shifts. Q J Exp Psychol Sect A. 2003;56:155–83. https://doi.org/10.1080/02724980244000215.
32. Basteris A, Nijenhuis SM, Stienen AH, Buurke JH, Prange GB, Amirabdollahian F. Training modalities in robot-mediated upper limb rehabilitation in stroke: a framework for classification based on a systematic review. J Neuroeng Rehabil. 2014;11:111. https://doi.org/10.1186/1743-0003-11-111.
33. Poli P, Morone G, Rosati G, Masiero S. Robotic technologies and rehabilitation: new tools for stroke patients' therapy. BioMed Res Int. 2013;2013:1–8. https://doi.org/10.1155/2013/153872.
34. Taravati S, Capaci K, Uzumcugil H, Tanigor G. Evaluation of an upper limb robotic rehabilitation program on motor functions, quality of life, cognition, and emotional status in patients with stroke: a randomized controlled study. Neurol Sci. 2022;43:1177–88. https://doi.org/10.1007/s10072-021-05431-8.
35. Varalta V, Picelli A, Fonte C, Montemezzi G, La Marchina E, Smania N. Effects of contralesional robot-assisted hand training in patients with unilateral Spatial neglect following stroke: a case series study. J Neuroeng Rehabil. 2014;11:160. https://doi.org/10.1186/1743-0003-11-160.

36. Moher D, Liberati A, Tetzlaff J, Altman DG, for the PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ. 2009;339:b2535–2535. https://doi.org/10.1136/bmj.b2535.
37. Huang X, Lin J, Demner-Fushman D. Evaluation of PICO as a knowledge representation for clinical questions. AMIA Annu Symp Proc. 2006;2006:359.
38. Plummer P, Morris ME, Dunai J. Assessment of unilateral neglect. Phys Ther. 2003;83:732–40. https://doi.org/10.1093/ptj/83.8.732.
39. Laeng B, Brennen T, Johannessen K, Holmen K, Elvestad R. Multiple reference frames in neglect? An investigation of the Object-Centred frame and the dissociation between near and Far from the body by use of a mirror. Cortex. 2002;38:511–28. https://doi.org/10.1016/S0010-9452(08)70020-0.
40. Li D, Karnath H-O, Rorden C. Egocentric representations of space co-exist with allocentric representations: evidence from Spatial neglect. Cortex. 2014;58:161–9. https://doi.org/10.1016/j.cortex.2014.06.012.
41. Babineau J. Product review: covidence (Systematic review Software). J Can Health Libr Assoc J Assoc Bibl Santé Can. 2014;35:68. https://doi.org/10.5596/c14-016.
42. Sterne JAC, Savović J, Page MJ, Elbers RG, Blencowe NS, Boutron I, et al. RoB 2: a revised tool for assessing risk of bias in randomised trials. BMJ. 2019;l4898. https://doi.org/10.1136/bmj.l4898.
43. Sterne JA, Hernán MA, Reeves BC, Savović J, Berkman ND, Viswanathan M, et al. ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. BMJ. 2016;i4919. https://doi.org/10.1136/bmj.i4919.
44. Higgins JPT, Morgan RL, Rooney AA, Taylor KW, Thayer KA, Silva RA, et al. A tool to assess risk of bias in non-randomized follow-up studies of exposure effects (ROBINS-E). Environ Int. 2024;186:108602. https://doi.org/10.1016/j.envint.2024.108602.
45. Rauch A, Cieza A, Stucki G. How to apply the International Classification of Functioning, Disability and Health (ICF) for rehabilitation management in clinical practice. Eur J Phys Rehabil Med. 2008;44(3):329–42.
46. Bernardi NF, Cioffi MC, Ronchi R, Maravita A, Bricolo E, Zigiotto L, et al. Improving left Spatial neglect through music scale playing. J Neuropsychol. 2017;11:135–58. https://doi.org/10.1111/jnp.12078.
47. Bowen A, McKenna K, Tallis RC. Reasons for variability in the reported rate of occurrence of unilateral Spatial neglect after stroke. Stroke. 1999;30:1196–202. https://doi.org/10.1161/01.STR.30.6.1196.
48. De Luca R, Lo Buono V, Leo A, Russo M, Aragona B, Leonardi S, et al. Use of virtual reality in improving poststroke neglect: promising neuropsychological and neurophysiological findings from a case study. Appl Neuropsychol Adult. 2019;26:96–100. https://doi.org/10.1080/23279095.2017.1363040.
49. Massetti G, Albini F, Casati C, Toneatto C, Terruzzi S, Etzi R, et al. Validation of Neurit.Space: three digital tests for the neuropsychological evaluation of unilateral Spatial neglect. J Clin Med. 2023;12:3042. https://doi.org/10.3390/jcm12083042.
50. Watanabe S, Amimoto K. Generalization of Prism adaptation for wheelchair driving task in patients with unilateral Spatial neglect. Arch Phys Med Rehabil. 2010;91:443–7. https://doi.org/10.1016/j.apmr.2009.09.027.
51. Frassinetti F, Angeli V, Meneghello F, Avanzi S, Ladavas E. Long-lasting amelioration of visuospatial neglect by Prism adaptation. Brain. 2002;125:608–23. https://doi.org/10.1093/brain/awf056.
52. Tippett WJ, Alexander LD, Rizkalla MN, Sergio LE, Black SE. True functional ability of chronic stroke patients. J Neuroeng Rehabil. 2013;10:20. https://doi.org/10.1186/1743-0003-10-20.
53. Ferraro F, Trombini M, Truffelli R, Simonini M, Dellepiane S. On the assessment of unilateral spatial neglect via digital tests. 2021 10th Int IEEEEMBS Conf Neural Eng NER. Italy: IEEE; 2021. pp. 802–6. https://doi.org/10.1109/NER49283.2021.9441471.
54. Plummer P, Dunai J, Morris ME. Understanding the effects of moving visual stimuli on unilateral neglect following stroke. Brain Cogn. 2006;60:156–65. https://doi.org/10.1016/j.bandc.2005.11.001.
55. Aravind G, Lamontagne A. Perceptual and locomotor factors affect obstacle avoidance in persons with visuospatial neglect. J Neuroeng Rehabil. 2014;11:38. https://doi.org/10.1186/1743-0003-11-38.
56. Aravind G, Lamontagne A. Effect of visuospatial neglect on Spatial navigation and heading after stroke. Ann Phys Rehabil Med. 2018;61:197–206. https://doi.org/10.1016/j.rehab.2017.05.002.
57. Dvorkin AY, Rymer WZ, Settle K, Patton JL. Perceptual assessment of spatial neglect within a virtual environment. 2007 Virtual Rehabil. Venice, Italy: IEEE; 2007. pp. 175–9. https://doi.org/10.1109/ICVR.2007.4362161.
58. Dvorkin AY, Rymer WZ, Harvey RL, Bogey RA, Patton JL. Assessment and monitoring of recovery of spatial neglect within a virtual environment. 2008 Virtual Rehabil. Vancouver, BC: IEEE; 2008. pp. 88–92. https://doi.org/10.1109/ICVR.2008.4625142.
59. Dvorkin AY, Bogey RA, Harvey RL, Patton JL. Mapping the neglected space: gradients of detection revealed by virtual reality. Neurorehabil Neural Repair. 2012;26:120–31. https://doi.org/10.1177/1545968311410068.
60. Fordell H, Bodin K, Bucht G, Malm J. A virtual reality test battery for assessment and screening of Spatial neglect: VR-test battery for assessment and screening of Spatial neglect. Acta Neurol Scand. 2011;123:167–74. https://doi.org/10.1111/j.1600-0404.2010.01390.x.
61. Hougaard BI, Knoche H, Jensen J, Evald L. Spatial neglect midline diagnostics from virtual reality and eye tracking in a Free-Viewing environment. Front Psychol. 2021;12:742445. https://doi.org/10.3389/fpsyg.2021.742445.
62. Jannink MJA, Aznar M, De Kort AC, Van De Vis W, Veltink P, Van Der Kooij H. Assessment of visuospatial neglect in stroke patients using virtual reality: a pilot study. Int J Rehabil Res. 2009;32:280–6. https://doi.org/10.1097/MRR.0b013e3283013b1c.
63. Kim DY, Ku J, Chang WH, Park TH, Lim JY, Han K, et al. Assessment of post-stroke extrapersonal neglect using a three-dimensional immersive virtual street crossing program. Acta Neurol Scand. 2010;121:171–7. https://doi.org/10.1111/j.1600-0404.2009.01194.x.
64. Kim T-L, Kim K, Choi C, Lee J-Y, Shin J-H. FOPR test: a virtual reality-based technique to assess field of perception and field of regard in hemispatial neglect. J Neuroeng Rehabil. 2021;18:39. https://doi.org/10.1186/s12984-021-00835-1.
65. Knobel SEJ, Kaufmann BC, Gerber SM, Cazzoli D, Müri RM, Nyffeler T, et al. Immersive 3D virtual reality cancellation task for visual neglect assessment: A pilot study. Front Hum Neurosci. 2020;14:180. https://doi.org/10.3389/fnhum.2020.00180.
66. Morse H, Biggart L, Pomeroy V, Rossit S. Exploring perspectives from stroke survivors, carers and clinicians on virtual reality as a precursor to using telerehabilitation for Spatial neglect post-stroke. Neuropsychol Rehabil. 2022;32:767–91. https://doi.org/10.1080/09602011.2020.1819827.
67. Ogourtsova T, Archambault PS, Lamontagne A. Post-stroke visual neglect affects goal-directed locomotion in different perceptuo-cognitive conditions and on a wide visual spectrum. Restor Neurol Neurosci. 2018;36:313–31. https://doi.org/10.3233/RNN-170766.
68. Ulm L, Wohlrapp D, Meinzer M, Steinicke R, Schatz A, Denzler P et al. SB <>Hamed editor 2013 A Circle-Monitor for computerised assessment of visual neglect in peripersonal space. PLoS ONE 8 e82892 https://doi.org/10.1371/journal.pone.0082892.
69. Wagner S, Belger J, Joeres F, Thöne-Otto A, Hansen C, Preim B, et al. iVRoad: immersive virtual road crossing as an assessment tool for unilateral Spatial neglect. Comput Graph. 2021;99:70–82. https://doi.org/10.1016/j.cag.2021.06.013.
70. Chen P, Boukrina O, Krch D. Visuomotor misalignment induced through immersive virtual reality to improve Spatial neglect: a case-series study. Neurocase. 2022;28:393–402. https://doi.org/10.1080/13554794.2022.2134037.
71. Eskes GA, Butler B. Using limb movements to improve Spatial neglect: the role of functional electrical stimulation. Restor Neurol Neurosci. 2006;24:385–98. https://doi.org/10.3233/RNN-2006-00353.
72. Fordell H, Bodin K, Eklund A, Malm J. RehAtt – scanning training for neglect enhanced by multi-sensory stimulation in virtual reality. Top Stroke Rehabil. 2016;23:191–9. https://doi.org/10.1080/10749357.2016.1138670.
73. Hagiwara A, Yasuda K, Saichi K, Muroi D, Kawaguchi S, Ohira M et al. Development of a visual cueing system using immersive virtual reality for object-centered neglect in stroke patients. 2018 IEEE Int Conf Syst Man Cybern SMC. Miyazaki, Japan: IEEE; 2018. pp. 1022–5. https://doi.org/10.1109/SMC.2018.00182.
74. Kang T-W, Oh D-W. Treatment of hemispatial neglect in patients with post-hemiparesis: A single-subject experimental design study using a whole-body Tilt exercise plus mental practice. NeuroRehabilitation Int Interdiscip J. 2012;31:197–206. https://doi.org/10.3233/NRE-2012-0789.
75. Stammler B, Flammer K, Schuster T, Lambert M, Neumann O, Lux M, et al. Spatial neglect therapy with the augmented reality app Negami for active exploration training: A randomized controlled trial on 20 stroke patients with Spatial neglect. Arch Phys Med Rehabil. 2023;104:1987–94. https://doi.org/10.1016/j.apmr.2023.07.017.
76. Chen Z-J, Gu M-H, He C, Xiong C-H, Xu J, Huang X-L. Robot-Assisted arm training in stroke individuals with unilateral Spatial neglect: A pilot study. Front Neurol. 2021;12:691444. https://doi.org/10.3389/fneur.2021.691444.
77. Choi H-S, Shin W-S, Bang D-H. Application of digital practice to improve head movement, visual perception and activities of daily living for subacute

stroke patients with unilateral Spatial neglect: preliminary results of a single-blinded, randomized controlled trial. Med (Baltim). 2021;100:e24637. https://doi.org/10.1097/MD.0000000000024637.

78. Shin J-H, Kim M, Lee J-Y, Kim M-Y, Jeon Y-J, Kim K. Feasibility of hemispatial neglect rehabilitation with virtual reality-based visual exploration therapy among patients with stroke: randomised controlled trial. Front Neurosci. 2023;17:1142663. https://doi.org/10.3389/fnins.2023.1142663.
79. Kim YM, Chun MH, Yun GJ, Song YJ, Young HE. The effect of virtual reality training on unilateral Spatial neglect in stroke patients. Ann Rehabil Med. 2011;35:309. https://doi.org/10.5535/arm.2011.35.3.309.
80. Kim J, Kim K, Kim DY, Chang WH, Park C-I, Ohn SH, et al. Virtual environment training system for rehabilitation of stroke patients with unilateral neglect: crossing the virtual street. Cyberpsychol Behav. 2007;10:7–15. https://doi.org/10.1089/cpb.2006.9998.
81. Castiello U, Lusher D, Burton C, Glover S, Disler P. Improving left hemispatial neglect using virtual reality. Neurology. 2004;62:1958–62. https://doi.org/10.1212/01.WNL.0000128183.63917.02.
82. Broeren J, Sunnerhagen KS, Rydmark M. Haptic virtual rehabilitation in stroke: transferring research into clinical practice. Phys Ther Rev. 2009;14:322–35. https://doi.org/10.1179/108331909X12488667117212.
83. Ansuini C, Pierno AC, Lusher D, Castiello U. Virtual reality applications for the remapping of space in neglect patients. Restor Neurol Neurosci. 2006;24:431–41. https://doi.org/10.3233/RNN-2006-00350.
84. Numao T, Amimoto K, Shimada T. Examination and treatment of unilateral Spatial neglect using virtual reality in three-dimensional space. Neurocase. 2021;27:447–51. https://doi.org/10.1080/13554794.2021.1999478.
85. Takazawa S, Yasuda K, Sabu R, Kawaguchi S, Iwata H. Development of a mixed reality rehabilitation system for real-life environment in stroke patients with unilateral spatial neglect. 2022 IEEE int Conf syst man Cybern SMC. Prague, Czech republic: IEEE; 2022. pp. 3379–83. https://doi.org/10.1109/SMC53654.2022.9945392.
86. Yasuda K, Muroi D, Hirano M, Saichi K, Iwata H. Differing effects of an immersive virtual reality programme on unilateral spatial neglect on activities of daily living. BMJ Case Rep. 2018;2018(bcr–2017–222860). https://doi.org/10.1136/bcr-2017-222860.
87. Carter AR, Foreman MH, Martin C, Fitterer S, Pioppo A, Connor LT et al. Inducing visuomotor adaptation using virtual reality gaming with a virtual shift as a Treatment for unilateral spatial neglect. J Intellect Disabil Diagn Treat. 2016;4(3):170–84.
88. Cho S, Chang WK, Park J, Lee SH, Lee J, Han CE, et al. Feasibility study of immersive virtual Prism adaptation therapy with depth-sensing camera using functional near-infrared spectroscopy in healthy adults. Sci Rep. 2022;12:767. https://doi.org/10.1038/s41598-022-04771-5.
89. Faity G, Sidahmed Y, Laffont I, Froger J. Quantification and rehabilitation of unilateral Spatial neglect in immersive virtual reality: A validation study in healthy subjects. Sensors. 2023;23:3481. https://doi.org/10.3390/s23073481.
90. Gammeri R, Turri F, Ricci R, Ptak R. Adaptation to virtual prisms and its relevance for neglect rehabilitation: a single-blind dose-response study with healthy participants. Neuropsychol Rehabil. 2020;30:753–66. https://doi.org/10.1080/09602011.2018.1502672.
91. Perez-Marcos D, Ronchi R, Giroux A, Brenet F, Serino A, Tadi T, et al. An immersive virtual reality system for ecological assessment of peripersonal and extrapersonal unilateral Spatial neglect. J Neuroeng Rehabil. 2023;20:33. https://doi.org/10.1186/s12984-023-01156-1.
92. Fattori P, De Vitis M, Filippini M, Vaccari FE, Diomedi S, Gamberini M, et al. Visual sensitivity at the service of action control in posterior parietal cortex. Front Physiol. 2024;15:1408010. https://doi.org/10.3389/fphys.2024.1408010.
93. Motomura K, Amimoto K, Numao T, Kaneko F. Effects of a stimulus response task using virtual reality on unilateral Spatial neglect: A randomized controlled trial. Arch Phys Med Rehabil. 2024;105:1449–57. https://doi.org/10.1016/j.apmr.2024.05.009.
94. Chapter 7. Considering bias and conflicts of interest among the included studies. https://training.cochrane.org/handbook/current/chapter-07. Accessed 12 Dec 2024.
95. Chapter 24. Including non-randomized studies on intervention effects. https://training.cochrane.org/handbook/current/chapter-24. Accessed 12 Dec 2024.
96. Banyai AD, Brișan C. Robotics in physical rehabilitation. Syst Rev Healthc. 2024;12:1720. https://doi.org/10.3390/healthcare12171720.
97. Park J-H. The effects of robot-assisted left-hand training on hemispatial neglect in older patients with chronic stroke: A pilot and randomized controlled trial. Med (Baltim). 2021;100:e24781. https://doi.org/10.1097/MD.0000000000024781.
98. Matarić MJ, Eriksson J, Feil-Seifer DJ, Winstein CJ. Socially assistive robotics for post-stroke rehabilitation. J Neuroeng Rehabil. 2007;4:5. https://doi.org/10.1186/1743-0003-4-5.
99. Sarfo FS, Ulasavets U, Opare-Sem OK, Ovbiagele B. Tele-Rehabilitation after stroke: an updated systematic review of the literature. J Stroke Cerebrovasc Dis. 2018;27:2306–18. https://doi.org/10.1016/j.jstrokecerebrovasdis.2018.05.013.
100. Linder SM, Reiss A, Buchanan S, Sahu K, Rosenfeldt AB, Clark C, et al. Incorporating Robotic-Assisted telerehabilitation in a home program to improve arm function following stroke. J Neurol Phys Ther. 2013;37:125–32. https://doi.org/10.1097/NPT.0b013e31829fa808.
101. Reinhart S, Schmidt L, Kuhn C, Rosenthal A, Schenk T, Keller I, et al. Limb activation ameliorates body-related deficits in Spatial neglect. Front Hum Neurosci [Internet]. 2012. https://doi.org/10.3389/fnhum.2012.00188. [cited 2025 Oct 13];6.
102. Machner B, Dorr M, Sprenger A, Von Der Gablentz J, Heide W, Barth E, et al. Impact of dynamic bottom-up features and top-down control on the visual exploration of moving real-world scenes in hemispatial neglect. Neuropsychologia. 2012;50:2415–25. https://doi.org/10.1016/j.neuropsychologia.2012.06.012.
103. Robertson IH, North N. Spatio-motor cueing in unilateral left neglect: the role of hemispace, hand and motor activation. Neuropsychologia. 1992;30:553–63. https://doi.org/10.1016/0028-3932(92)90058-T.
104. Formisano R, Barbanti P, Catarci T, Vuono G, Calisse P, Razzano C. Prolonged muscular flaccidity: frequency and association with unilateral Spatial neglect after stroke. Acta Neurol Scand. 1993;88:313–5. https://doi.org/10.1111/j.1600-0404.1993.tb05349.x.
105. Crosbie JH, Lennon S, Basford JR, McDonough SM. Virtual reality in stroke rehabilitation: still more virtual than real. Disabil Rehabil. 2007;29:1139–46. https://doi.org/10.1080/09638280600960909.
106. Higgins J, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, et al. Cochrane handbook for systematic reviews of interventions. 2nd ed. Newark: John Wiley & Sons, Incorporated; 2019.
107. Barten JA, Pisters MF, Huisman PA, Takken T, Veenhof C. Measurement properties of patient-specific instruments measuring physical function. J Clin Epidemiol. 2012;65:590–601. https://doi.org/10.1016/j.jclinepi.2011.12.005.
108. McCairn KW, Isoda M. Pharmacological animal models of tic disorders. Int Rev Neurobiol. 2013;179–209. https://doi.org/10.1016/B978-0-12-411546-0.00007-X.

Publisher's note