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A Systematic review and meta-analysis on prospective memory rehabilitation in adults with non-progressive acquired brain injury

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Prospective memory (PM) is often impaired following acquired brain injury (ABI). However, its rehabilitation remains challenging for neuropsychologists. Following PRISMA guidelines, we conducted a systematic review and meta-analysis to evaluate the effectiveness, durability, and real-life impact of PM interventions in adults suffering from non-progressive ABI. Twenty-seven studies published between January 2008 and December 2024 met the inclusion criteria: fourteen randomized controlled trials (RCTs), seven non-randomized trials, four pre-post studies, and two case series. Ten RCTs were included in the meta-analysis. Interventions encompassed compensatory strategies and restitutive methods. PM outcomes were measured using validated tools (e.g., the Cambridge Prospective Memory Test and Rivermead Behavioural Memory Test). The pooled analysis showed a moderate, statistically significant effect of rehabilitation on PM performance. Some evidence of transfer were found but outcome measures are typically based on scales or questionnaires, which are subjective measures, rarely reported in detail, therefore unreliable in the case of patients with reduced awareness. Information about maintenance is scarce: a follow-up to a maximum of 12 months was conducted only in seven RCTs. Our results identified moderate heterogeneity across studies and multiple indicators pointed to the possible presence of publication bias. However, overall evidence quality was rated as moderate. Taken together, these findings support the clinical value of rehabilitation for PM deficits after ABI, while highlighting the need for more consistent methodologies and long-term outcome data.

Keywords Prospective memory, Neuropsychological rehabilitation, Memory, Systematic review

Memory impairments are among the most common consequences of brain injuries. These deficits often affect daily living activities, as well as social, leisure, and vocational activities[1,2]. Furthermore, memory disorders negatively impact other cognitive domains (e.g., language comprehension and planning of future activities), hampering their rehabilitation.

Prospective memory (PM) is the ability to remember to execute delayed intentions at the appropriate moment in the future. PM is commonly classified into two primary subtypes: event-based and time-based. In event-based PM, an external cue signals the appropriate moment for execution (e.g., remembering to take medication at breakfast). In time-based PM, a certain time or a specified interval of time serves as the cue that signals the appropriate moment for execution (e.g., remembering to take medication at 9:00 a.m.). Time-based tasks are generally regarded as more demanding than event-based tasks, as they rely on the individual's ability to engage in self-initiated, strategic monitoring of elapsed time[3]. Both time-based and event-based PM tasks rely

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on the interplay of prospective and retrospective components. The prospective component enables individuals to remember that an intended action must be carried out at the appropriate moment, while the retrospective component supports retrieval of the specific content of the intention and recognition of whether it has already been executed[4].

PM deficits can result from an impairment of these components together or separately and are a frequent consequence of acquired brain injuries (ABI)[5–7].

Neuroimaging and lesion studies have demonstrated that the anterior prefrontal cortex and frontoparietal networks play a central role in PM[8], particularly for the prospective component of PM. These regions are vulnerable to damage from traumatic brain injury (TBI), stroke, encephalitis, and hypoxic brain injury, which helps explain the high prevalence of PM deficits in these populations. Lesions affecting retrospective memory systems, including the hippocampus and diencephalic circuits, can impair PM by disrupting retrieval of the intention content.

PM is actively engaged in everyday life and plays a critical role in maintaining functional independence[7,9], making its rehabilitation an important focus in clinical practice.

As for the neuropsychological rehabilitation in general, the two main approaches are remediation (restorative approach) and compensation (adaptive approach)[10]. In detail, compensation refers to the use of internal strategies (e.g., visual imagery and self-generated mnemonics to form associations) or external strategies (e.g., environmental changes, checklists, and personal electronic devices) aimed at reducing memory problems on a functional level without necessarily improving the underlying memory function[11], while remediation refers to a series of techniques consisting of repetitive drills and memory training. However, there is no complete agreement on which techniques are restorative and which are compensatory. Indeed, while in the US literature internal strategies are considered as restorative ones, in the UK literature [e.g[12,13]., they are considered compensatory. We adhere to this classification, nevertheless, reporting results, we will use the terminology adopted by the authors and when they compare remediation and compensation, we will specify that internal strategies are compared to external aids.

Several reviews on PM rehabilitation have been already performed[14–17]. These reviews included a different number of studies each, but all came to the conclusion that the use of internal strategies and external memory compensations is recommended for people with mild memory impairments after ABI, while the use of external compensations, with direct application to functional activities, is recommended for individuals with severe memory deficits[14–16,18,19].

Most of the cited reviews highlight some limitations of the included studies, namely the variability of the design, samples, assessment and intervention, the lack of a standardized qualitative account of the injury profile, the lack of studies directly comparing different approaches (e.g., remediation vs compensation) in order to evaluate the superiority of one type of intervention over the other, and the limited number of studies and their low methodologic quality for some new approaches such as Virtual Reality[14,20,21]. Despite these limitations, memory rehabilitation is recognized as a component of rehabilitation programs for individuals with ABI in several national clinical guidelines (i.e., Italian Stroke Guidelines - SPREAD, American Stroke Association, UK Royal College of Physicians; INCOG guidelines). In particular, the INCOG 2.0 guidelines for Cognitive Rehabilitation Following TBI[18] do not recommend remediation approaches when applied as a singular treatment or the use of Transcranial Direct Current Stimulation (tDCS) for memory rehabilitation outside clinical trials. The most recent reviews have some additional limitations: one concerns PM rehabilitation either in children and adults with different etiologies and does not include a meta-analysis[14], others focused exclusively on older healthy adults[22] or included them alongside clinical groups[23]. Finally, the already reported one by Velikonja et al.[18], which covers the literature until 2021, is focused on individuals with moderate-to-severe TBI.

In the last decade, there has been an explosion in information and communication technologies offering new devices to overcome memory impairments, new rehabilitation tools such as Computer-Based Training, virtual reality, Transcranial Magnetic Stimulation (TMS) and tDCS and new modalities in which rehabilitation can be delivered (i.e., telerehabilitation). Two recent systematic reviews explored the effects of TMS and tDCS on neuropsychological rehabilitation in people with TBI[24] and stroke[25]; they covered the literature published until 2020 but included rehabilitation studies of cognitive functions other than memory. The only review on memory rehabilitation in participants with ABIs reporting novel approaches is the one by Spreij et al.[21], but it extends until 2014, and it mainly focuses on WM.

In summary, even though several reviews on memory rehabilitation in individuals with ABI have been published, most of the recent ones have considered specific subgroups of participants or specific rehabilitation approaches, while others have included general cognitive rehabilitation studies. Therefore, the present study aimed to provide a systematic review of the literature published in the last fifteen years on the effectiveness of PM rehabilitation, including new emerging approaches. Compared to other recent reviews, we specifically focused on non-progressive conditions (overall, TBI and stroke) and included interventions involving computer-based techniques and virtual reality, a tool increasingly employed in neurorehabilitation, particularly because of telerehabilitation. Our primary aim was to evaluate the effectiveness of PM rehabilitation. Additionally, we tried to assess whether improvements are maintained over time and whether they transfer to everyday activities. Finally, we examined the influence of age and other clinical variables on treatment outcomes, as these factors can affect the magnitude and durability of rehabilitation effects, guide the development of personalized interventions, and inform clinical decision-making.

Methods

The systematic review and meta-analysis were performed with the aim of quantitatively and qualitatively assessing the efficacy of cognitive rehabilitation interventions specifically targeting PM deficits in adults with ABI, including stroke and TBI. The systematic review was performed following the PRISMA guidelines[26], encompassing both randomized controlled trials (RCT) and non-randomized controlled trials (nRCT) studies. The meta-analysis included only RCTs reporting standardized PM outcomes.

Search strategy and eligibility criteria

The eligibility criteria were established a priori. The research was initially kept broad in order to capture all relevant studies concerning memory rehabilitation interventions for adults with ABI (this includes types of memory and names of the approaches and techniques that are typically used in memory rehabilitation). A literature search from January 2008 to December 2024 was initially performed across five electronic databases—namely, PubMed, PsycINFO, Web of Science, ScienceDirect, and Scopus. Keywords were: (1) "prospective memory"; "episodic memory"; "memory"; "amnesia" AND (2) "rehabilitation"; "remediation"; "intervention"; "treatment"; "neuro-rehabilitation"; "training"; "brain-trainer"; "PQRST"; "SQ3R"; "vanishing cues"; "external aids"; "errorless learning"; "repetition priming"; "neuro pages"; "spaced retrieval"; "mind maps"; "meta-memory techniques"; "visual imagery"; "TMS"; "tDCS"; "non-invasive brain stimulation"; "method of loci"; "first letter cues"; "environmental modification".

Eligible studies met the following inclusion criteria: (1) adult participants with non-progressive ABI; (2) intervention explicitly targeting PM functioning; (3) use of validated, continuous outcome measures of PM; and (4) provision of sufficient statistical data for effect size computation (e.g., means, standard deviations, or standard errors). Studies were excluded if they focused on other memory subtypes (e.g., working or semantic memory), involved participants with progressive neurological diseases (e.g., dementia), or lacked peer review, English-language publication, or adequate outcome data. Also, single case reports, studies on healthy adults or pharmacological treatments were excluded. Unpublished studies were excluded to ensure methodological transparency, replicability, and quality control, as peer-reviewed publications typically undergo rigorous evaluation. While this may increase the risk of publication bias, the decision was made to prioritize data accessibility, consistency in reporting standards, and feasibility of quality assessment across included studies.

Data extraction and coding procedures

Titles, abstracts, and keywords of the extracted studies were screened using Rayyan QCRI (RyyanQCRI, Qatar Computing Research Institute, HBKU, Doha, Quatar)[27]. After duplicates' exclusion, each study was independently assessed by all reviewers to reduce selection bias. Studies were excluded if they did not meet one or more of the abovementioned criteria. Studies rated as relevant by at least 4 of the 8 reviewers were included for further consideration. Articles with conflicting ratings were resolved by discussion. Extracted data included: authors, design of the study, participants' details (number of participants, type of ABI, age, time after lesion, deficit on inclusion), intervention characteristics (type of intervention and description, duration, intensity, eventually control condition), outcome measures, results, levels of evidence on Physiotherapy Evidence Database (PEDro) scale and on Cochrane Collaboration's tool for assessing risk of bias, where applicable, and modified Sackett scale (mSS). Significance was settled at $p<0,05$.

For studies included in the meta-analysis, we extracted data on sample sizes, means, and standard deviations. When both pre- and post-treatment outcomes were reported, effect sizes were calculated based on the difference in change scores between the treatment and control groups. If only post-treatment values were available, we computed standardized mean differences (SMDs) based on post-intervention group comparisons. In cases where studies reported standard errors instead of standard deviations, we converted them using the formula: $SD = SE \times \sqrt{n}$. When necessary, we contacted corresponding authors to obtain missing data.

Quality assessment

Interventions were assessed for level of evidence and methodology quality and strength. Also in this case, two authors independently evaluated the characteristics and the quality of the previously included studies, with conflicts resolved by discussion between all the authors until consensus was reached. The methodological quality was assessed using the PEDro scale and the Cochrane Collaboration's tool for assessing risk of bias[28], as reported above. A grade for the level of evidence was assigned to each study according to the mSS[29,30], following a method used in previous reviews[31,32].

The PEDro scale is an 11-item scale designed for rating the quality of clinical trials. This scale has been used to rate the quality in several systematic reviews[33–36]. Each satisfied yes/no item (except for item 1, which, unlike other scale items, pertains to external validity) contributes one point to the total PEDro score (range 0–10 points). Individual item level and total PEDro scores showed good agreement between raters[37]. Moreover, Foley et al.[37] have arbitrarily defined the following criteria for rating the methodologic quality of a study: 9 to 10, excellent; 6 to 8, good; 4 to 5, fair; and <4, poor.

In the Cochrane Collaboration's tool for assessing risk of bias in randomised trials, bias is assessed as a judgement (high, low, or unclear) for individual elements from five domains (selection, performance, attribution, detection, reporting) and others[28].

The mSS, with 5 levels of evidence, was used to determine the strength of evidence for each intervention[38]. The modified scale was created to simplify the 10 subcategories present in the Sackett scale into a system with 5 levels. Level 1 included RCT with a PEDro score greater than or equal to 6, whereas RCTs with scores lower than 6 were given level 2(a) evidence. Prospective controlled trials and cohort studies were also included in level 2(b) evidence. Level 3 evidence consisted only of case control trials. Pre-post studies, post-test, and case series were considered level 4 evidence. Lastly, level 5 evidence consisted of observational studies, clinical consensus, and case reports.

The four tools mentioned above (PEDro, Cochrane, mSS, and GRADE) were applied to capture different dimensions of study quality. PEDro and Cochrane address methodological rigor and risk of bias, mSS classifies the strength of study design, and GRADE rates the certainty of the overall evidence. This combined approach provides a balanced and transparent appraisal of study and evidence quality.

Meta-analytic procedure and statistical model

All statistical analyses were conducted using the *Comprehensive Meta-Analysis* software, Version 4[39]. Hedges' g was chosen as the effect size index, as it corrects for small sample bias and allows comparison across heterogeneous study designs. A random-effects model was employed to account for expected variability in intervention modalities, participant characteristics, and settings.

Heterogeneity across studies was evaluated using the Q-statistic and I^2. In addition to standard heterogeneity indices, we calculated a 95% prediction interval to estimate the likely range of true effect sizes across future studies in similar contexts.

Assessment of publication bias and sensitivity analyses

To evaluate the presence and impact of potential publication bias, we employed multiple procedures: visual inspection of funnel plots[39], Egger's regression test for small-study effects, and Duval & Tweedie's Trim and Fill method[40]. Adjusted estimates were computed under both fixed-effect and random-effects assumptions, and results are presented as sensitivity analyses rather than definitive corrections.

Risk of Bias and Certainty Assessment Risk of bias was assessed using the GRADE framework (https://www.gradepro.org).

Results

Study selection

After removal of duplicates, the initial search identified 5434 articles that were evaluated according to the inclusion criteria. Screening of citations and references provided seven additional studies for review. Following screening of titles and abstracts, 176 articles were selected for full-text review. Of the 176 articles assessed in the full-text screening, 149 were excluded. The reasons for exclusion were the following: theoretical/non-empirical studies (54 excluded), reviews (34), papers not published in peer-reviewed journals (22), primary objective different from memory rehabilitation (11), articles not in English (6), single case reports (5), studies with no quantitative assessment of memory through validated neuropsychological tests (8), studies including participants with brain tumors or participants with neurodegenerative disease, therefore "progressive" diseases (6), studies where the intervention was pharmacological or a general stimulation of cognitive abilities (3). Ultimately, 27 articles met the full inclusion criteria and were used for this review. Figure 1 shows a flowchart of the selection process.

Study characteristics

Details of the studies included in this review are shown in Tables S1 and S2. Of the 27 studies selected according to the inclusion criteria, 14 were RCT[41–54], seven were nRCT[55–61], four had a pre- and post-measurement design[62–65], and two involved case series[66,67]. Of the 14 RCT studies, 13 employed a between-subjects design and only one used a crossover within-subjects design[47]. Regarding nRCT studies, seven used a between-subjects design, four a within-subjects design and one a wait-list-based control.

A total of 1405 participants were involved in the included records. Sample sizes ranged from 4[67] to 328[42], with a mean sample size of 52 (SD=65). The participants' mean age ranged from 27.5 to 65, with the majority being in their early 30 s or 40s. All participants had suffered an ABI (the lesion interval - that is the time interval between the onset of the brain injury and the start of rehabilitation - ranges from an average of approximately 38 days to around 80 months). Inspection of etiological factors indicated that 58,8% (n=826) had a diagnosis of TBI, 28,8% (n=404) of stroke, 0,6% of hypoxia (n=8), 0,1% of encephalitis or encephalopathy (n=2) and 11,7% (n=165) of other ABI (arteriovenous malformation, hydrocephalus, systemic lupus erythematosus, cyst or not specified).

Twenty-two group studies reported results for PM rehabilitation (or LTM including PM)[41–50,55–66]. Five other studies[51–54,67] reported results for both PM and STM/WM rehabilitation, covering a variety of neuropsychological approaches, including internal or external memory strategies, individual-based or group-based psychoeducational intervention, computer-based cognitive training, cognitive training with mobile technologies, internet-based cognitive training, virtual reality memory training and holistic rehabilitation approach. Regarding the duration of treatment, a high variability was generally observed between the different studies in terms of both length (range from 5 hours to over 1000 hours) and intensity (ranged from 5–9 one-hour sessions within 8 weeks at several hours per day, three to four times a week for months or even years) (see Supplementary Tables S1, S2, S3, S4).

Methodological quality

Among the 14 RCTs, 12 obtained a PEDro score >6 and hence were considered "high-quality" (mSS Level 1). Specifically, only one study obtained a PEDro score of 10, two studies a PEDro score of 9, three of 8, four of 7 and two of 6. The remaining two RCTs obtained a PEDro score of 5 and were considered as "fair-quality" RCTs (mSS Level 2a). Among the 13 studies using nRCT designs, eight studies were ranked as Level 2b and five as Level 4 at the mSS. The results of the assessment performed using the Cochrane Collaboration's tool for assessing risk of bias are shown in Table 1.

Qualitative summary and synthesis

PM rehabilitation techniques in RCT

Restitution-oriented therapies were applied in four out of the fourteen studies[50–53]. Eight studies were based on compensation techniques[41,43–49]. Das Nair et al.[42] used mixed techniques. Finally, Withiel et al.[54] compared a compensatory memory skills group with a restorative computerized group focused on functional goal attainment.

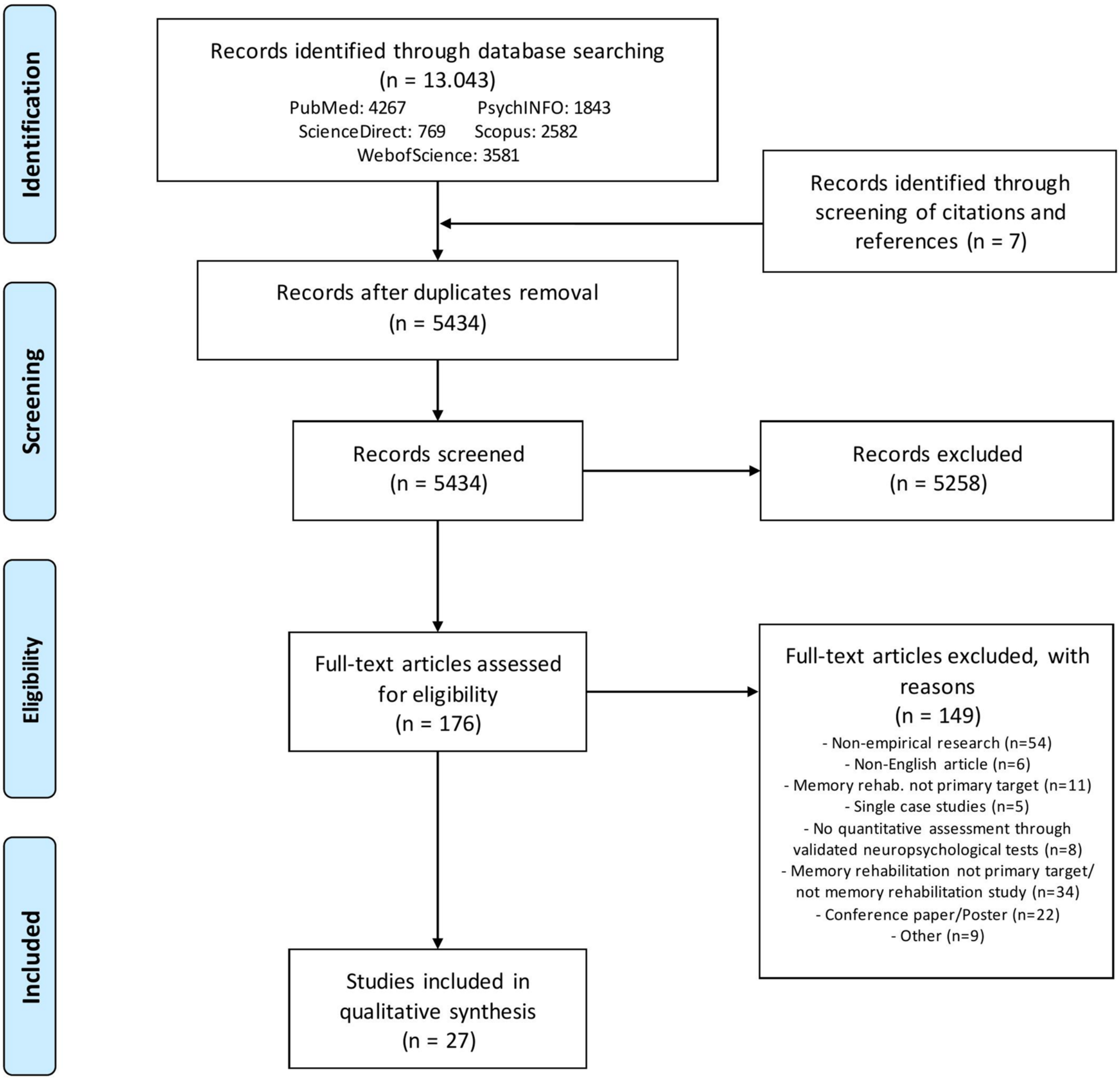

Fig. 1. PRISMA Flow diagram.

The treatment was delivered either individually[43–45,47,48, 50–54], or in group[41,42,49], with two further studies comparing the effectiveness of group versus individual interventions[46,54].

Different computerized interventions were used, such as a personal digital assistant[44], Google Calendar as a memory external aid[47], and other software such as VILAT-G[51] that trains semantic structuring of verbal information and spaced retrieval, or the computerized and adaptive cognitive training Lumosity™[54]. A virtual reality program was used by Yip & Man[50], where a virtual store was developed for PM training. Furthermore, telerehabilitation was applied by Lemoncello et al.[45]: the authors employed a Television Assisted Prompting system, which provides audiovisual reminders at scheduled times, directly at home on the patient's television.

Interventions varied in number of sessions (range 4–21), with a frequency of 1–6 days per week, and in duration of each session (30 - 120 minutes).

The etiology of the samples differed among the studies: three out of the fourteen included chronic TBI[42,48,49]. One more study included participants at 1-month post-discharge[43]. Two studies included only stroke participants[41,54]. The remaining studies included mixed ABI participants (TBI, encephalitis and cerebrovascular accidents).

A follow-up was conducted in half of the studies and varied from 1 week to 12 months post-interventi on[41–44,46,49,54]. Other studies only run an immediate post-training assessment[47,48,50–53].

Treatment outcome

PM and LTM outcome measures improved in many studies. Two studies reported a gain at the Cambridge Prospective Memory Test (CAMPROMPT), after a compensatory training in TBI participants[48], and after a virtual reality training in a group of participants with mixed etiologies[50]. A similar improvement was reported by Fleming et al.[43], in TBI individuals performing a Compensatory strategy training associated to Metacognitive skills training (COMP-MST); a positive trend, however, was observed also in participants who did COMP training

	Random sequence generation (*Selection bias*)	Allocation concealment (*Selection bias*)	Binding of participants and researchers (*Performance bias*)	Binding of outcome assessment (*Detection bias*)	Incomplete outcome (*Attrition bias*)	Selective reporting (*Reporting bias*)	Other bias
Aben et al. (2014)[41]	Low	Low	High	Low	Low	Low	Low
Das Nair et al. (2019)[42]	Low	Low	High	Low	High	Low	High
Fleming et al. (2022)[43]	Low	Low	Low	Low	Low	High	Low
Hildebrandt et al. (2014)[51]	Low	Low	Low	Low	Low	Low	Low
Lannin et al. (2014)[44]	Low	High	High	Low	Low	Low	High
Lemoncello et al. (2011)[45]	Low	High	High	High	Low	Low	Low
Lesniak et al. (2018)[46]	Low	High	High	Low	High	Low	Low
McDonald et al. (2011)[47]	Unclear	High	High	High	Low	High	High
Richter et al. (2015)[52]	Low	Low	High	Low	Low	High	Low
Shum et al. (2011)[48]	Low	Low	High	Low	Low	High	High
Storzbach et al. (2017)[49]	Unclear	High	High	High	Low	Low	Low
Yip & Man (2013)[50]	Unclear	High	High	Low	Low	Low	Low
Whithiel et al. (2019)[54]	Unclear	Low	High	Low	High	Low	High

Key

• (green) = Low risk of bias

• (red) = High risk of bias

• (yellow) = Unclear risk of bias

Table 1. Risk of bias in PM RCT studies as assessed using the Cochrane Collaboration tool.

alone and in the waitlist control group. Storzbach et al.[49] employed a manualized group-based compensatory cognitive training (CCT), using daily strategies and external aids (calendar systems and assistive devices) in mild TBI. The authors found a significant post-treatment decrease of self-reported difficulties in memory and the use of cognitive strategies increased.

An improvement of PM was described by using Google Calendar, considered more effective and more appreciated than a standard diary[47]. Indeed, motivation plays an important role as reported by Lemoncello et al.[45] who found significant advantage of PM prompting using the Television Assisted Prompting system (72% completion of daily tasks) over no prompting (43%).

Rehabilitation can improve retrieval processes (not encoding and consolidation)[51] by explaining strategies: computer training, compared to a group training, increased episodic memory performance. During the sessions, participants were supported by a neuropsychologist, who taught the strategy of semantic structuring and spaced retrieval and how to handle the program. Nevertheless, no generalization was found to PM measures.

Withiel et al.[54] demonstrated that participants allocated to the Memory skills group had greater improvement in PM at post-intervention, with significant reduction of everyday memory complaints, than those who did CCT.

Finally, when individual vs. group training were compared, contrasting results were obtained. Leśniak et al.[46] found a significant improvement after the individual training but not after the group training, However, they performed different treatments. Therefore, the comparison between individual and group training should be interpreted with caution.

Evidence of transfer

Evidence of transfer was detected with restitution-oriented techniques, using virtual reality to improve everyday PM[50]. A significant improvement was also reported in a behavioral checklist of PM tasks in the real environment and on a self-efficacy questionnaire, while "traditional" internal-external strategies did not significantly change relatives' ratings of PM failures and of psychosocial reintegration of participants[48]. A working memory training combined with semantic structuring and verbal fluency generalized to ability of remembering future events[52].

The same authors found far transfer effects on Everyday Memory Test (EMT), combining working memory and recollection training[53].

Focusing on studies that used compensation techniques, namely internal/external strategies and psychoeducation, Leśniak et al.[46] found an extended effect of training, showing an enhancement not only in neuropsychological tests, but also in objective tests of everyday memory, such as the RBMT; however, they also found gains in a control group (no therapy) without detecting a specific effect of training. A significant improvement in Memory Self-Efficacy and in Quality of Life (QoL) was especially found in younger (< 65 years old) participants[41].

Using mixed techniques (internal and external strategies, psychoeducation) there were fewer memory failures on the Goal Attainment Scale[44], or there were improvements in everyday memory functioning measures, such as the Everyday Memory Questionnaire (EMQ)[42]. Accordingly, caregivers reported a reduced amount of forgetting at the Memory Functioning Questionnaire (MFQ)[44] and a decrease of memory failures at the EMQ in group treatment as compared to individual therapy[42]. The remaining studies did not find any evidence of transfer.

Maintenance over time

Effectiveness of interventions over a longer time was assessed in six studies. Improvement was sustained after 6 months in Aben et al.[41], remaining stable over 12 months. In contrast, Das Nair et al.[42] detected a maintenance of memory rehabilitation effects at 6 months, but not at 12 months. Leśniak et al.[46] found that with group training, improvement in RBMT continued at 4-month follow-up. Storzbach et al.[49] planned a 5-week follow-up that confirmed the results found at the post-treatment assessment. In Withiel' et al. (2019)'s study[54], gains in functional goal attainment and internal strategies after memory skill groups were maintained for 6 weeks after training. Lastly, Fleming et al.[43] detected a clinically relevant change at 3-month follow-up on psychosocial reintegration (Sydney Psychosocial Reintegration Scale version 2) and on Everyday PM failure (Brief Assessment of Prospective Memory, BAPM) as reported by participants' caregivers.

Some studies did not include a follow-up[47,48,50]. Finally, in Lannin et al.[44] this was limited to 8 weeks with no evidence of maintenance.

Neurological and demographic factors associated with rehabilitation effectiveness

Two RCT studies included only stroke participants[41,54] and four studies only TBI[42,43,48,49]. Finally, two studies between those including participants with mixed etiologies[46,47] considered neurological factors as associated with outcome. The remaining RCT studies did not explore specific effects of treatment based on these variables.

Concerning stroke, as already reported, a psychoeducational intervention was more fruitful for younger people[41]; nevertheless, older individuals were mainly men, having lower memory scores, that could explain this result. There is a limited number of studies on early intervention after stroke, as spontaneous recovery can mask the effects of treatment.

Concerning TBI, since participants are often unaware of their PM deficits, a combined training, consisting of a compensatory intervention preceded by a self-awareness training has been considered the best option[43,48] but the superiority of combined training on compensatory strategy training alone was not confirmed.

An additional variable that could affect treatment effectiveness is time since the event, but results are inconsistent: this did not seem to affect effectiveness in Das Nair et al.[42]' study, while in Leśniak et al. (2018)'s study[46], a significant improvement between pre- and post-assessment was found only in late recovery (>6 months from ABI).

PM rehabilitation techniques in nRCT

Thirteen nRCTs studies focusing on PM rehabilitation were included: seven addressed TBI, five considered stroke and one studied ABI individuals in general.

Concerning TBI, compensatory methods were the preferred approach. Only two studies employed a restorative approach with individuals who suffered a TBI at least 1 year before treatment: in detail, Raskin and Sohlberg[60] found a significant improvement in intentional memory at 1-year follow-up, and a reduction of the total number of PM failures; there was also a generalization to the Everyday Memory Questionnaire and to the efficiency in accomplishing 10 everyday PM tasks. The sessions lasted 1 hour and were delivered 2 times per week for 6 months. A similar approach was used by Raskin et al.[61] with moderate-severe TBI individuals, combining visual imagery of events with rote repetition. Even this treatment was effective on memory for future intentions and the positive effect generalized to attention and executive functions; in addition, the use of diaries generalized. All these gains were stable at 1-year assessment.

Three studies on TBI participants used external aids, such as an internet-based calendar compared to an internet-based diary training: a therapist delivered the cognitive treatment through an online instant messaging system, as a telerehabilitation method[55] for a total of 60 sessions; compensatory strategies increased, especially in participants that already used them. In addition, patients' relatives reported improved memory and mood after completion of all sessions. An internet-based calendar to compensate for PM difficulties was used also by Evald[63]. The treatment consisted in learning to use a smartphone to remember appointments and to compensate for memory difficulties. The treatment lasted 6 weeks, for a total of 9 hours (1 individual session and 5 group sessions). Post-treatment scores at the Prospective Memory Questionnaire and at the Prospective and Retrospective Memory Questionnaire showed perceived reduced memory deficit. At 2-month follow-up a significant decrease of self-reported memory problems emerged.

Similar compensation of time-based PM deficits with external memory aids was found in Dowds et al. (2011)'s study[56], where different palmtop computers as memory aids, namely the Palm OS and the Microsoft's Pocket PC OS have been compared. The Palm version produced better results with respect to the alternative conditions.

In two studies, instead, participants were treated with internal memory strategies (I-MEMS), such as errorless learning and metacognitive strategies in a group treatment[65]. Training consisted of semantic association, processing and chaining, visual-auditory imagery; however, in this study, additional external memory aids, already used by participants, were continued. This treatment led to an improvement in verbal LTM, with a transfer to everyday memory effectiveness (RBMT-II). The results of the immediate post-treatment assessment were maintained and slightly increased 1 month later, mainly in individuals with mild to moderate TBI. Finally, Potvin et al.[59] studied the efficacy of visual imagery on PM, carrying out 10 weekly individual rehabilitation sessions (15 hours). PM exercises gradually increased in complexity and ecological aspects, using a spaced-retrieval technique, with the aim of applying visual imagery to everyday situations. Compared to the control group, individuals in the rehabilitation group reached higher total scores on the Ecological Test of PM and made less intrusion errors; moreover, they recalled more actions on the time-based condition, but not on the event-based condition; self-evaluated PM failures seemed fewer at the post-test than at the initial assessment, in accordance with relatives' reports on Comprehensive Assessment of Prospective Memory. No training transfer effects were detected.

All nRCT studies on stroke participants applied compensatory strategies. Miller & Radford[58], delivered a mixed treatment, including psychoeducation, internal strategies and external memory aids, in groups of 8–12 participants. There was a significant improvement on learning and delayed recall that continued to improve over the 3-month follow-up. Demographic and clinical variables were relevant: both older age and lower degree of depression were associated with higher probability of completing the training; higher intelligence quotient or education increased the number of strategies used; a shorter interval after stroke was related to more gains in PM, while a longer interval was associated to reduced improvement.

Virtual reality was also effective on PM abilities[54] applying visual imagery strategies to everyday context, as in Potvin et al. (2011)'s previously described study on TBI[59]. The improvement remained stable after four weeks.

Withiel et al.[67] investigated the effectiveness of a manualized memory skills group training in four stroke individuals (4–41 months since injury), inspired from a previous training, namely "Making the Most of your Memory: An Everyday Memory Skills Program"[68]. The training consisted in six weekly two-hour group sessions of psychoeducation, learning internal and external compensatory strategies, discussion everyday memory issues and homework assignments. In addition, patients' family members participated in a separate session. The result was a reduction of memory complaints during the training with participants attaining at least one specific goal after treatment, maintained at the follow-up. Lawson et al.[57] compared face-to-face individual training with a telehealth delivery condition conducted via Zoom in stroke survivors, at least 3-months from onset. Both treatments were delivered weekly, during a 6-week period, 2-hour per session. The training consisted in a modified version of the Monash Memory Skills Group program[58]. They found significant improvements in both groups, with maintenance of gains at six-week follow-up; a reduction in everyday lapses of PM was also found, although confirmed at follow-up only for the telehealth group. Lawson et al.[57] explored the promising role of booster sessions with a 12-week follow-up in maintaining gains on subjective measures of everyday memory and PM. Telehealth participants were younger than those in the face-to-face group.

A few years later, Lawson et al.[66] proposed the same compensatory memory intervention to five chronic stroke individuals with mild to moderate memory deficit. All participants reported attaining at least one of the two personally memory-related goals immediately post-training and maintained or improved their level of function at 6-week follow-up. High rates of participant satisfaction and good adherence to treatment were observed.

The last study, by Anaki et al.[62] concerned ABI of mixed etiologies selected on average three years after the injury for a holistic and intensive rehabilitation program[69]. Internal and external techniques were trained and extended to ecological contexts. Participants were treated several hours per day, 3–4 times a week, for months or years. Training consisted in individual and group interventions, involving many actors: occupational therapists, psychologists, speech therapists, physiotherapists and caregivers. Post-treatment assessment was administered on average four years after the end of the rehabilitation program. Memory performance enhanced in RBMT-II in both the experimental and control groups (who received a similar program without specific memory exercises). Furthermore, more intensity produced better outcomes, mostly in non-TBI participants.

Meta-analysis results

Characteristics of included studies

A total of 10 randomized controlled trials[42–46,50–54,67], involving 477 participants, met the inclusion criteria and were included in the quantitative synthesis. The studies utilized a variety of intervention approaches, encompassing compensatory strategies (e.g., the utilization of memory aids, metacognitive training) and restitutive methods (e.g., computerized cognitive rehabilitation, virtual reality). The assessment of prospective memory involved the use of various validated instruments, including the EMQ, CAMPROMPT, RBMT, and PRMQ.

Main effects of rehabilitation on prospective memory

The pooled analysis revealed a statistically significant moderate effect of cognitive rehabilitation on PM outcomes in individuals with ABI. Specifically, the mean effect size was Hedges' $g = 0.55$, with a 95% confidence interval ranging from 0.29 to 0.80. The result obtained corresponds to a Z-value of 4.20 ($p < .001$), thereby indicating a robust deviation from the null hypothesis that rehabilitation has no benefit over control conditions (see Figure 2: Forest plot of PM effect size).

Heterogeneity and prediction interval
The analysis identified moderate heterogeneity across studies. The Q-statistic was 16.73 with 9 degrees of freedom ($p = 0.05$), and the I^2 statistic was 46%, suggesting that nearly half of the variance in observed effects is attributable to true between-study differences rather than sampling error.

Assuming a normal distribution of the true effects, the 95% prediction interval ranged from −0.15 to 1.26, implying that while the average effect is beneficial, future studies may observe effects ranging from negligible to large, depending on context and implementation.

Publication bias and sensitivity analyses
Multiple indicators pointed to the possible presence of publication bias. Egger's regression test yielded an intercept of 2.98 ($p = 0.040$), suggesting asymmetry in the funnel plot (Figure 3) and a tendency for smaller studies to report larger effect sizes. The classic fail-safe N was calculated at 76, indicating that 76 unpublished null studies would be required to overturn the statistical significance of the observed effect publication bias report. Using the Trim and Fill method, three studies were imputed to the left of the mean (see Figure 3), yielding an adjusted effect size of Hedges' g = 0.347 (95% CI: 0.054, 0.640) under a random-effects model. This adjustment reduced the pooled estimate but preserved statistical significance, affirming the overall robustness of the findings.

The certainty of the evidence was evaluated by considering factors such as the risk of bias, inconsistency, indirectness, imprecision, and publication bias. The GRADE assessment for PM outcomes was rated as moderate, primarily due to concerns regarding blinding (Table 2).

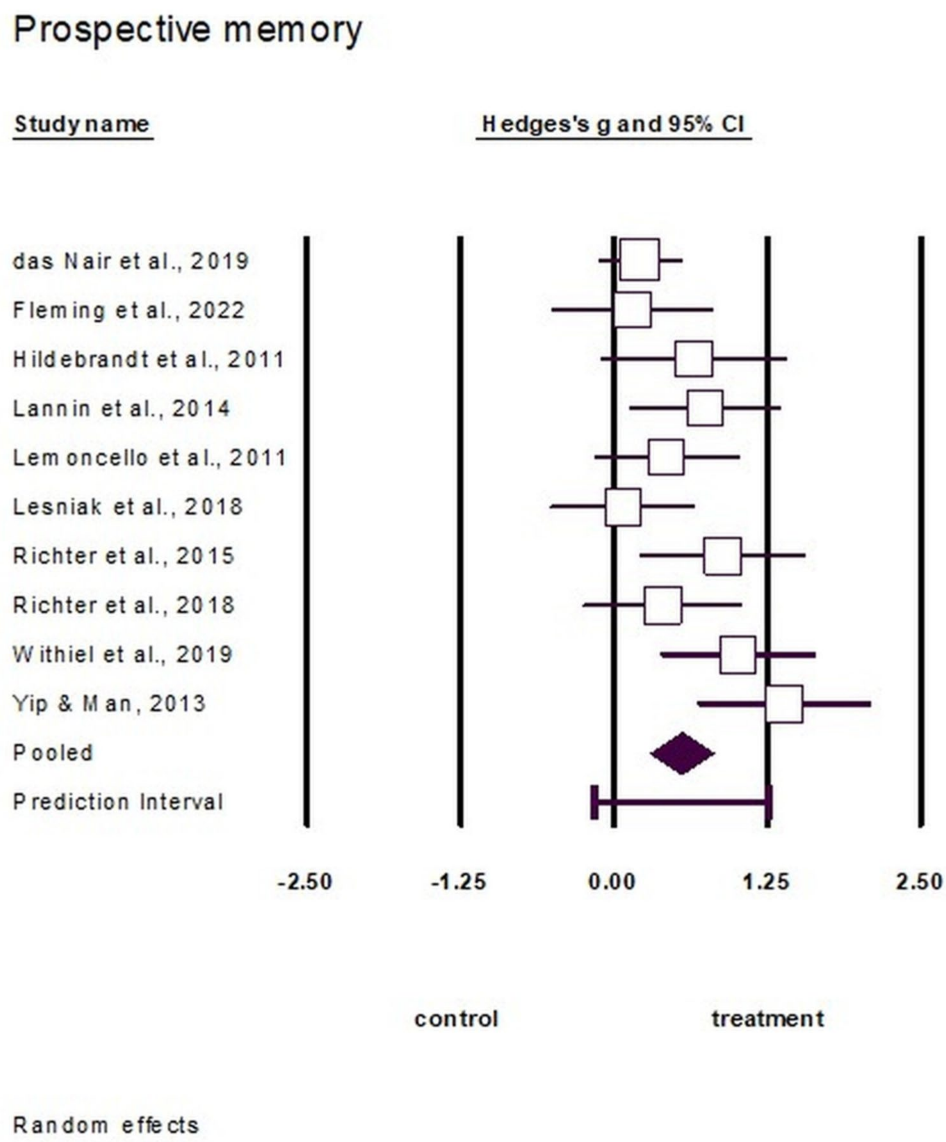

Fig. 2. Forest plot.

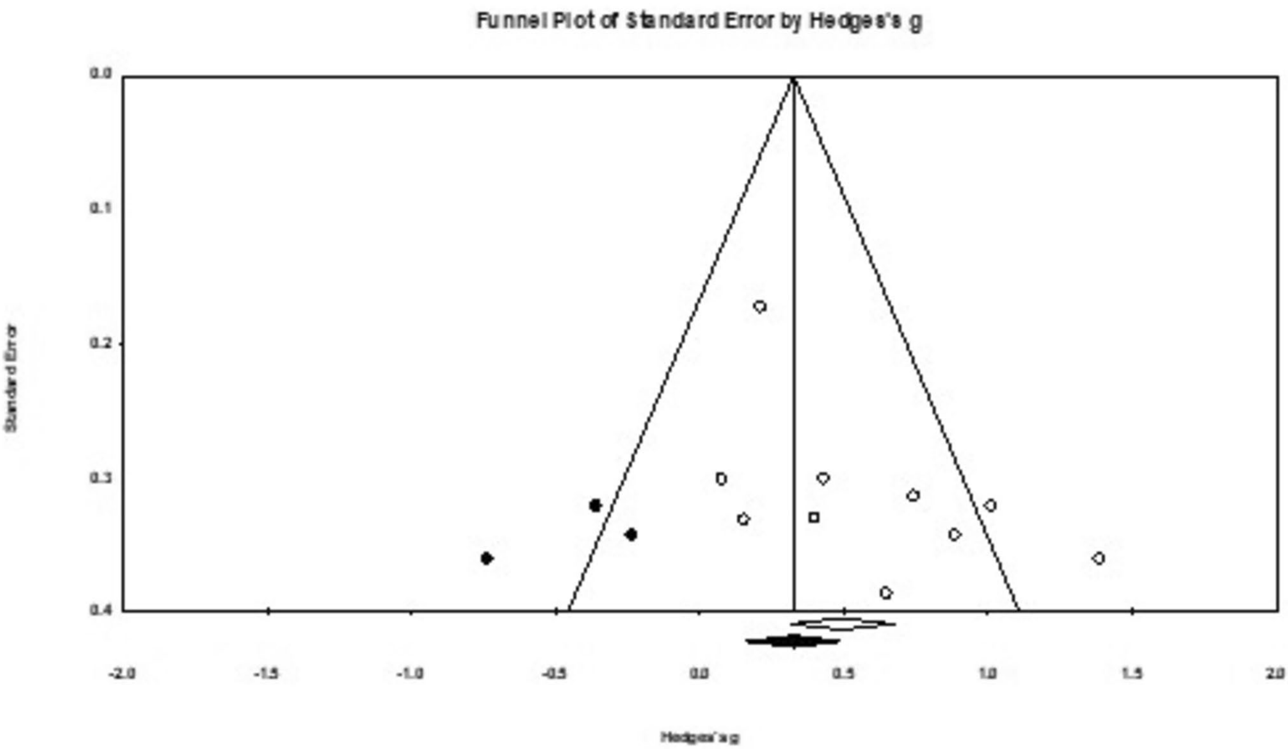

Fig. 3. Funnel plot of standard error by Hedges'g.

Certainty assessment							№ of patients		Effect SMD		
№ of studies	Study design	Risk of bias	Inconsistency	Indirectness	Imprecision	Other considerations	Memory rehabilitation	Control	Absolute (95% CI)	Certainty	Importance
PROSPECTIVE MEMORY											
10	randomized trials	serious[a]	not serious	not serious	not serious	none	243	234	Hedge's g **0.55 SD** (0.29 to 0.80)	⊕⊕⊕◯ Moderate	IMPORTANT

Table 2. GRADEpro **Question:** Memory rehabilitation compared to the control condition. **CI:** confidence interval; **SMD:** standardized mean difference as Hedge's g. *Explanations*. [a.] Blinding of participants and researchers was reported in a small number of included studies.

While moderator analyses could have offered valuable insights into the differential impact of intervention types or outcome measures, the limited number of included studies did not permit their reliable execution. As a result, planned exploratory comparisons—such as those contrasting compensatory versus restitutive approaches, or performance-based versus self-reported measures of prospective memory—were not pursued in the present analysis.

Discussion

We systematically reviewed the literature on the effectiveness of PM rehabilitation, in adult patients after stroke or TBI. Very few additional different etiologies (such as infective diseases) were considered. We did not include participants with epilepsy (see Joplin et al.[70]for a review on memory rehabilitation in this group of patients), multiple sclerosis (see Mazo et al[71]., although limited to WM), and neurodegenerative diseases. More specifically, we were interested in highlighting whether new treatments, such as NIBS, virtual reality or computer-based rehabilitation are employed with success in combination or alone, compared to more "traditional" techniques (a summary of the different techniques adopted in the reviewed studies can be found in Table 3). We evaluated the methodology of studies, the outcomes, the level of generalization and maintenance over time. Furthermore, we verified the effects of demographic variables on results. Finally, we performed a meta-analysis on the effects of treatment on PM, and we also assessed the level of evidence with the GRADE methodology for RCT studies.

We included 14 RCT. Both, restorative and compensation treatments were used, balanced between individual and group treatment, or both. Computer rehabilitation training programs were applied, as well as virtual reality programs (see for example Yip & Man[50]) or technical devices of which the most fruitful appeared to be Google Calendar[47]. It must be noted, however, that this last study received a PEDro score <6 and high risk of

Neuropsychological Approach	Studies
Internal/external memory strategies	Aben et al.[41]; das Nair et al.[42]; Fleming et al.[43]; Hildebrandt et al.[51]; Lannin et al.[44]; McDonald et al.[47]; Shum et al.[48]; Storzbach, et al.[49]; Withiel et al.[67]; Dowds et al.[56]; Evald[63]; Lawson et al.[66]; Lawson et al.[57]; Miller & Radford[58]; O'Neil-Pirozzi et al.[65]; Potvin et al.[59]; Sohlberg[60]; Raskin et al.[61]
Psychoeducational intervention	Aben et al.[41]; Leśniak et al.[46]; Lawson et al.[57]; Lawson et al.[66]
Computer-based cognitive training	Hildebrandt et al.[51]; Leśniak et al.[46]; Richter et al.[52]; Richter et al.[53]; Withiel et al.[54]; Mitrovic et al.[64]
Cognitive training with mobile technologies	Lemoncello et al.[45]; Lawson et al.[66]
Internet-based cognitive training	Bergquist et al.[55]
Virtual reality memory training	Yip & Man[50]
Holistic rehabilitation approach	Anaki et al.[62]

Table 3. Summary of the different rehabilitation approaches adopted in the reviewed studies.

selection, performance, detection and reporting bias according to the Cochrane scale; therefore, the results must be considered with caution. Individual vs. group treatment does not seem to produce significant differences but, again, the observation is speculative and limited by the scarce number of confrontations. Similarly, when asked, caregivers reported a decrease of memory failure, but data are limited to two studies[42,44]. Also in these cases, the meta-analysis revealed a positive effect of treatment but, again, given the limited number, we did not differentiate among types of treatment. Moreover, the level of improvement varied, ranging from very mild effects to moderate ones. More studies are required to confirm these results. However, the level of evidence as assessed with the GRADE methodology, was moderate.

The different studies did not distinguish between deficits due to the prospective vs. retrospective component of memory: for example, Chiaravalloti et al.[72] trained new learning abilities, while Shum et al.[48] employed compensatory training for prospective deficits, as was done in the majority of training examined, but they did not explicitly define why this type of treatment was preferred based on the neuropsychological examination. In addition, PM is not a unitary process; consequently, it is difficult to determine the best rehabilitation paradigm for PM, as it remains unclear whether interventions were focused on specific components of PM (e.g., time-based vs. event-based, retrospective vs. prospective components).

Concerning the distinction between compensatory and restitutive strategies, all the reviewed studies that only considered PM (not those considering WM as well, see below) adopted the first type of treatment with the exception of Sohlberg[60], who reviewed the literature concerning three different approaches (behavioral/compensatory, metacognitive, restorative) and found that a restorative approach is beneficial in the domain of prospective memory.

Although the use of virtual reality emerged as the intervention contributing most to the moderate pooled effect[50], the etiology of the participants' condition appears to be the most influential factor in determining the success of an intervention. For instance, both Withiel et al.[54] and Fleming et al.[43] employed internal and external memory strategies; however, outcomes varied significantly. While Withiel et al. reported substantial improvements in stroke individuals, Fleming et al. (TBI participants) observed the lowest gains in our meta-analysis, suggesting that the underlying cause of cognitive impairment may moderate the effectiveness of similar intervention techniques.

Information about maintenance is scarce. A follow-up to a maximum of 12 months has been conducted only in seven RCTs. There was limited evidence that age affects recovery when the etiology is stroke[41] while time since TBI did not prove to affect treatment.

Finally, we considered a group of five studies treating both WM and PM. Four of these were RCTs comparing restitution-oriented therapies, in three cases targeting WM vs. compensatory (strategies) methods. The results show that WM training generalized to PM. The nRCT study instead used compensatory methods. Strategies do not seem to be effective in PM for TBI individuals, as observed by Mioni et al.[73], who used the Virtual Week task applying implementation of actions as a strategy to improve performance. Implementation intentions involved making explicit plans specifying when, where, and how, a task had to be performed in the future. Compared to controls, TBI participants did not benefit from it. However, in a subsequent study, it was found that future event simulation substantially reduced TBI-related deficits in PM performance, probably due to facilitation of retrieval of the intended action as a result of pre-experiencing the specific visual–spatial context through imagination[74]. However, as Mioni et al.[75] suggest, in the case of compensatory strategies, the most relevant aspect is whether or not participants are aware of their deficits and therefore are willing to adopt them.

The results of the meta-analysis are encouraging and suggest that in the case of PM, rehabilitation should be recommended, but more evidence is required to confirm this positive result. Moreover, it may be more effective to conceptualize PM not as a unitary system, but rather by differentiating its components. Based on a thorough neuropsychological evaluation, clinicians could then determine whether it would be more beneficial to target the retrospective or the prospective component in rehabilitation. In particular, it is interesting to observe that a computer training for WM can improve memory for the future.

Virtual reality also seems to be a very promising tool, although under-utilized until now.

Limitations of this review

We must acknowledge the limitations of this review that were in part due, as reported, to the number and quality of the examined studies.

First, techniques are highly variable, as well as the software employed. The review was limited to studies published in English.

Second, terminology is inconsistent across studies: long-term memory (LTM) tests have been used both for baseline and outcome assessments, even though the primary target of training is PM.

Third, individuals with mixed etiologies are often grouped together, which hinders the possibility to analyze the effects of specific etiologies. This is a significant limitation, as recently highlighted in a voxel-based lesion-symptom mapping study[76].

Fourth, neuropsychological batteries and outcome measures vary widely. In many cases, it appears that parallel forms of the tests were not used, and outcomes were not evaluated by independent, blinded examiners. Standardized tests were not always used.

Fifth, we identified a limited number of studies comparing paper-and-pencil aids with digital tools, and, unexpectedly, none of the examined studies employed non-invasive brain stimulation (NIBS). This can be partially explained by the fact that structures involved in memory systems are not reachable for stimulation. However, PM deficits could possibly benefit from NIBS applied over the dorsolateral prefrontal cortex[77].

Sixth, it is not always clear whether event-based or time based PM was trained and if the effects were found on both subtypes. Finally, outcome measures related to everyday functioning are typically based on scales or questionnaires, which are rarely reported in detail (see for instance[42,53,60,61]). Using Self-Report Measures is critical and hopefully future studies should incorporate objective, performance-based measures of real-life functioning. Indeed, most patients, particularly those with TBI, often have a poor awareness of their cognitive deficits, and the correlation between self-reported PM and actual performance on various PM tasks is low. For instance, using self-report PM questionnaires, such as the PRMQ and the PMQ, TBI participants have been found to underestimate the frequency of their everyday PM difficulties when compared to a healthy control group (see[75]). Moreover, a substantial proportion of variability in PM self-report scores is also due to verbal intelligence, personality, activities engagement[78]. Therefore, the reliance on self-report questionnaires to assess real-life improvements in PM is problematic and should be considered with extreme caution.

Directions of future research

Summing up, our findings add new data to the existing literature, including new techniques such as Virtual Reality. Moreover, with respect to previous reviews, we did not focus only on traumatic brain injuries. The level of evidence was assessed using the GRADE methodology.

Finally, we suggest directions for future research. Namely, the selection of participants should be more homogeneous concerning the demographic variables: for example, in many studies participants ranged between 18 and 70 years, and this could have affected the use of new technologies, in which younger people are certainly more familiar; younger people can be more motivated than older people; the cerebrovascular response to cognitive stimulation differs depending on age[79]. Etiology must be considered, ecological outcomes should be constantly evaluated: too frequently, the success of a treatment is based on the test score even when no parallel forms of the same test are adopted. Another crucial point is to have an examiner assessing the post-treatment performance, different from the person who conducted the treatment; this is not specified in most of the papers we analyzed, and this was not considered in previous reviews. As already mentioned, objective performance-based measures are required to correctly establish improvements after training.

The take-home message is that PM rehabilitation is promising, especially when employing new technologies, but more targeted studies must be performed, both in terms of retrospective vs. prospective component treatment and event-based vs. time-based subtypes. A detailed neuropsychological assessment should provide necessary information to guide treatment.

Probably, memory treatment could benefit from a multicentric consortium of memory centers, employing comparable assessment methods, treatment techniques and specific outcome evaluation, distinguishing participants with different etiology and demographic variables. Only in this way, enough homogeneous participants can be recruited to develop effective guidelines for the treatment of such a disabling deficit.

Data availability

This study is a systematic review and meta-analysis. The data analyzed were extracted from previously published studies. As such, the original data are not owned by the authors. However, the dataset compiled and used for the meta-analysis is available from the corresponding author upon reasonable request.

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Author contributions

M.S., L.B., E.B., E.Ba., S.T., and L.Z. conceived the study and developed the review and meta-analysis protocol. All authors participated at different stages in literature screening and data extraction. M.S., L.B., E.B., E.Ba., S.T., and L.Z. conducted data extraction and quality assessment for the systematic review and contributed to the preparation of all tables, except those related to the meta-analysis. M.B. performed data extraction for the meta-analysis, carried out all statistical analyses, and produced the corresponding figures and tables. C.P. supervised the project, drafted the manuscript, and revised its final version. All authors contributed to data interpretation, critically reviewed the manuscript, and approved the final version for submission.

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Declarations

Competing interests
The authors declare no competing interests.

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