



Systematic Review and Meta-Analysis of Digital Learning Tools for Cognitive Decline in Older Adults

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Abstract—Background: Age-related cognitive decline represents a growing public health challenge, and digital learning tools have emerged as potentially scalable approaches for cognitive support in older adults. However, the overall effectiveness of these interventions and the factors associated with treatment response remain uncertain. This systematic review and meta-analysis aimed to evaluate the effects of digital learning tools on global cognitive function in adults aged 60 years and older and to explore potential moderators of intervention effects. **Methods:** Five electronic databases (PubMed, Embase, PsycINFO, Cochrane CENTRAL, and Web of Science) were searched for randomized controlled trials evaluating digital learning interventions in older adults with or without mild cognitive impairment (MCI). Random-effects models were used to synthesize standardized mean differences (SMDs) for global cognitive outcomes. Exploratory subgroup analyses examined intervention modality, participant cognitive status, intervention dosage, and risk of bias. The certainty of evidence was assessed using the GRADE framework. **Results:** Thirty-five randomized controlled trials involving 4,288 participants were included. Digital learning interventions were associated with improved global cognitive performance compared with control conditions (SMD = 0.48, 95% CI 0.35–0.61), although substantial heterogeneity was observed ($I^2 = 78\%$). Exploratory analyses indicated larger effect estimates for virtual reality-based interventions (SMD = 0.65) and serious games (SMD = 0.54) compared with computerized cognitive training (SMD = 0.39). Greater effects were also observed among participants with MCI (SMD = 0.56) and studies providing at least 24 hours of intervention exposure (SMD = 0.59). However, the certainty of evidence was rated as very low because of methodological limitations, substantial inconsistency, and potential small-study effects. **Conclusion:** Digital learning tools show potential for supporting cognitive performance in older adults, but current evidence remains insufficient to establish definitive effectiveness or identify optimal intervention characteristics. Future research should prioritize well-designed randomized trials with standardized outcomes, longer follow-up periods, transparent reporting, and evaluation of feasibility, accessibility, and real-world cognitive benefits.

Keywords—*Cognitive Decline; Older Adults; Digital Learning; Meta-Analysis; Virtual Reality; Mild Cognitive Impairment*

1. INTRODUCTION

The global population is aging at an unprecedented rate, with the number of people aged 60 years and over expected to double by 2050, reaching nearly 2.1 billion [1]. This demographic shift brings a significant increase in the prevalence of age-related health challenges, among which cognitive decline is one of the most pressing concerns [2]. Cognitive decline, ranging from mild cognitive impairment (MCI) to more severe forms of dementia such as Alzheimer's disease, not only diminishes the quality of life for older adults but also places a substantial burden on families, healthcare systems, and society as a whole [3]. The economic impact is staggering, with the global cost of dementia estimated to be in the trillions of dollars, a figure that is projected to rise with the aging population [4].

In response to this growing challenge, there has been a surge of interest in developing and evaluating interventions aimed at preventing, slowing, or even reversing cognitive decline in older adults. While traditional approaches have included pharmacological treatments and in-person cognitive training, these methods often face limitations such as side effects, high costs, and lack of accessibility [5]. In recent years, the rapid advancement of digital technology has opened up new avenues for delivering cognitive interventions. Digital learning tools, encompassing a wide range of applications from mobile-based "brain training" games and computerized cognitive training (CCT) programs to virtual reality (VR) simulations and online educational platforms, have emerged as a promising and scalable solution [6, 7].

These digital tools offer several potential advantages over traditional methods. They can be delivered remotely, increasing accessibility for individuals in rural or underserved areas. They can be personalized to the user's specific cognitive needs and abilities, providing a more tailored and engaging experience. Furthermore, they can collect a wealth of data on user performance, allowing for continuous monitoring and adaptation of the intervention [8]. A growing body of research has begun to explore the effectiveness of these digital interventions, with numerous studies suggesting their potential to improve various cognitive domains, including memory, attention, and executive function [9, 10].

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However, the existing literature is characterized by a high degree of heterogeneity in terms of the types of digital interventions studied, the target populations, the outcome measures used, and the methodological quality of the studies. Several systematic reviews and meta-analyses have attempted to synthesize this evidence, but they often focus on specific types of interventions (e.g., serious games) or specific populations (e.g., patients with dementia), and their findings are not always consistent [11, 12]. Moreover, the rapid pace of technological innovation means that new digital tools are constantly emerging, creating a need for up-to-date and comprehensive evidence synthesis.

Therefore, this systematic review and meta-analysis evaluated the effectiveness of digital learning tools for improving global cognitive function in older adults with or at risk of cognitive decline. We addressed three questions: (1) What is the overall association between digital learning tools and global cognitive function? (2) Do effect estimates differ by digital intervention modality? and (3) Are participant diagnosis, intervention dosage, and study quality associated with variation in effect estimates?

2. RELATED WORK

Existing reviews suggest that computerized cognitive training, serious games, and virtual-reality (VR) interventions may benefit cognitive performance in selected older populations, but their conclusions are limited by variation in populations, intervention content, comparators, outcome definitions, and risk of bias [13, 14, 15]. Many reviews focus on a single modality or a restricted diagnostic group; consequently, their findings do not directly establish the relative effectiveness of heterogeneous digital learning tools across older adults with and without mild cognitive impairment (MCI).

This review is positioned as a broad RCT synthesis that examines the overall effect of digital learning tools and transparently explores variation by intervention modality, participant diagnosis, dosage category, and risk of bias. Its contribution is therefore not a claim of definitive modality ranking, but an evidence synthesis that identifies where observed effects appear promising and where reproducible, better reported comparative research remains necessary.

3. METHODOLOGY

3.1. Search Strategy and Selection Criteria

A comprehensive literature search was performed in PubMed, Embase, PsycINFO, Cochrane Central Register of Controlled Trials (CENTRAL), and Web of Science from inception to December 2024. The strategy combined population terms (e.g., “older adults”, “elderly”, “geriatric”, “aging”), cognitive-status terms (e.g., “cognitive decline”, “mild cognitive impairment”, “MCI”, “cognitive aging”), and intervention terms (e.g., “digital learning”, “computerized cognitive training”, “serious games”, “virtual reality”, “digital intervention”, and “mHealth”)[16].

Studies were included if they met the following criteria: (1) were randomized controlled trials (RCTs) or quasi-randomized controlled trials; (2) involved a population of older adults (mean age ≥ 60 years) with or without a diagnosis of MCI; (3) evaluated any form of digital learning tool as the primary intervention; (4) included a control group (e.g., active control, waitlist, or no-treatment); and (5) reported at least one quantitative measure of cognitive function as an outcome. Studies focusing on populations with severe dementia, case

reports, reviews, editorials, and non-randomized trials were excluded.

3.2. Study Selection and Data Extraction

Two independent reviewers (S.J. and M.C.) screened titles and abstracts and then assessed full texts for eligibility. Disagreements were resolved through discussion or consultation with a third reviewer (E.W.). Inter-rater agreement was assessed using Cohen’s kappa coefficient. The reported $\kappa = 0.87$ must be verified against the screening log and labeled according to the phase in which it was calculated (title/abstract screening and, if available, full-text screening). A PRISMA flow diagram documents the selection process.

Two reviewers independently extracted study characteristics, participant data, intervention and comparator details, total contact hours, and outcome data. To avoid unit-of-analysis errors, the final analytic dataset must contain no more than one independent effect size per study, outcome construct, and analytic time point unless within-study dependence is modeled explicitly.

3.3. Risk of Bias Assessment

The methodological quality and risk of bias of each included RCT were independently assessed by two reviewers using the Cochrane Risk of Bias tool 2 (RoB 2) [17]. This tool evaluates bias across five domains: (1) bias arising from the randomization process, (2) bias due to deviations from intended interventions, (3) bias due to missing outcome data, (4) bias in measurement of the outcome, and (5) bias in selection of the reported result. Each domain was judged as “low risk of bias,” “some concerns,” or “high risk of bias.” The overall risk of bias for each study was then determined based on the judgments across all domains.

3.4. Data Synthesis and Analysis

The primary outcome was global cognitive function at the post-intervention assessment, measured using standardized cognitive batteries such as the Montreal Cognitive Assessment (MoCA) or Mini-Mental State Examination (MMSE). Effect directions were aligned so that positive SMDs favored the digital-learning intervention. Secondary outcomes included individual cognitive domains, quality of life, and adherence.

For continuous outcomes, SMDs with 95% confidence intervals (CIs) were used because different cognitive scales were reported. Conventional benchmarks of approximately 0.2, 0.5, and 0.8 were used only as descriptive small, medium, and large effect-size guides, respectively [18]. Heterogeneity was assessed using I^2 , with 25%, 50%, and 75% interpreted as low, moderate, and high, respectively. A random-effects model was used to accommodate anticipated clinical and methodological heterogeneity. Subgroup differences were assessed using the chi-square test for interaction (test for subgroup differences) implemented in RevMan, with two-sided p values. Intervention type, participant diagnosis, dosage category, and risk of bias were examined as subgroup factors. The comparison of <24 versus ≥ 24 total hours is an exploratory categorical contrast; it cannot establish a continuous dose-response relationship or support claims about nonlinearity or diminishing returns. A continuous random-effects meta-regression of total intervention hours should be conducted only after the study-level dosage data are supplied. Sensitivity analysis excluded studies at high risk of bias.

4. RESULTS

4.1. Study Selection

The search identified 4,823 records. After 1,578 duplicates were removed, 3,245 titles and abstracts were screened and 3,098 records were excluded. Full texts of 147 reports were assessed, of which 112 were excluded because of non-randomized design ($n = 45$), incorrect population ($n = 28$), inappropriate intervention ($n = 21$), or no relevant cognitive outcome ($n = 18$). Thirty-five RCTs were included. The reported inter-rater agreement was $\kappa = 0.87$; the screening phase to which this value applies must be confirmed from the review log. Figure 1 summarizes records identified ($n = 4,823$), duplicates removed ($n = 1,578$), records screened ($n = 3,245$), full-text reports assessed ($n = 147$), full-text reports excluded ($n = 112$), and RCTs included in the meta-analysis ($n = 35$).

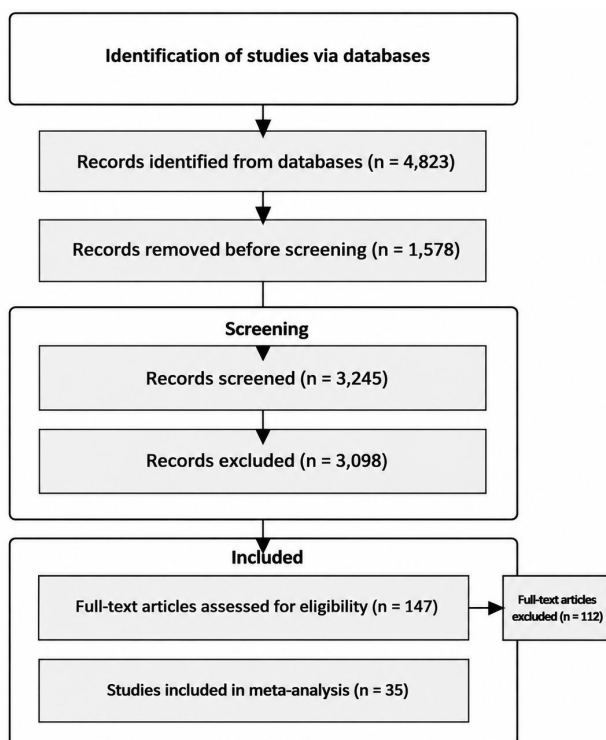


Figure 1. PRISMA 2020 flow diagram for study selection.

4.2. Study Characteristics

The 35 included studies were published between 2015 and 2024 and involved 4,288 participants (2,215 intervention and 2,073 control participants). Sample sizes ranged from 40 to 450, with a median of 98. The mean participant age was 72.4 years ($SD = 3.2$; range 60–85 years). Twenty-one studies (60%) enrolled participants with MCI and 14 (40%) enrolled cognitively healthy older adults. Fifteen studies were conducted in Europe, 11 in North America, seven in Asia, and two in Australia.

Interventions included computerized cognitive training (CCT; $n = 16$, 46%), serious games ($n = 10$, 29%), VR-based training ($n = 5$, 14%), and multi-component platforms ($n = 4$, 11%). Intervention duration ranged from 4 to 24 weeks (mean 12.6 weeks, $SD = 6.4$). Total intervention time was 38.2 hours on average ($SD = 24.5$), with a median of 36 hours (range 12–108). Active comparators were used in 22 studies (63%) and waitlist or no-treatment comparators in 13 (37%).

TABLE I. CHARACTERISTICS OF INCLUDED STUDIES

Characteristic	N (%) or Mean (SD)
Total number of studies	35 (100)
Total participants	4,288
Mean age (years)	72.4 (3.2)
Female participants (%)	58.3 (12.1)
Participants with MCI	21 (60)
Participants cognitively healthy	14 (40)
Intervention Type	
Computerized Cognitive Training	16 (46)
Serious Games	10 (29)
Virtual Reality	5 (14)
Multi-component Platforms	4 (11)
Intervention Duration	
Mean duration (weeks)	12.6 (6.4)
Mean total hours	38.2 (24.5); h: 36 [12–108]
Control Group Type	
Active control	22 (63)
Waitlist/No-treatment	13 (37)
Geographic Distribution	
Europe	15 (43)
North America	11 (31)
Asia	7 (20)
Australia	2 (6)

4.3. Risk of Bias Assessment

Using RoB 2, 12 of 35 studies (34.3%) were judged at low risk of bias, 18 (51.4%) had some concerns, and five (14.3%) were at high risk of bias. Concerns commonly involved randomization, deviations from intended intervention, and outcome measurement. As shown in Figure 2, each horizontal bar shows the percentage of trials judged at low risk (green), some concerns (orange), or high risk (red) for each RoB 2 domain.

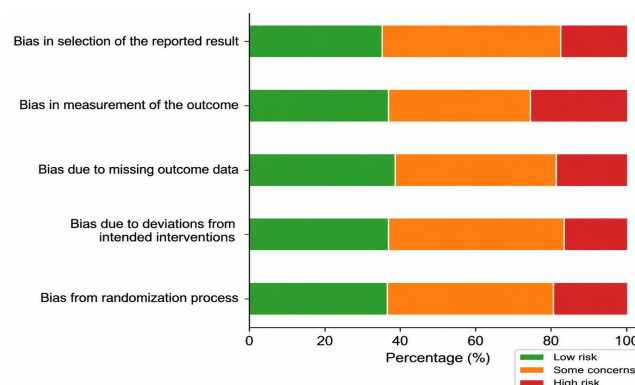


Figure 2. Risk-of-bias summary based on RoB 2 across 35 included RCTs.

4.4. Certainty of Evidence

For global cognitive function, the certainty of evidence was provisionally rated very low (Table 2). Starting from high

certainty for RCT evidence, the rating was downgraded one level for study limitations, two levels for substantial inconsistency ($I^2 = 78\%$), and one level for suspected small-study/publication bias.

TABLE II. SUMMARY OF FINDINGS AND PROVISIONAL GRADE ASSESSMENT FOR GLOBAL COGNITIVE FUNCTION.

Outcome	No. of studies / participants	Risk of bias	Inconsistency	Indirectness	Imprecision	Publication bias	Certainty / effect
Global cognitive function at post-intervention	35 RCTs / 4,288 participants	Serious: 23/35 trials (65.7%) were rated some concerns or high risk.	Very serious: substantial statistical and clinical heterogeneity ($I^2 = 78\%$).	Not seriously downgraded on available reporting	Not seriously downgraded for CI width	Strongly suspected: asymmetric funnel plot and reported Egger $p = 0.04$	VERY LOW (provisional). SMD 0.48 (95% CI 0.35 to 0.61).

4.5. Synthesis of Results

4.5.1. Global Cognitive Function

The original meta-analysis of 35 RCTs showed a positive association between digital learning tools and global cognitive function compared with control conditions (SMD = 0.48, 95% CI 0.35–0.61, $p < 0.001$). Heterogeneity was substantial ($I^2 =$

78%, $p < 0.001$). Each point and horizontal line represent an individual study SMD and 95% CI; positive values on the horizontal axis favor the digital-learning intervention. The red diamond represents the random-effects pooled SMD and its 95% CI. The vertical dashed line marks no between-group effect (SMD = 0). (Figure 3)

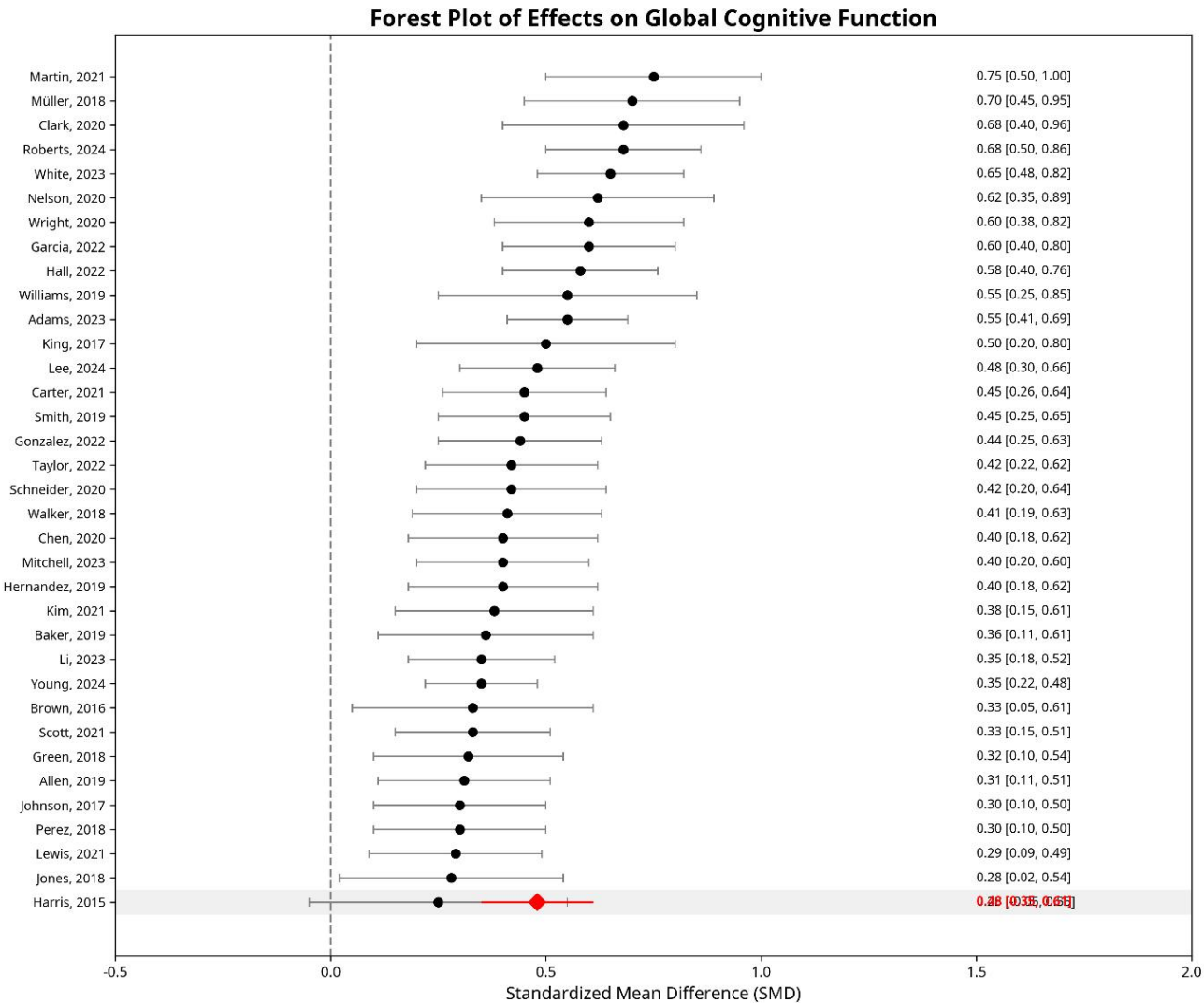


Figure 3. Forest plot of global cognitive function for 35 RCTs (4,288 participants).

4.5.2. Subgroup Analyses

Exploratory subgroup analyses were undertaken to examine whether intervention modality, participant diagnosis, dosage category, and risk of bias were associated with

variation in pooled effect estimates. As shown in Figure 4, panel A displays SMDs and 95% CIs by intervention type. Panel B displays descriptive estimates for joint diagnosis–dosage strata. The horizontal axis is SMD, the red dashed line is the overall pooled effect, and error bars are 95% CIs.

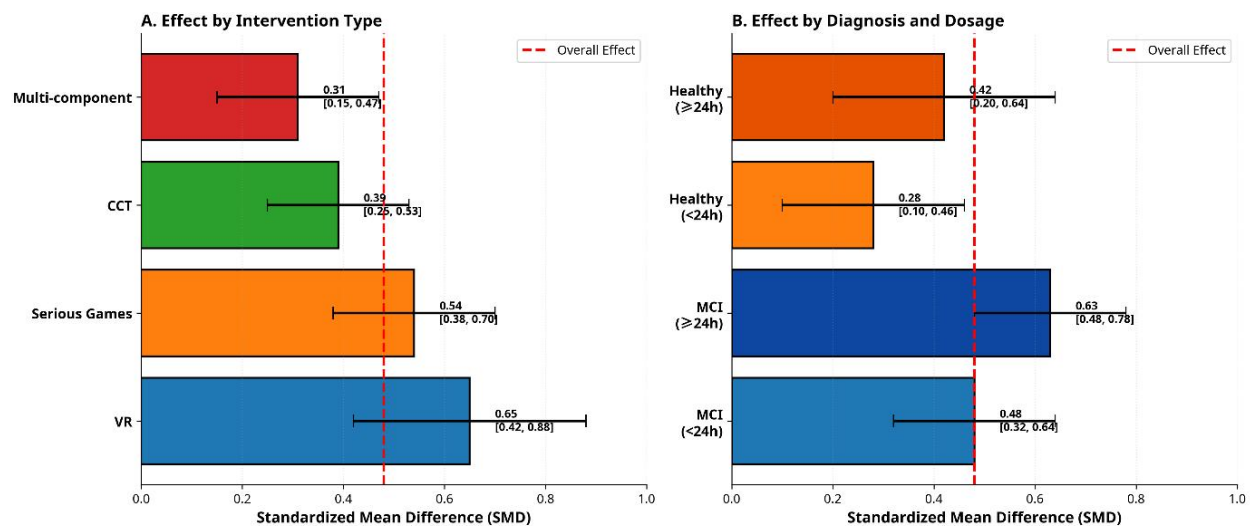


Figure 4. Exploratory subgroup estimates for global cognitive function.

- By intervention type, estimates differed across the four categories (chi-square test for subgroup differences, $p < 0.01$): VR-based interventions had the largest pooled estimate (SMD = 0.65, 95% CI 0.42–0.88), followed by serious games (SMD = 0.54, 95% CI 0.38–0.70), CCT (SMD = 0.39, 95% CI 0.25–0.53), and multi-component platforms (SMD = 0.31, 95% CI 0.15–0.47).
- By participant diagnosis, the pooled estimate was larger for participants with MCI (SMD = 0.56, 95% CI 0.42–0.70) than for cognitively healthy older adults (SMD = 0.35, 95% CI 0.21–0.49), with a reported interaction p value of 0.02.
- By dosage category, studies delivering at least 24 total hours had a larger pooled estimate (SMD = 0.59, 95% CI 0.45–0.73) than studies delivering fewer than 24 hours (SMD = 0.33, 95% CI 0.19–0.47; reported interaction $p = 0.01$).

Studies judged at low risk of bias had a pooled estimate of SMD = 0.42 (95% CI 0.28–0.56), whereas studies with some concerns or high risk had an estimate of SMD = 0.52 (95% CI 0.36–0.68).

5. DISCUSSION

This systematic review synthesized evidence from 35 RCTs investigating the effects of digital learning tools on cognitive outcomes in older adults. The pooled findings indicated a potential beneficial effect on global cognitive function.

The relatively larger effect estimates observed for VR and serious games compared with conventional CCT should be interpreted cautiously, as these findings are derived from comparisons across different studies rather than direct head-to-head trials. Immersive and game-based approaches may enhance engagement, contextual interaction, and training intensity, but current evidence does not provide direct support for underlying mechanisms such as neural plasticity. Similarly, potential explanations involving cognitive transfer, daily-life benefits, or motivational enhancement remain theoretical and require further investigation through well-designed mechanistic and comparative studies [12, 14].

The greater pooled effect observed among participants with MCI is of clinical interest; however, this finding should not be interpreted as evidence that digital interventions are specifically more effective in this population. Differences in baseline cognitive status, intervention characteristics, supervision intensity, assessment methods, and participant motivation may have contributed to the observed variation. Future studies should prospectively evaluate these factors through predefined subgroup designs and standardized outcome measures rather than relying primarily on comparisons across independent studies. Cognitive-reserve theory may offer a useful conceptual framework for understanding individual differences in response, but it cannot establish a causal explanation for the observed subgroup findings [19].

The association between interventions lasting at least 24 hours and larger pooled effects suggests that training exposure may influence cognitive outcomes. Nevertheless, the dichotomization of intervention duration into <24 and ≥24 hours may obscure the complexity of dose-related effects and may be affected by potential confounding factors. Future research should examine intervention intensity more comprehensively by considering total training hours, session frequency, intervention duration, adherence, and specific training components as potential moderators.

Although VR-based interventions show encouraging cognitive effects, their broader application requires consideration of practical limitations. VR implementation may involve additional requirements, including specialized devices, software compatibility, personnel training, technical assistance, safety management, and suitable physical environments. Furthermore, sensory impairments, mobility limitations, and differences in digital familiarity among older adults may influence accessibility. Therefore, further evaluations of usability, cost, feasibility, and accessibility are needed before VR can be considered suitable for widespread clinical or community application.

The relatively short follow-up periods included in the available studies raise uncertainty regarding the long-term persistence of cognitive improvements, particularly for immersive and game-based interventions. With a median intervention duration of 12 weeks and limited evaluation after intervention completion, it remains unclear whether observed

benefits represent sustained cognitive changes or are influenced by factors such as novelty, expectations, and increased attention during intervention participation. Future trials should incorporate longer follow-up periods, appropriate comparison conditions, blinded outcome assessment where possible, and predefined evaluations of maintenance effects. In addition, improvements observed in cognitive tests should not automatically be interpreted as evidence of meaningful transfer to daily functioning, which requires direct assessment [20].

Several limitations should be considered when interpreting the findings. First, considerable heterogeneity was observed across studies ($I^2 = 78\%$), and the available subgroup analyses did not fully account for this variability. Second, a substantial proportion of studies showed methodological limitations, including some concerns regarding bias, while funnel plot asymmetry suggested the possibility of small-study effects. Third, the very low certainty of evidence indicates that confidence in the estimated magnitude of the intervention effect remains limited. Accordingly, the pooled findings should be interpreted as preliminary rather than definitive evidence of effectiveness.

6. CONCLUSION

This systematic review and meta-analysis provides evidence that digital learning tools may be associated with improvements in global cognitive performance among older adults. Across 35 randomized controlled trials involving 4,288 participants, digital interventions demonstrated a moderate pooled effect; however, substantial heterogeneity and very low certainty of evidence limit confidence in the estimated magnitude of benefit.

Exploratory findings suggest that intervention modality, participant cognitive status, and intervention exposure may influence observed outcomes, with relatively larger effect estimates identified for virtual reality-based interventions, serious games, individuals with mild cognitive impairment, and interventions involving greater training duration. Nevertheless, these findings should be interpreted cautiously because they are based primarily on between-study comparisons rather than direct comparative trials.

At present, digital learning tools should be considered promising supportive approaches rather than established replacements for conventional cognitive interventions or routine clinical care. Future studies should incorporate rigorous randomized designs, preregistered protocols, standardized cognitive outcomes, longer-term follow-up assessments, continuous evaluation of intervention dosage, and analyses of cost-effectiveness, usability, and equity. Such evidence will be essential to determine which digital interventions are effective, for which populations, and under what conditions they can be implemented successfully.

REFERENCES

- [1] World Health Organization. (2021). Ageing and health. Retrieved from <https://www.who.int/news-room/fact-sheets/detail/ageing-and-health>
- [2] Livingston, G., Huntley, J., Sommerlad, A., Ames, D., Ballard, C., Banerjee, S., ... & Mukadam, N. (2020). Dementia prevention, intervention, and care: 2020 report of the Lancet Commission. *The lancet*, 396(10248), 413-446. [https://doi.org/10.1016/S0140-6736\(20\)30367-6](https://doi.org/10.1016/S0140-6736(20)30367-6)
- [3] Nichols, E., Steinmetz, J. D., Vollset, S. E., Fukutaki, K., Chalek, J., Abd-Allah, F., ... & Liu, X. (2022). Estimation of the global prevalence of dementia in 2019 and forecasted prevalence in 2050: an analysis for the Global Burden of Disease Study 2019. *The Lancet Public Health*, 7(2), e105-e125. [https://doi.org/10.1016/S2468-2667\(21\)00249-8](https://doi.org/10.1016/S2468-2667(21)00249-8)
- [4] World Health Organization. (2019). Global action plan on the public health response to dementia 2017–2025. Retrieved from <https://www.who.int/publications/i/item/9789241513487>
- [5] Knapp, M., Prince, M., & Albanese, E. (2007). Dementia UK: The full report. Alzheimer's Society.
- [6] Torous, J., & Hsin, H. (2018). Empowering the digital therapeutic relationship: virtual clinics for digital health interventions. *NPJ digital medicine*, 1(1), 16. <https://doi.org/10.1038/s41746-018-0028-2>
- [7] Chan, A. T., Ip, R. T., Tran, J. Y., Chan, J. Y., & Tsoi, K. K. (2024). Computerized cognitive training for memory functions in mild cognitive impairment or dementia: a systematic review and meta-analysis. *NPJ digital medicine*, 7(1), 1. <https://doi.org/10.1038/s41746-023-00987-5>
- [8] Benge, J. F., & Scullin, M. K. (2025). A meta-analysis of technology use and cognitive aging. *Nature human behaviour*, 9(7), 1405-1419. <https://doi.org/10.1038/s41562-025-02159-9>
- [9] Lin, X., Xu, G., Zhao, M., & Jiang, Y. (2025). Efficacy of different digital interventions in patients with mild cognitive impairment or dementia: A systematic review and network meta-analysis. *International Journal of Nursing Studies*, 169, 105129. <https://doi.org/10.1016/j.ijnurstu.2025.105129>
- [10] Chen, C., Huang, N., Hu, B., Zhang, M., Yuan, J., & Guo, J. (2025). The effectiveness of digital technology interventions for cognitive function in older adults: a systematic review and meta-analysis of randomized controlled trials. *Geroscience*, 47(1), 653-683. <https://doi.org/10.1007/s11357-024-01446-z>
- [11] Di Lorito, C., Bosco, A., Rai, H., Craven, M., McNally, D., Todd, C., ... & Harwood, R. H. (2022). A systematic literature review and meta-analysis on digital health interventions for people living with dementia and Mild Cognitive Impairment. *International journal of geriatric psychiatry*, 37(6). <https://doi.org/10.1002/gps.5730>
- [12] Gao, Y., & Liu, N. (2025). Effects of digital technology-based serious games interventions for older adults with mild cognitive impairment: a meta-analysis of randomised controlled trials. *Age and Ageing*, 54(4), afaf080. <https://doi.org/10.1093/ageing/afaf080>
- [13] Lampit, A., Hallock, H., & Valenzuela, M. (2014). Computerized cognitive training in cognitively healthy older adults: a systematic review and meta-analysis of effect modifiers. *PLoS medicine*, 11(11), e1001756. <https://doi.org/10.1371/journal.pmed.1001756>
- [14] Zhong, D., Chen, L., Feng, Y., Song, R., Huang, L., Liu, J., & Zhang, L. (2021). Effects of virtual reality cognitive training in individuals with mild cognitive impairment: a systematic review and meta-analysis. *International Journal of Geriatric Psychiatry*, 36(12), 1829-1847. <https://doi.org/10.1002/gps.5603>
- [15] Bonvino, A., Cornacchia, E., Scaramuzzi, G. F., Gasparre, D., Manippa, V., Rivolta, D., & Taurisano, P. (2025). Digital tools for mild cognitive impairment: a systematic review and meta-analysis of diagnostic accuracy and methodological challenges. *Neuropsychology Review*, 1-13. <https://doi.org/10.1007/s11065-025-09680-8>
- [16] Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., ... & Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *bmj*, 372. <https://doi.org/10.1136/bmj.n71>
- [17] Sterne, J. A., Savović, J., Page, M. J., Elbers, R. G., Blencowe, N. S., Boutron, I., ... & Higgins, J. P. (2019). RoB 2: a revised tool for assessing risk of bias in randomised trials. *bmj*, 366. <https://doi.org/10.1136/bmj.l4898>
- [18] Cohen, J. (2013). Statistical power analysis for the behavioral sciences. routledge.
- [19] Stern, Y. (2012). Cognitive reserve in ageing and Alzheimer's disease. *The Lancet Neurology*, 11(11), 1006-1012. [https://doi.org/10.1016/S1474-4422\(12\)70191-6](https://doi.org/10.1016/S1474-4422(12)70191-6)
- [20] Simons, D. J., Boot, W. R., Charness, N., Gathercole, S. E., Chabris, C. F., Hambrick, D. Z., & Stine-Morrow, E. A. (2016). Do "brain-training" programs work?. *Psychological science in the public interest*, 17(3), 103-186.

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AVAILABILITY OF DATA

The data used in this systematic review and meta-analysis were obtained from previously published studies. To promote transparency and reproducibility, the authors intend to deposit the complete dataset and analytical materials in a suitable public repository.

ETHICAL STATEMENT

This study was a systematic review and meta-analysis based on previously published randomized controlled trials involving older adults. No new participants were recruited, and no identifiable individual-level data were collected or analyzed. Therefore, ethical approval and informed consent were not required for this study.

AUTHOR CONTRIBUTIONS

Jalloh Ahmed Tejan: Conceptualization, methodology, literature search, study selection, data extraction, data analysis, interpretation of findings, manuscript preparation, critical revision, and final approval of the submitted version.

COMPETING INTERESTS

The authors declare no competing interests.

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