Technology-based cognitive training and rehabilitation interventions for individuals with mild cognitive impairment: a systematic review

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Abstract

Background: Individuals with mild cognitive impairment (MCI) are at heightened risk of developing dementia. Rapid advances in computing technology have enabled researchers to conduct cognitive training and rehabilitation interventions with the assistance of technology. This systematic review aims to evaluate the effects of technology-based cognitive training or rehabilitation interventions to improve cognitive function among individuals with MCI.

Methods: We conducted a systematic review using the following criteria: individuals with MCI, empirical studies, and evaluated a technology-based cognitive training or rehabilitation intervention. Twenty-six articles met the criteria.

Results: Studies were characterized by considerable variation in study design, intervention content, and technologies applied. The major types of technologies applied included computerized software, tablets, gaming consoles, and virtual reality. Use of technology to adjust the difficulties of tasks based on participants’ performance was an important feature. Technology-based cognitive training and rehabilitation interventions had significant effect on global cognitive function in 8 out of 22 studies; 8 out of 18 studies found positive effects on attention, 9 out of 16 studies on executive function, and 16 out of 19 studies on memory. Some cognitive interventions improved non-cognitive symptoms such as anxiety, depression, and ADLs.

Conclusion: Technology-based cognitive training and rehabilitation interventions show promise, but the findings were inconsistent due to the variations in study design. Future studies should consider using more consistent methodologies. Appropriate control groups should be designed to understand the additional benefits of cognitive training and rehabilitation delivered with the assistance of technology.

Keywords: Technology, Cognition, Cognitive training, Cognitive rehabilitation, Systematic review

Background

Due to the aging of the world’s population, the number of people who live with dementia is projected to triple to 131 million by the year 2050 [1, 2]. Development of preventative strategies for individuals at higher risk of developing dementia is an international priority [3, 4]. Mild cognitive impairment (MCI) is regarded as an intermediate stage between normal cognition and dementia [5, 6]. Individuals with MCI usually suffer with significant cognitive complaints, yet do not exhibit the functional impairments required for a diagnosis of dementia. These people typically have a faster rate of progression to dementia than those without MCI [5], but the cognitive decline among MCI subjects has the potential of being improved [7, 8]. Previous systematic reviews of cognitive intervention studies, both cognitive training and cognitive rehabilitation, have demonstrated promising effects on improving cognitive function among subjects with MCI [3, 7, 9, 10].

Recently, rapid advances in computing technology have enabled researchers to conduct cognitive training and rehabilitation interventions with the assistance of
technology. A variety of technologies, including virtual reality (VR), interactive video gaming, and mobile technology, have been used to implement cognitive training and rehabilitation programs. Potential advantages to using technology-based interventions include enhanced accessibility and cost-effectiveness, providing a user experience that is immersive and comprehensive, as well as providing adaptive responses based on individual performance. Many computerized cognitive intervention programs are easily accessed through a computer or tablet, and the technology can objectively collect data during the intervention to provide real-time feedback to participants or therapists. Importantly, interventions delivered using technology have shown better effects compared to traditional cognitive training and rehabilitation programs in improving cognitive function and quality of life [11–13]. The reasons for this superiority are not well-understood but could be related to the usability and motivational factors related to the real-time interaction and feedback received from the training system [13].

Three recent reviews of cognitive training and rehabilitation for use with individuals with MCI and dementia suggest that technology holds promise to improve both cognitive and non-cognitive outcomes [14–16]. The reviews conducted by Coyle, et al. [15] and Chandler, et al. [14] were limited by accessing articles from only two databases, and did not comprehensively cover available technologies. Hill, et al. [16] limited their review to papers published until July 2016 and included only older adults aged 60 and above. More technology-based intervention studies have been conducted since then, and only including studies with older adults 60 and above could limit the scope of the review given that adults can develop early-onset MCI in their 40s [17]. Therefore, the purpose of this review is to 1) capture more studies using technology-based cognitive interventions by conducting a more comprehensive search using additional databases 2) understand the effect of technology-based cognitive interventions on improving abilities among individuals with MCI; and 3) examine the effects of multi-modal technology-based interventions and their potential superiority compared to single component interventions.

**Methods**

**Search strategy**

PRISMA guidelines were followed for conducting this systematic review [18]. Based on the research aims and key words, an experienced librarian searched five databases: PubMed (Medline), PsycholoINFO (EBSCOhost), CINAHL (EBSCOhost), Embase, and Cochrane Library (Wiley). The search strategy used a combination of subject headings and key words for these main concepts: technology, MCI, training, and rehabilitation. The full search strategy is available in Additional file 1. The literature search was limited to empirical studies among human subjects. We did not set boundaries on age since MCI can occur among middle aged to older adults. The literature search was completed on December 1, 2017.

**Inclusion and exclusion of publications**

Two authors (SG and ESM) independently reviewed the list of articles found in the literature search. Inclusion criteria were: 1) participants were diagnosed with MCI; 2) a technology-based cognitive training or rehabilitation intervention was evaluated; and 3) an empirical study was conducted. Exclusion criteria were: 1) the effect of the intervention on MCI participants could not be extracted from effects among healthy or dementia participants, and 2) the publication was not in English.

Titles were first reviewed for obvious exclusions. Then, for those retained from the first-round title screening, abstracts were screened. A third-round of full-text screening was then conducted. Any uncertainties or discrepancies between the two authors (SG and ESM) were discussed and resolved.

**Quality assessment**

The quality of studies identified as relevant was assessed by two independent reviewers (SG and ZZ) using the Joanna Briggs Institute (JBI) critical appraisal checklist for randomized controlled trials (RCT) and JBI checklist for quasi-experimental studies [19]. Any disagreements that arose were resolved through discussion, or with a third reviewer (BW). The studies were generally methodologically sound with some variations in quality across studies (see Additional file 1: Table S2 and S3).

**Data extraction and synthesis**

Two reviewers (SG and ZZ) independently extracted information from each article into the Tables 1 and 2. Disagreements on data extraction were resolved by consensus with the assistance of a third author. A meta-analysis of the 26 articles was inappropriate due to the large variability between the study designs, intervention contents, outcomes measured, and population samples across different studies [20, 21]. We selectively calculated effect sizes for a pair of studies that used the same intervention materials [22, 23]. All data syntheses were conducted by using Revman 5.3 [24]. The forest plot is presented in Additional file 1: Figure S1.

**Results**

Based on the strategy and criteria described above, 26 of 411 studies identified were deemed eligible for review. The PRISMA flowchart in Fig. 1 presents the decision pathway for final inclusion of studies.
| First author | Year of publication | Location | Setting/context | Sample size<sup>a</sup> | Age<sup>b</sup> (year) | MCI Criteria | Baseline cognitive characteristic<sup>c</sup> |
|--------------|---------------------|----------|----------------|-------------------------|----------------------|-------------|----------------------------------|
| Cipriani, 2006 [29] | 2006 | Italy | Dayhospital | 10(AD) + 10(MCI) | 70.6 | Not specified | MMSE: 28.0 |
| Rozzini, 2007 [40] | 2007 | Italy | Medical centers | 59 | 63–78 | Petersen criteria | MMSE: KI:1.264 KG:26.0 CG:26.8 |
| Talassi, 2007 [36] | 2007 | Italy | Community-dwelling | 37(MCI) + 29(AD) | IG:76.2 CG:76.1 | Not specified | MMSE: KI:27.5 CG:269 |
| Barnes, 2009 [22] | 2009 | US | Medical centers | 47 | IG:74.1 CG:74.8 | IWG criteria | BRMS: IG:85.2 CG:87.8 |
| Finn, 2011 [25] | 2011 | Australia | Medical center | 27 | IG:69.00 CG:76.38 | IWG criteria | MMSE: IG:28.5 CG:27.5 |
| Rosen, 2011 [23] | 2011 | US | Community-dwelling | 12 | IG:70.67 CG:78.00 | IWG criteria | MMSE: KI:29.33 CG:27.83 |
| Gagnon, 2012 [43] | 2012 | Canada | Medical centers | 24 | IG:68.42 CG:67.00 | Petersen criteria | MMSE: KI:27.83 CG:28.08 |
| Herrera, 2012 [42] | 2012 | France | Medical center | 22 | IG:75.09 CG:78.18 | Petersen criteria | MMSE: KI:27.36 CG:27.18 |
| Man, 2012 [13] | 2012 | Hong Kong | Community service setting | 44 | IG:80.30 CG:80.28 | Petersen criteria | MMSE: KI:21.05 CG:23.00 |
| Gonzalez-Palau, 2014 [33] | 2014 | Spain | Community centers | 39(HE) + 11(MCI) | 74.60 | Petersen criteria | MEC: 35: 29.61 |
| Han, 2014 [30] | 2014 | Korea | Medical center | 10 | 72.1 | IWG criteria | MMSE: 26.7 |
| Hughes, 2014 [45] | 2014 | US | Community setting | 20 | IG:78.5 CG:76.2 | MYHAT Cognitive Classification | MMSE: KI:27.2 CG:27.1 |
| Fiatarone Singh, 2014 [26] | 2014 | Australia | Community-dwelling | 100 | 70.1 | Petersen criteria | ADAS-Cog: IG:18.79 KG:28.29 IG:38.02 CG:8.09 |
| Manera, 2015 [32] | 2015 | France | Medical Center and research unit | 9(MCI) + 12(AD) | 75.8 | National Institute on Aging and Alzheimer Association group clinical criteria | MMSE: 27.2 |
| Stylladis, 2015 [34] | 2015 | Greece | Medical facility | 70 | IG:71.21 KG:70.42 KG:72.71 CG:71.07 CG:67.64 | Petersen criteria | MMSE: KI:25.85 KG:26.21 KG:25.14 CG:26.21 CG:22.25 |
| Barban, 2016 [39] | 2016 | Italy, Greece, Norway and Spain | Medical centers | 114(HE) + 106(MCI) + 81(AD) | IG:74.4 CG:72.9 | Petersen criteria | MMSE: KI:27.3 CG:28.1 |
| Gooding, 2016 [35] | 2016 | US | Medical center | 74 | 75.59 | Petersen criteria | mMMSE: KI:51.25 KG:50.29 CG:50.39 |
| Heyer, 2016 [28] | 2016 | US | Community-dwelling | 68 | IG:75.1 CG:75.2 | IWG criteria | MMSE: 26 |
| Klados, 2016 [37] | 2016 | Greece | Not specified | 50 | IG:69.60 CG:67.92 | Petersen criteria | MMSE: KI:26.04 CG:25.64 |
### Table 1 Sample characteristic of included studies (Continued)

| First author | Year of publication | Location | Setting/context | Sample size<sup>a</sup> | Age<sup>b</sup> (year) | MCI Criteria | Baseline cognitive characteristic<sup>c</sup> |
|--------------|---------------------|----------|----------------|--------------------------|------------------------|--------------|---------------------------------------------|
| Lin, 2016 [44] | 2016 | US | Community-dwelling | 24 | IG:72.9 CG:73.1 | Albert criteria | MoCA: IG:24.4 CG:25.6 |
| Vermeij, 2016 [31] | 2016 | Netherlands | Community setting | 25(HE) + 22(MCI) | 68.4 | Petersen criteria | MMSE > 27.1 Not specified |
| Bahar-Fuchs, 2017 [27] | 2017 | Australia | Community-dwelling | 9(MCI) + 11(MrNPS) + 25(MCI+MrNPS) | 74.8 | National Institute on Aging and Alzheimer Association group clinical criteria | GDS: 2.9 |
| Delbroek, 2017 [47] | 2017 | Belgium | Residential care center | 20 | IG:8669 CG:87.5 | Not specified | MoCA: IG:17.5 CG:16.3 |
| Hagovská, 2017 [12] | 2017 | Slovakia | Outpatient psychiatric clinics | 60 | IG:67.8 CG:68.2 | Albert criteria | MMSE: IG:25.6 CG:24.9 |
| Mansbach, 2017 [38] | 2017 | US | Community-dwelling | 38 | 7808<sup>d</sup> | Petersen criteria | BCAT: IG:38.65 CG:35.72 |
| Savulich, 2017 [41] | 2017 | UK | Research and medical center | 42 | IG:75.2 CG:76.9 | Albert criteria | MMSE: IG:26.6 CG:26.8 |

<sup>a</sup>HE Healthy elderly with no history of neurological or psychiatric deficits, MrNPS Mood-related neuropsychiatric symptoms

<sup>b</sup>Data only included elderly with MCI

<sup>c</sup>Data only included elderly with both MCI and AD

IG Intervention group, CG Control group
| First author and year | Study design | Intervention and Technology | Control | Technology description | Sessions/Duration | Follow-up | Cognitive outcome measures | Other outcome measures | Key findings |
|------------------------|-------------|----------------------------|---------|------------------------|-------------------|------------|---------------------------|-----------------------|-------------|
| Cipriani, 2006 [29]   | Pre-post study | Computer-based Cognitive Rehabilitation (cb-CR) programs | NA      | TNP software: delivers individualized cognitive rehabilitation exercises in the following cognitive domains: attention, memory, perception, visuospatial cognition, language, and non-verbal intelligence | 2 * 16 * 13–45 min sessions for 8 weeks | 3 months | MMSE Attention: Visual search; Executive function: Trail Making Test A and B; Behavioral Memory: RBMT; Psychomotor learning: digit symbol test; Verbal fluency: phonemic and semantic verbal fluency | Depression (GDS); Anxiety: STAI-X1, STAI-X2; ADL: AADL; QOL: SF-12 | MCI: Only significantly improved in memory (RBMT) |
| Rozzini, 2007 [40]     | RCT         | TNP + ChEIs CG1: ChEIs CG2: No treatment | TNP Software | 20 * 1 h/session, five days/week for four weeks | 1 yr | MMSE Memory: Short story recall; Executive function: Rey’s figure copy and recall, Raven’s colored matrices; Verbal fluency: Letter verbal fluency; Semantic verbal fluency | Mood: depression: GDS; anxiety, apathy Behavioral disturbances: NPI Activities of daily living: BADL | IG: significant improvement in memory, abstract reasoning, and depression CG1: no improvements on any cognition but benefit in depression CG2: no improvement in any outcome measures |
| Talassi, 2007 [36]   | CCT         | TNP + OT + BT PR + OT + BT | TNP Software | 30–45 min/session, 4 days/week for 3 weeks | Intervention end | MMSE Working memory: forward and backward digit span; Executive function: Rey’s figure copy; Verbal fluency: phonemic and semantic verbal fluency; CDT; Episodic Memory: episodic memory subset of RBMT; Verbal fluency: Phonemic and semantic verbal fluency; Attention: visual search, processing speed: digit symbol test | Mood: depression GDS; anxiety (Stai-Y1,Stai-Y2); ADL: BADL, IADL, PPT; | MCI subjects in IG improved in executive function, visuospatial memory, anxiety, depression, and PPT but not IADL MCI subjects in CG: no improvements |
| Barnes, 2009 [22] | RCT         | cb-CT Passive computer activities | Computer-based cognitive training software developed by Posit Science Corporation (San Francisco, CA), involving seven exercises including primary and working auditory memory tasks to improve processing speed and accuracy in the auditory cortex | IG: 100 min/day five days/week for 6 weeks CG: 90 min/day, 5 days/week for 6 weeks | Intervention end | Global cognitive function: RBANS total score, 5 RBANS index score Memory: CVLT-II Language: COWAT, BNT Executive function: California Trail Making Test Attention: Design Fluency test; Working memory: Spatial Span test | Mood: depression (GDS) | IG showed greater improvement on RBANS total scores but no significant between group difference. Effect sizes for verbal learning and memory measures tended to favor IG. Effect sizes for language and visuospatial function measures tended to favor CG (control group). |
| First author and year | Study design  | Intervention and Technology | Control | Technology description | Sessions/Duration | Follow-up | Cognitive outcome measures | Other outcome measures | Key findings |
|-----------------------|---------------|-----------------------------|---------|------------------------|-------------------|-----------|---------------------------|----------------------|--------------|
| Finn, 2011 [25]       | RCT           | Computerized Cognitive Training Package | No intervention | Lumosity software on a computer contains four or five cognitive exercise that targeted four cognitive domains | 30 sessions, 4–5 sessions/week | Intervention end | Executive function: IED; Attention: RVP Subjective memory impairment: MFQ Visual memory: PAL | Mood: Depression Anxiety and Stress Scale | IG had significant improvement in visual attention but not processing speed, visual memory, nor mood |
| Rosen, 2011 [23]      | RCT           | cb-CT | Listening to audio books, reading online newspapers, and playing a visuospatial oriented computer game | Computer-based cognitive training software developed by Posit Science Corporation | IG: 24 sessions, 100 mins/day, 5 days/week CG: 24 sessions, 90 min/day, 5 days/week | Intervention end | Global cognitive function: RBANS Neuroimaging: fMRI | Not specified | IG > CG: improvement in verbal memory and left hippocampal activation CG: declined in VM |
| Gagnon, 2012 [43]     | RCT           | Computer-based VP | AC: Computer-based FP | Computer-based divided attention dual-task training: VP: performing both tasks concurrently and varying allocation priorities across the series of blocks, feedbacks are provided; FP: perform both tasks concurrently and to allocate 50/50 attentional resources to each task, no feedbacks provided | 6 * 1 h/session, 3 times/week for two weeks | Intervention end | Attention: dual task (digit span task, visual detection task); Executive subtest of TEA Attention: Trail Making Test A; Executive function: Trail Making Test B; | QOL: Well-Being Scale Divided attention: Divided Attention Questionnaire | VP showed significant advantage over FP in improving accuracy and reaction time FP and VP both produced improvements on focused attention, speed of processing, and switching abilities No reliable advantage for VP over FP |
| Herrera, 2012 [42]    | RCT           | Computer-based Memory and attention training | Stimulating Cognitive activities | Computer-based cognitive training that involved a memory task and an attention task | 24 * 60 min/session twice/week for 12 weeks | 6 months | MMSE-recall; Memory: the forward and backward digit span test, BVM-144 12-word-list recall, the 16-item free and cued reminding test, sub-score recall of the MMSE, visual recognition subtest from the Doors and People memory battery, the DS548 test; executive function: Rey-Osterrieth Complex Figure recall test | N/A | Significant improvement in memory, both episodic recall and recognition |
| Man, 2012 [13]        | CCT           | VR-based memory training program | Therapist-led program | VR: participants use either the joystick or the direction buttons of the keyboard to control the navigation action and give responses to a memory task | 10 sessions, 30 min/session 2–3 times/week | Intervention end | Memory: MMQ Episodic Memory: FMGE | ADL: Lawton IADL | VR significant improvement in total encoding, total recall, delayed recall and MMQ-strategy Therapist-led: significant improvement in total recall, delayed recall and MMQ-contentment |
| First author and year | Study design | Intervention and Technology | Control | Technology description | Sessions/Duration | Follow-up | Cognitive outcome measures | Other outcome measures | Key findings |
|-----------------------|--------------|-----------------------------|---------|------------------------|------------------|-----------|---------------------------|----------------------|--------------|
| Gonzalez-Palau, 2014 [33] | Pre-post study | LLM included CTC and PTC | NA | CTC: Gradior Software, a multi-domain cognitive training program including attention, perception, episodic memory and working memory tasks. Principles of feedback and difficulty adaptation are used. PTC: FFA: an innovative, low-cost game platform. Work our intensity gradually increases | CTC: 40/ session, three times/week for 12 weeks | Interventions end | Global cognitive function: The Mini Examen Cognitivo (MEC 35) Memory: Logical Memory subtests of the WMS III Attention: The Color Trail Test 1 and 2 Verbal learning and memory: HVLT-R | Mood: depression(GDS) For MCI subjects: Significant improvement in global cognitive function, verbal memory, episodic memory, and decrease in symptoms of depression. | |
| Han, 2014 [30] | Pre-post study | Ubiquitous Spaced Retrieval-based Memory Advance- ment and Rehabilitation Training USMART Program | NA | USMART program app on iPad | 24 face-to-face sessions | Interventions end | CERAD-K-N including: verbal fluency: the Categorical Fluency test, the Modified BNT; MMSE; memory: WLMT, WLRT, the Word List Recognition Test, CRT; visuospatial: Constructional Praxis Test; Attention: Trail Making Test A; executive function: Trail Making Test B | N/A | Significantly improved only in memory (WLMT); number of training sessions correlated with WLMT scores |
| Hughes, 2014 [45] | RCT | Interactive video games (Wii) | Healthy aging education program | Nintendo Wii gaming console for interactive video gaming (bowling, golf, tennis, and baseball) | 24 * 90 min, 1 session/week for 24 weeks | 1 year | Global cognition: CAMC; Processing speed: Tracking A; Executive function: Tracking B; Subjective cognitive ability Mood/social functioning: CSRO-25; ADL: TIADL | IG: No significant improvement in any of the outcome measures. Medium effect size estimates were found for global cognition, subjective cognition, executive function, and gait speed. | |
| Fiatarone Singh, 2014 [26] | RCT | IG1: CT + Sham exercise IG2: PRT + Sham cognitive intervention IG3: CT + PRT | Sham exercise + Sham cognitive intervention | COGPACK program: computer-based multi-modal and multi-domain exercises targeting memory, executive function, attention, and speed of information processing, including 14 progressively more difficult exercises | CG: 60 min IG: 75 min IG2/IG3: 100 min combined 2–3 days/week for 6 months | 18 months | Global cognition: ADAS-Cog. Executive function: WAIS-III; Verbal fluency: COWAT, animal naming; Memory: BVRT-R, auditory Logical Memory I and II, subsets of WMS-III, List Learning subsection of ADAS-Cog; Attention: SDMT | ADL: B-IADL | CT prevented memory decline only up until 6 months PRT improved global and executive function until 18 months; PRT was better than CT + PRT in improving global and executive function |
### Table 2: Overview of included studies (Continued)

| First author and year | Study design | Intervention and Technology | Control | Technology description | Sessions/Duration | Follow-up | Cognitive outcome measures | Other outcome measures | Key findings |
|-----------------------|--------------|-----------------------------|---------|------------------------|-------------------|-----------|----------------------------|-----------------------|--------------|
| Manera, 2015 [32]     | Pre-post Study | ‘Kitchen and Cooking’ Game | NA      | Computerized Kitchen and Cooking serious game which challenges attention, executive function, and praxis | 4 weeks           | Intervention end | Attention: Trail Making Test A | ADL, IADL, ADL | Significant improvement in executive function; Improvement in MCI > AD. Longer time played correlated with better executive function |
| Styliadis, 2015 [34]  | CCT IG1: Long-Lasting Memories (LLM) | Intervention: combined cognitive training (CT) and physical training (PT) | CG1: Active Control (AC) (documentaries viewing) CG2: Passive Control | LLM training system CT and PT as follows: CT: Greek adaptation of Brain Fitness Software: 6 self-paced exercises focused on categories: Attention and Auditory Processing Speed. PT: FFA game platform incorporating Nintendo Wii balance games | 8 weeks | Intervention end | Electroencephalogram (EEG) measures of Cortical activity for delta, theta, beta 1 and beta 2 bands | N/A | A significant training effect was identified in the LLM group revealed by EEG measures but no training effects on the MMSE |
| Barban, 2016 [39]     | RCT Process-based-Cognitive Training (pb-CT) plus reminiscence therapy (RT) + rest | Reminiscence therapy (RT) + pb-CT | Reminiscible software on a touch screen computer containing 27 games designed to improve function in 7 cognitive domains: attention, executive function, memory, logical reasoning, orientation, language, and constructional Praxis | 24 * 1 h treatment sessions, 2 sessions/week for about 3 months | Intervention end | MMSE Memory: RAVLT; Executive function: Rey–Osterreith Complex Figure Test, Phonological Verbal Fluency Test; Executive function: Trail Making Test | IADL | pb-CT: Significant training effects on memory in MCI subjects and the effect was maintained after reminiscence period; Significant training effect on MMSE was not maintained during reminiscence period; Medium effect sizes |
| Gooding, 2016 [35]    | CCT IG1: Computer based Cognitive Training (cb-CT) IG2: Cognitive Vitality Training (CVT): cb-CT + Neuropsychological and Educational Approach to Remediation (NEAR) | Active Control Group (AGG) cb-CT: Brain Fitness: repeated drill-and-practice exercises involving memory, attention, and executive functions within domain-specific training modules that allow for adaptive training with titrated difficulty levels. Same CT exercises delivered within a framework that allows for personalization, individual control, and contextualization of exercises | cb-CT: Brain Fitness: repeated drill-and-practice exercises involving memory, attention, and executive functions within domain-specific training modules that allow for adaptive training with titrated difficulty levels. Same CT exercises delivered within a framework that allows for personalization, individual control, and contextualization of exercises | 30 * 60 min/ session, twice/week for 16 weeks | 4 months | Intellectual functioning: WRAT-3; mMMS; Verbal learning and Memory: the BSRT, the WMS-R LM I and II subtests Visual learning and memory: the WMS-R Visual Reproductions (VR) I and II subtests | Mood: depression (BDI-II) | CVT and cb-CT groups had improvements in global cognition, verbal learning, and verbal memory; CVT and cb-CT had significantly greater improvements than ACG in global cognition, verbal memory, and verbal learning. No significant difference between cb-CT and CVT; Largest mood improvement in CVT, significant difference between CVT and ACG but not between CVT and cb-CT |
| First author and year | Study and design | Intervention and Technology | Control | Technology description | Sessions/Duration | Follow-up | Cognitive outcome measures | Other outcome measures | Key findings |
|-----------------------|-----------------|-----------------------------|---------|------------------------|------------------|-----------|--------------------------|----------------------|--------------|
| Hyer, 2016 [28]      | RCT             | Computerized CT program     | Sham cognitive training | Cogmed computer training program: Uses multiple rotating exercises daily that are designed to train working memory. | 25 * 40 min/day for over 5 to 7 weeks | 3 months | Working Memory: WMS-III Span Board subtest, WAIS-III Letter Number Sequencing subtest; Attention: Trail Making Test Part A; Executive function: Trail Making Test Part B; Subjective memory: CFQ | ADL: the Functional Activities Questionnaire | Significant improvement of executive function, verbal and non-verbal working memory in both CG and IG; Significant improvement of subjective memory in IG but not CG. Significant between group difference in working memory (Span Board) and in adjustment (FAQ) |
| Klados, 2016 [37]    | CCT             | Long Lasting Memories (LLM) | Active Control (AC): watching documentary and answering questionnaire | Brain Fitness Software FitForAll | CT: 1 h/day, 3–5 days/week for 8 weeks PT: 1 h/day, 3–5 sessions/week for 8 weeks for 8 weeks | Intervention end | Cortical Activity, Cortical Functional Connectivity: beta band | Not specified | IG showed beta band functional connectivity of MCI patients |
| Lin, 2016 [44]       | RCT             | VSOP MLA Software | MLA | Software INSIGHT: online program designed by Posit Science, included five training tasks: eye for detail, peripheral challenge, visual sweeps, double decision, and target tracker | 1 h/day 4 days/week for 6 weeks | Intervention end | Processing speed: The Useful Field of View Executive function: The EXAMINER | ADL: TIADL Neuroimaging data: magnetic resonance imaging | IG > CG: improvement in trained (processing speed and attention) and untrained (working memory) cognitive domains, IADL, CEN and DMN |
| Vermeij, 2016 [31]   | Pre-post study  | WM training program         | NA | Cogmed computer program | 25 sessions, 45 min per session for 5 weeks | 3 months | Working memory: WAIS-III Digit Span forward and backward, WMS-III Spatial Span forward and backward; Verbal memory: Dutch equivalent of RAVLT; Figural Fluency: RFFT; Cognitive impairment: CFQ | N/A | IG: Significant improvement in trained verbal and visuospatial working memory tasks as well as executive function. Training gain was larger in the healthy elderly (HE) and was only maintained among HEs. Improvements in non-trained near-transfer tasks, maintained after 3 months follow-up |
| First author and year | Study design | Intervention and Technology | Technology description | Sessions/Duration | Follow-up | Cognitive outcome measures | Other outcome measures | Key findings |
|-----------------------|--------------|-----------------------------|------------------------|-------------------|-----------|---------------------------|-----------------------|--------------|
| Bahar-Fuchs, 2017 [27] | RCT | home-based individually-tailored and adaptive cb-CT | CogniFit Software: a computer-based program involving 33 tasks designed to train a broad range of cognitive abilities | 2 sessions/day, 3 days/week, for 8–12 weeks | 12 weeks | Composite score global cognition | Mood | MCI in IG: greater improvement in memory, learning, and global cognition. No training effect in mood, self-reported memory. Training gains in MCI (including ADL) were consolidated over time. Large effect sizes of intervention at the follow-up assessments in learning, delayed memory, and global cognitive function, medium effect size in non-memory composite. |
| Delbroek, 2017 [47] | RCT | VR dual task training with the BioRescue | BioRescue Software: nine exercises to train balance, weight bearing, memory, attention and dual tasking. Led by a therapist, participants stand on a platform, adjustable difficulties based on performances | Gradually increased from 18 min in week 1 to 30 min in week 5 | Intervention end | The Dutch version of MoCA | Motivation: The Dutch version of IMI | IG significantly improved on balance, but not on global cognitive function or cognitive-motor dual tasking or gait performance. |
| Hagovská, 2017 [12] | RCT | Cb-CT Classical group-based cognitive training | CogniPlus program: on a computer, includes five sub-programs that involved activities that are similar to everyday activities, targets attention, working memory, long-term memory, planning of everyday activities, and visual-motor abilities. | 20 *30 min, 2 sessions/week for 10 weeks | 10 weeks | Self-reported functional activities: FAQ Global cognition: ACE Attention: The Stroop Test | QOL: Spitzer QOL index Functional activities: The Functional Activities Questionnaire | IG demonstrated larger improvements in QoL and attention than CG. The transfer to functional activities was the same between groups. |
| Mansbach, 2017 [38] | CCT | cb-CR No intervention | Memory Match online cognitive rehabilitation module: designed to improve attention and visual memory, requires the participant to visually pair “matching pictures” by remembering their location | 9*30 min/session | Intervention end | Global cognitive functioning: BCAT AD8 Dementia Screening Interview, KPT | Attitudes about their cognitive abilities: SRI Mood: depression: GDS-SF | IG > CG in global cognition at post-intervention assessment. |
| First author and year | Study design | Intervention and Technology | Control | Technology description | Sessions/Duration | Follow-up | Cognitive outcome measures | Other outcome measures | Key findings |
|-----------------------|-------------|----------------------------|---------|------------------------|------------------|-----------|-----------------------------|--------------------|-------------|
| Savulich, 2017 [41]   | RCT         | CT                         | No intervention | Game Show on iPad: a novel learning and memory game, target to improve episodic memory | 8 sessions, 1 h/session | Intervention end for 4 weeks | MMSE: Episodic memory and new learning; CANTAB PAL; Visual/spatial abilities: BVMT-R; Processing speed: CANTAB CRT | GDS-SF: Anxiety and depression; HADS; Apathy; AES | IG > CG: significantly better performance in episodic memory, visuospatial abilities, MMSE, and less apathy |

*Note: RCT = Randomized Controlled Trial, CT = Cognitive Training, Cb-CT = Computer-based Cognitive Training, CB-CR = Computer-based Cognitive Rehabilitation, CB-CT = Computer-based Cognitive Training, CCT = Computer Cognitive Training, CBT = Cognitive Behavioral Therapy, PBT = Physical Behavioral Therapy, CH = Cognitive Hypnosis, OT = Occupational Therapy, PR = Physical Rehabilitation, VR = Virtual Reality, ACG = Active Control Group, CB-CR = Cognitive Behavioral Rehabilitation, LM = Long Lasting Memories, CCT = Clinical Controlled Trials, CCT = Computer Cognitive Training, CCT = Clinical Controlled Trials, C/R = Cognitive Rehabilitation, MMSE = Mini-Mental State Examination, GDS = Geriatric Depression Scale, AES = Apathy Evaluation Scale, HADS = Hospital Anxiety and Depression Scale, MMQ = Memory Functioning Questionnaire, WRAT = Wide Range Achievement Test, FAQ = Functional Activities Questionnaire, BVRT = Benton Visual Retention Test, CANTAB = Cambridge Neuropsychological Test Automated Battery, PAL = Paired Associates Learning, BBAT = Buschke Selective Reminding Test, CES-D = Center for Epidemiological Studies Depression Scale, STAX = Stanford-Tolman Mental Map Test, BP = Beck Depression Inventory, MMSE = Mini-Mental State Examination, GDS-SD = Geriatric Depression Scale-Short Form, CANTAB PAL = Cambridge Neuropsychological Test Automated Battery Paired Associates Learning, BVMT-R = Brief Visuospatial Memory Test-Revised, CANTAB CRT = Cambridge Neuropsychological Test Automated Battery Choice Reaction Time, AES = Apathy Evaluation Scale, HADS = Hospital Anxiety and Depression Scale, PVS = Problem Solving Scale, WRAT = Wide Range Achievement Test, FAQ = Functional Activities Questionnaire, BVRT = Benton Visual Retention Test, CANTAB = Cambridge Neuropsychological Test Automated Battery, PAL = Paired Associates Learning, BBAT = Buschke Selective Reminding Test, AES = Apathy Evaluation Scale, HADS = Hospital Anxiety and Depression Scale, CEN = Central Executive Network, WRAT = Wide Range Achievement Test, FAQ = Functional Activities Questionnaire, BVRT = Benton Visual Retention Test, CANTAB = Cambridge Neuropsychological Test Automated Battery, PAL = Paired Associates Learning, BBAT = Buschke Selective Reminding Test.
Quality of the studies
Additional file 1: Tables S2 and S3 summarize the quality assessment of the 26 eligible studies using the JBI criteria, which included both randomized controlled trials and quasi-experimental studies. Of these, 15 were randomized controlled trials (Table 2), 6 were controlled clinical trials, 5 were pretest-posttest studies (Table 2).

Among the RCT studies, only four articles [12, 25–27] reported the procedure for randomization. Two studies allocated the participants by utilizing computer-generated random numbers [26, 27], while the other two studies [12, 25] randomized participants by having an independent person use sealed envelopes. The remaining 11 articles did not report the randomization procedure used for allocating participants. Only three studies [26–28] reported that they were double-blinded sham-control trials.

In the quasi-experimental studies, five studies [29–33] utilized pretest-posttest design. The convenience samples and limited sample sizes (n = 10; n = 10; n = 22; n = 9; n = 11) restricted their generalizability. Six studies utilized a controlled clinical trial design [13, 34–38]. All the studies lacked external validity due to use of convenience samples or sampling methods that were not clearly described. Quasi-experimental studies which lacked randomization also were limited by a potential allocation bias.

Sample characteristics of the included studies
The sample and design characteristics of each study are summarized in Table 1. More than 40% of the included studies were published from 2016 to 2017 (n = 11). Studies were conducted in different countries: United States (n = 7), Italy (n = 3), Australia (n = 3), France (n = 2), Greece (n = 2), Canada (n = 1), Hong Kong (n = 1), United Kingdom (n = 1), Belgium (n = 1), Slavonia (n = 1), Spain (n = 1), South Korea (n = 1), and Netherlands (n = 1). Only one study [39] reported recruitment across multiple countries.

The total number of the participants with MCI included in this systematic review was 1040. Seven studies included both participants living with MCI and those with other cognitive statuses (either individuals who were cognitively normal or individuals who had dementia), and reported intervention effects for groups of MCI individuals. The
Eight studies utilized multimodal interventions (Table 2). Multimodal interventions varied widely. Seventeen different interventions were utilized in the cognitive training programs studied (see details in Table 2).

**Characteristics of interventions**

**Single-component interventions**

The majority of the studies (n = 18, or 69%) involved single-component technology-based cognitive interventions (Table 2). Characteristics of the interventions varied widely. Seventeen different interventions were utilized in the cognitive training programs studied (see details in Table 2).

**Multimodal interventions**

Eight studies utilized multimodal interventions (Table 2). One approach was cognitive training combined with different types of therapies [35, 36, 39, 40]; another approach was cognitive training combined with physical training [26, 33, 34, 37].

**Cognitive training plus therapy**

Four studies combined the technology-based cognitive training with other therapies as intervention, specifically reminiscence therapy [39], Neuropsychological and Educational Approach to Remediation (NEAR) [35], occupational therapy [36], and medications (cholinesterase inhibitors (ChEIs)) [40]. Two types of software were involved in the cognitive intervention component, including SOCIABLE [39], and NeuroPsychological Training (TNP) [36, 40]. The training sessions lasted for a minimum of 3 weeks [36] to a maximum of 16 weeks [35].

**Cognitive training combined with physical training**

Four studies examined the combined effects of technology-based cognitive and physical training. Two studies used the Long-Lasting Memories (LLM) intervention to provide integrated cognitive and physical training [34, 37], and the physical component was delivered using the FitForAll platform. Gonzalez-Palau, et al. [33] also used the FitForAll platform to provide physical training, but used Gradior program to deliver the cognitive training. Singh and colleagues used Pneumatic resistance machines (Keiser Sports Health Equipment, Ltd) to provide progressive resistance training [26]. The length of these physical trainings lasted from 6 weeks [34] to 6 months [26].

**Overview of technologies**

The studies reviewed used the following types of technologies: traditional keyboard computers (n = 16), touch screen computers (n = 4), gaming consoles or platforms (n = 5), and tablets (n = 3). Gonzalez-Palau, et al. [33] and Styliadis [34] used both computer and gaming platforms in their interventions. Since 2014, technologies that are more interactive and immersive (virtual reality, gaming console, exergaming platform) have been introduced in cognitive intervention studies.

Compared to traditional therapist-led or pen and paper cognitive interventions, technologies are “smarter” in tracking participants’ performances and adjusting the intervention difficulty. By applying technologies as a delivery method, researchers were able to record the participants’ performance throughout the intervention process. Thirteen studies tracked participants’ performance as one of the outcome variables. Twelve studies used intervention programs that could adjust the intervention difficulties to keep challenging the participants’ abilities, as well as avoid distressing them with too many training failures.

**Effects of interventions**

**Cognitive outcomes**

**Global cognitive function** Twenty-two studies assessed the effects of the interventions on global cognitive function (Table 2). Various instruments were used, including MMSE, Repeatable Battery for Assessment of Neuropsychological Status (RBANS), Computerized Assessment of Mild Cognitive Impairment (CAMCI), Alzheimer’s Disease Assessment scale-cognitive subscale (ADAS-Cog), Brief Cognitive Assessment Tool (BCAT), Addenbrooke’s Cognitive Examination (ACE), Montreal Cognitive Assessment (MoCA), Spanish version MMSE (MEC35), and composite score from measured cognitive domains.

Out of the 22 studies, eight studies found their intervention significantly improved global cognitive function among individuals with MCI. These studies used different cognitive interventions, all but one [20] of them were interventions targeting multiple cognitive domains. Five studies used an active control group, and three of them found a significant between-group difference in global cognition improvement. Barban, et al. [39] reported a significant treatment effect of a computerized multi-domain process-based cognitive training combined with reminiscence therapy in MMSE mean scores (Cohen’s d = 0.44). Gonzalez-Palau, et al. [33] reported a significant improvement in global cognitive function (MEC35) among MCI individuals who went through a multi-domain cognitive training program including both cognitive and physical training components. Gooding, et al. [35] compared the...
computerized cognitive training and cognitive vitality training to an active control group, and reported significantly larger improvements in both intervention groups than the active control group in mMMSE mean score \(F (2, 71) = 11.56, p < 0.001, \eta^2_p = 0.25\) with a medium effect size (Cohen’s \(d = 0.30 – 0.53\)). However, this training effect was not maintained at 3-month follow-up. Bahar-Fuchs, et al. [27] reported a significantly greater improvement in global cognition composite score in the training group than the active control with a large effect size (Cohen’s \(d = 0.80\)). On the other hand, Barnes, et al. [22] found significant RBANS total score improvement in the intervention group after an auditory processing speed and accuracy training, but the between-group difference compared to the active controls was not significant (SD = 0.33). All the other three studies that did not use an active control found significant between-group differences in changes in global cognitive function [26, 38, 41].

Two studies that compared the computer-based cognitive training with listening to audio books, reading online newspapers, and playing a visuospatially-oriented computer game met the requirement for meta-analysis [22, 23]. The design of study, content of intervention, duration and length of follow-up were similar. A total of 59 individuals were included in the meta-analysis. In Additional file 1: Figure S1, the pool weighted standard mean difference score of RBANS total score was 1.62 (95% CI: -1.63 - 4.87). This result indicated that there was no significant difference in the effectiveness for computer-based cognitive training in improving RBANS total score for individuals with MCI after intervention.

**Attention and working memory** Eighteen studies assessed the effects of technology-based cognitive training or rehabilitative programs on attention/working memory, which are required for storage of new information. The most commonly used measures were the digit span test. Other measures included the spatial span test, Trail Making Test A and B, visual search, spanboard, dual task (digit span task + visual detection task), subscale of Addenbrooke’s Cognitive Examination, and Symbol Digit Modalities Test (SDMT).

Out of 18 studies, eight studies reported significant improvement in attention/working memory. Two studies compared computerized training programs (Cogmed Software) with no intervention or a sham cognitive intervention [28, 31]. Significant improvements on span-board \((p = .01)\) [28], digit span \((p < .01)\) [31], and spatial span \((p < .05)\) [31] performance were observed at a 3-month follow-up in the intervention group. Other interventions included memory and attention training, variable priority training, and vision-based speed-of-processing training. Significant improvements were found in digit span forward ability \((\eta^2_p = .14, p < .05)\) [42], accuracy \((p = 0.001)\), reaction time \((p < .01)\) [43], spatial span \((p = .003)\) [22] and working memory \((\eta^2_p = .28, p = .01)\) [44]. However, three other studies that measured attention using digit span did not report significant results [23, 33, 36].

In terms of technologies used among the eight studies, all of them applied computerized programs to deliver the interventions. Specifically, they all used a keyboard, not a touch screen, to record the test responses.

**Executive function** Sixteen studies assessed the effect of technology-based cognitive intervention on executive function. Among them, six studies used the Trail Making Task B, six studies used the phonemic and semantic fluency test, four studies used the Rey-Osterreith Complex Figure Test. Other measures included: WAIS Matrices, Ruff Figural Fluency Test, Test of Everyday Attention (TEA), the intra-/extra-dimensional set shifting, and Executive Abilities: Measures and Instruments for Neurobehavioral Evaluation and Research (EXAMINER).

Out of the 16 studies, nine studies reported significant improvement in executive function [22, 26-28, 31, 32, 36, 40, 44]. The interventions used in these studies included both multi-domain cognitive training, specific training tasks, and gaming. The length of interventions ranged from 3 [36] to 24 weeks [26]. Interestingly, three studies used TNP software as an intervention component [29, 36, 40]; although the intervention length varied, two out of the three studies found significant improvement in executive function but used different measures [36, 40]. Talassi [36] found that TNP integrated with occupational therapy and behavioral therapy had a significant improvement in the Rey-Osterreith Complex Figure Test. Rozzini and Costardi [40] found that MCI individuals receiving cognitive training and ChEIs reported significant improvements in Ravens Coloured Progressive Matrices post-intervention \((p < 0.02)\). This beneficial effect was not found when using TNP only [29]. However, both Talassi [36] and Rozzini [40] failed to report an effect size for their intervention effect. Other studies that demonstrated significant improvements in executive function varied greatly in terms of sample size, intervention content, total intervention time, and executive function measures.

**Memory** Nineteen studies assessed memory. Sixteen out of the 19 studies found a significant effect on memory. The measures of memory varied greatly. Major measures included the Wechsler Memory Scale (WMS) and Rey Auditory Verbal Learning Test (RAVLT). Four studies
used the WMS-III and three out of the four studies found significant improvements in memory after intervention. The intervention used in the three studies included Cogmed computer program [31], Game show on iPad [41], and LLM including both cognitive and physical training components [33]. The intervention period ranged from 5 to 12 weeks and significant improvement in memory was reserved until end of the three months' follow-up [31]. The other study used GOPACK multi-domain cognitive training program to conduct a 6-month intervention but did not find a significant improvement in memory measured by subsets of WMS-III [26]. Three studies used RAVLT to measure verbal memory and all of them found significant benefit of the cognitive interventions being used [27, 31, 39]. The interventions included SOCIABLE, Cogmed, and CogniFit software programs, with the intervention lengths ranged from 5 to 12 weeks and follow-up period up to 3 months [27, 31]. Among the three training software programs, Cogmed targeted on working memory, while the other two targeted on multiple cognitive domains.

Other studies that studied memory as an outcome variable each used various measures including the 12-word-list recall test from the BEM-144 memory battery, the 16-item free and cued reminding test, Buschke Selective Reminding Test, Hopkins Verbal Learning Test, Auditory Logical Memory, Short story recall, WMS-R Visual Reproductions I and II subtests, Pattern recognition memory, Benton Visual Retention Test, short story recall, Rivermead behavioral memory test, and Brief Visuospatial Memory Test-Revised. The interventions of these studies lasted for 3 [36] to 16 weeks [35] with the follow-up time up to 6 months. All but one [32] of these studies demonstrated significant improvements in memory. Manera et al. [32] found the 4-week “kitchen and cooking game” intervention had no significant effect on improving memory.

In terms of technologies, all but two studies used computer to deliver the interventions and used keyboard to collect the data. Only two studies used iPad [41] and VR technology [38] to deliver their memory training programs.

**Non-cognitive outcomes**

**Mood** Nine studies assessed depression. The most commonly used measures were Geriatric Depression Scale (GDS) and its short form GDS-SF [22, 29, 33, 36, 38, 40, 41], other inventory used included Beck's Depression Inventory [35] and Depression Anxiety and Stress Scale [25]. Four studies reported significant reduction of depression among individuals with MCI [33, 35, 36, 40]. None of these studies reported effect sizes for their interventions reducing depression. Two out of these four studies used a multimodal intervention that also integrated physical trainings [33, 36].

Five studies assessed anxiety [25, 29, 36, 40, 41]. The most often used measure was the State Trait Anxiety Inventory (STAI) [29, 36] used in two studies. Only one study showed a significant reduction in anxiety for individuals with MCI. Talassi used a multimodal intervention including cognition, behavioral, and occupational training compared to its control group that had physical rehabilitation, occupational, and behavioral training, and found that the intervention group had significant decrease in anxiety but not the control group participants [36].

**ADL** Eleven studies assessed ADL as a secondary outcome. The Basic Advanced and Instrumental Activities of Daily Living scales were used in 5 studies [29, 36, 40, 44, 45]. Other measures included the Functional Activities Questionnaire [28], B-IADL scale [26], and HK Lawton IADL [13]. Two out of nine studies reported a statistically significant improvement in ADL [27, 44]. However, only one study found a significant between-group difference with a small to medium effect size ($\eta^2 = 0.21$) [44].

**Quality of life** Three studies assessed quality of life [12, 29, 43]. Measures included SF-12 [29], Well-Being Scale [43] and Spitzer-QOL [12]. Only one study reported significant results. Hagovská, et al. [12] found that technology-based cognitive training produced a larger improvement in QoL than classical group-based cognitive training with a medium effect size ($r = 0.69$).

**Discussion**

In the past decade, technology-based cognitive interventions have gained increased research interest worldwide. Almost half (42%) of the studies reviewed were published in 2016 and 2017, suggesting the growth in the importance of technology-based interventions. The vast majority of the studies were conducted in developed countries, which may be associated with the limited availability of and familiarity with technology among older adults in lower income countries.

The types of technology used varied across studies and included computers, tablets, VR, and gaming consoles. Computers were the most widely used technology with 77% using computers to assist delivery of cognitive interventions. The majority utilized commercially available software or programs, with only nine of the studies used training programs developed by the study researchers for the specific study purpose. Therapists or coaches were used to teach, assist, or even supervise the use of technologies along the intervention process. In nearly half of studies ($n = 12$) therapists provided instructions...
to the variability among interventions. With the rapid development of technologies, we can anticipate new types of technologies being utilized to assist cognitive training and rehabilitation interventions in the future.

Overall, technology-based cognitive training and rehabilitation have demonstrated promising beneficial effects on various domains of cognition with moderate to large effect sizes. Most studies (e.g., [28, 31, 44]) assessed participants on different cognitive domains that were not limited to the trained task, but also in other non-trained tasks and other cognitive domains, suggesting a transferable beneficial effect of cognitive training and rehabilitation. For example, Hyer, et al. [28] found that working memory training also improved executive function among trained MCI participants, and the impact was preserved until the end of the 3-month follow-up. This transferability is consistent with previous systematic reviews [14, 15]. However, the training gain and transferability of the training gain varied by intervention (e.g., [22]) and delivery method (e.g., [13]). Therefore, future studies are still needed to understand which intervention would benefit various cognitive domains most efficiently.

Only one study included in this review examined whether applying technology as the delivery method would have a stronger effect on the intervention outcomes, in comparison to the use of a traditional manual delivery. Man, et al. [13] compared the training effect of a memory training program delivered with a non-immersive VR-based system versus with color-print images that matched the VR images. This study found that the VR group showed greater improvement in objective memory but the non-VR group reported greater contentment with memory performance, highlighting the potential importance of receiving verbal and emotional support from training therapists on improving participants’ satisfaction with their memory performance. This study shows that depending on the outcomes that an intervention targets, technology-based and manual trainings may have their own strengths and weaknesses. No conclusions can be made whether one type of intervention is generally more effective than the other.

The effect of the same technology-based cognitive intervention seems to vary between groups with different level of cognitive decline. Some but still limited evidence suggested that participants without cognitive impairment seem to obtain a larger cognitive improvement from technology-based cognitive interventions than those with MCI. Vermeij, et al. [31] found that healthy participants had a larger gain in both trained working memory tasks and untrained executive function tasks than those with cognitive impairment. However, the findings are not conclusive. Barban, et al. [39] found that process-based cognitive training improved verbal memory among MCI participants and improved executive function among healthy participants. On the other hand, participants with MCI seem to gain a larger cognitive benefit than those with Alzheimer’s disease (AD). Cipriani, et al. [29] found that the TNP program significantly improved memory and global cognition among participants with MCI, but only improved memory among those with AD. Similarly, Manera, et al. [32] found that the serious cooking game significantly improved executive function among participants with MCI but not those with AD.

Measures of physical function and mood were used in most studies, but unfortunately most of these were used to ensure non-biased randomization assignment at baseline rather than as outcome measures, so we have limited understanding of the effects of technology-based cognitive interventions on these outcomes. Nine studies evaluated mood (e.g., depression, anxiety) as an outcome, and eleven studies included ADL as an outcome variable. Among these, four studies found technology-based cognitive interventions had beneficial effect on mood and two studies found beneficial effect on functional activity. Technology-based cognitive training studies included in this review may have limited impact on mood and functional activity.

Two studies of technology-based cognitive training and one study of technology-based cognitive rehabilitation examined the effect of their interventions on quality of life [12, 29, 43]. However, only one of the four studies reported significant result. Hagovská, et al. [12] found that technology-based cognitive training produced a larger improvement in QoL than classical group-based cognitive training. This lack of effect of cognitive intervention on QoL is consistent with previous systematic review on the efficacy of cognitive interventions on QoL [14]. However, each study used a different QoL instruments, and various research designs (e.g., types of interventions, lengths of follow-up, and types of control groups). Given the limited number of studies conducted, future studies using comparable designs are still needed to further understand the effectiveness of the intervention on quality of life.

A previous systematic review suggested that multimodal cognitive inventions were a promising research area [15]. In our review, we found eight studies that applied multimodal interventions combining technology-based cognitive training and physical exercise or other therapeutic methods. We expected to see the findings of these studies
would provide support for speculation that multimodal cognitive interventions would produce a greater impact on improving cognitive function as well as mood and functional abilities. However, the eight reviewed articles provided insufficient evidence to support this conjecture. Five out of the eight studies were not designed to compare the efficacy of multimodal cognitive intervention compared to cognitive intervention alone [33, 34, 36, 37, 39], and it was difficult to draw any conclusions from the remaining three studies remained due to the great variability in the designs across studies. According to one study, customized technology-based cognitive training produced additional benefit, and technology-based cognitive intervention plus ChEIs was superior to ChEls alone [35]. Interestingly, Fiatarone-Singh, et al. [26] found that progressive resistance training produced more improvement in executive function and global cognition than both cognitive training and multimodal intervention including cognitive training and progressive resistance training. Findings from this study suggest that physical exercise may particularly benefit executive function, but that implementing multimodal cognitive and physical interventions may be too challenging for people with MCI. Previous systematic review on the efficacy of combined cognitive and exercise intervention in older adults with and without cognitive impairment did not find sufficient evidence to confirm the beneficial effect among older adults with cognitive impairment [46]. Taken together, more studies are needed to understand the advantages of a multimodal cognitive intervention in individuals with MCI. Future studies should design appropriate control groups to understand the additional value produced by a multimodal cognitive intervention than a single model intervention. Additionally, researchers should also bear in mind the possibility that older adults with MCI may not be able to manage the cognitive challenge associated with multimodal interventions.

The studies reviewed generally had small sample sizes, ranged widely from 10 [13] to 301 participants [39]. The average sample size across studies was 54; 39% of the studies had sample sizes of less than 30. The small sample sizes may be related to the complicated diagnostic criteria of MCI, the ethical challenges of conducting intervention studies in older adults with MCI, and the limited availability of some technology-based cognitive intervention programs. More importantly, potential beneficial effects of an intervention could be diminished due to a small sample size.

The measures applied varied greatly across studies, which created challenges in the comparison and generalizability of the study findings. Future studies should consider using measures that have been shown to have good validity and reliability as well as have been frequently used among the MCI population (e.g., CES-D, MMSE, QOL-AD, etc.). Neuroimaging techniques have emerged to be more widely used to obtain information on how technology-based cognitive interventions would affect neural connectivity [37], activation [23], and brain atrophy [31].

We conducted a comprehensive search of literature on the topic area using five major databases. However, this systematic review should be considered in light of its limitations. We only reviewed articles in English language. There may be other relevant studies that were published in other languages. We also need to be aware that technology is developing rapidly so that promising technology-based cognitive training and rehabilitation programs may exist that have not yet been published due to concerns about protecting participants.

Conclusion

The findings from this systematic review suggest that technology-based cognitive training and rehabilitation programs show promise for improving cognitive function, with some interventions showing moderate to large effect sizes. Computers, tablets, gaming consoles and platforms, and VR systems were the common types of technologies used. Both general and domain-specific cognitive training have led to improved cognition, primarily in memory, but with some evidence that executive function may also be positively affected. Studies that examined the impact of cognitive training on improving mood and functional abilities, have generated less convincing evidence. Multimodal intervention programs integrated technology-based cognitive intervention and other therapies have produced inconsistent findings on the superiority over only applying technology-based single model cognitive intervention. Overall, technology-based cognitive training and rehabilitation are promising intervention methods to improve cognitive function. Future studies should put effort to clarify whether the added benefits of implementing multimodal interventions exist, and carefully consider the potential extra burden caused to individuals with MCI. Additionally, future studies should aim to lessen the variabilities in intervention design and measures applied.

Additional file

Additional file 1: Table S1. Searching Strategy. Table S2. Results of quality assessment based on JBI critical appraisal checklist for randomized controlled trials*. Table S3. Results of quality assessment based on JBI critical appraisal checklist for quasi-experimental studies*. Figure S1. Forest plot - RBANS score (computer-based intervention VS. Control). (DOCX 34 kb)

Abbreviations

ACE: Addenbrooke’s Cognitive Examination; AD: Alzheimer’s disease; ADAS-Cog: Alzheimer’s Disease Assessment scale-cognitive subscale; BCAT: Brief
Cognitive Assessment Tool; CAMCI: Computerized Assessment of Mild Cognitive Impairment; ChEIs: cholinesterase inhibitors; GDS: Geriatric Depression Scale; GDS-5F: Geriatric Depression Scale short form; IWG: International Working Group; JBI: Joanna Briggs Institute; LLM: Long-Lasting Memories; M-MSE: Mini-mental state examination; MoCA: Montreal Cognitive Assessment; MYHAT: Monongahela-Youghiogheny Healthy Aging Team; NEAR: Neuropsychological and Educational Approach to Remediation; RAVLT: Rey Auditory Verbal Learning Test; RBANS: Repeatable Battery for Assessment of Neuropsychological Status; RCT: randomized controlled trial; SDMT: Symbol Digit Modalities Test; STA: State Trait Anxiety Inventory; TEA: Test of Everyday Attention; TNP: Neuropsychological Training; VR: virtual reality; WMS: Wechsler Memory Scale

Availability of data and materials
All data generated or analysed during this study are included in this published article [and its supplementary information files].

Authors’ contributions
SG designed and conducted the study, abstracted data, interpreted the results, and played a major role in writing the manuscript. BW helped conceive the methodological support, helped abstracted data, appraised quality, and played a major role in writing the manuscript. ZZ provided methodological support, helped abstracted data, appraised quality, and helped wrote a certain section of the manuscript. BW helped conceive the study and edited the manuscript. ESM helped conceive the study, screened citations and full-text articles, and edited the manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate
Not applicable.

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The authors declare that they have no competing interests.

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