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REVIEW

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The application of technology to improve cognition in older adults: A review and suggestions for future directions

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Abstract

The rapidly increasing worldwide population of older adults, along with the increasing prevalence of cognitive impairment and dementia in this population, is a growing health-care problem. As such, advances in technology-based cognitive interventions and games are playing an increasingly key role in preserving and improving older adults' cognitive function, especially during the COVID-19 pandemic when opportunities for face-to-face activities or training are few. In this paper, we summarize from previous studies systematic reviews and meta-analyses on the various types of technology used in cognitive interventions (namely, computerized cognitive training, virtual-reality interventions and robot-assisted interventions) and the empirical evidence on the effects of these technologies on global and specific cognitive functions in healthy and clinical populations of older adults (e.g., older adults with mild cognitive impairment or dementia). We also describe older adults' perceptions, experiences and acceptance of these technologies. Finally, we discuss the limitations, challenges and future avenues of research in this field.

KEYWORDS
cognition, cognitive interventions, older adults, robot, technology, virtual reality

Decreasing birth rates and increasing life expectancies are fueling a continual increase in older adult populations worldwide (Valls Martínez et al., 2021). Advancing age has been linked to cognitive decline in adults aged over 60 (Salthouse, 2009), and the prevalence of cognitive deteriorative diseases, such as mild cognitive impairment (MCI) and Alzheimer's disease (AD), is increasing in this age group. These cognitive impairments affect the quality of life and social functioning of older adults, and they also place a heavy financial burden on families and health-care systems (Piña-Escudero et al., 2021).

To delay the age-related cognitive deterioration in or improve the cognitive abilities of older adults, researchers have developed computerized cognitive training, virtual-reality (VR) cognitive interventions, and robot-assisted cognitive interventions. The ongoing COVID-19 pandemic has highlighted the importance of adopting digital technologies in interventions (Bodner et al., 2020; Cheung & Peri, 2021). A number of studies have demonstrated the positive effects of technology-based cognitive interventions on the cognitive performance of older adults (for systematic reviews, see Alnajjar et al., 2019; Zhong et al., 2021). In the following section, we summarize information on each type of technology-based cognitive intervention for older adults.

This article is a contribution to the special serial: embracing the new decade of the PsyCh Journal: State of the art and future perspectives.

TYPES OF TECHNOLOGY-BASED COGNITIVE INTERVENTIONS

Computerized cognitive training programs

Computerized cognitive training has been widely studied in the past two decades, and consists of game-based cognitive exercises that can be completed on computers or mobile devices (Bodner et al., 2020). Pioneering studies found that older adults who played classic video games, such as Pac-Man, on a weekly basis exhibited improved reaction times and executive function (Clark et al., 1987; Dustman et al., 1992). Currently, sedentary commercial video games or brain-training programs, such as Lumosity, Brainer1, and Nintendo Wii Big Brain Academy, are used in interventions for both healthy older adults and those with MCI or dementia. Some other programs developed by researchers, such as the prospective memory training program (i.e., Virtual Week; Rose et al., 2015), require older adults to remember to perform a particular task at the appropriate time, such as taking medicine at breakfast. Cognitive exercises and games that can be completed on smartphones and tablets have also recently been developed (e.g., the "Kitchen and cooking" game in which patients with MCI or AD can "cook" with various recipes on a tablet to stimulate executive function; Manera et al., 2015) and smartphone-based brain anti-aging and memory reinforcement training (SMART; Oh et al., 2018), which offers 10 training tasks involving attention and memory.

VR interventions

"VR" refers to an artificial computer-simulated environment wherein individuals can interact in real-time in scenarios that closely resemble reality (Bacha et al., 2018; Thapa et al., 2020). It makes use of the visual modality and non-visual modalities, such as realistic sounds. VR systems can be sub-categorized into non-immersive VR and immersive VR (Clay et al., 2020;). Non-immersive VR uses a computer monitor or projector screen to display a two-dimensional virtual environment, and individuals interact with the virtual entities in the environment using a controller, such as a joystick or mouse (Clay et al., 2020). Action video games (also known as exergames) that involve physical and cognitive demands are considered non-immersive VR games. The most popular VR systems are those developed by Nintendo (Kyoto, Japan) and Xbox (Microsoft Corp., Redmond, WA). The Nintendo Wii system provides a virtual environment for playing sports games, in which the player holds a wireless controller and performs upper-body movements to simulate actions (e.g., throwing a ball; Hughes et al., 2014). In the Xbox Kinect system, the sensor is equipped with a camera system and depth-sensing technology for capturing the full-body movements of the player, which are reproduced in the movements of an avatar in the virtual environment (Ordnung et al., 2017; Phirom et al., 2020). "Space Pop," a Kinect game that involves cognitive engagement (e.g., attention and processing speed), requires the player to flap their arms to pop the bubbles that appear on screen (Bacha et al., 2018). Immersive VR, which generates a greater sense of presence and requires more brain resources for cognitive or motor control than non-immersive VR (Slobounov et al., 2015), is a three-dimensional virtual world created using a head-mounted display (HMD) or Cave Automatic Virtual Environments (CAVE systems), which consist of walls and floors for video display, motion-capture systems and stereoscopic liquid-crystal display shutter glasses (Clay et al., 2020). For example, in Liao et al. (2019), MCI patients performed VR-based cognitive training by wearing an HMD and manually operating a motor controller to complete several instrumental activities of daily living (IADL) tasks. VR allows older adults to practice various daily activities or cognitive tasks in a safe and controlled environment.

Robot-assisted interventions

While VR provides users with the sense of being physically present in a virtual world, socially assistive robots (SARs) provide users with the feeling of interacting with a "real person" (Cohavi & Levy-Tzedek, 2022), by interacting with and assisting users (Alnajjar et al., 2019; Cohavi & Levy-Tzedek, 2022). Van Patten et al. (2020) denoted cognitively assistive robots as SARs that provide cognitive interventions to support and improve people's cognitive functioning. Most robots used in interventions are humanoid robots (i.e., artificial human-like entities), while some are animal-like.

Humanoid robots display human-like emotional expressions and body language to establish an immersive and close interaction with older adults during cognitive interventions (Manca et al., 2021; Mois et al., 2020). One example is Sil-bot, which can display approximately 30 emotional expressions to stimulate the interest of and provide encouragement for older adults (Park et al., 2021). Another example is the humanoid robot NAO, which can address users by their name and provide personalized feedback (Pino et al., 2019). Furthermore, being equipped with sensors, cameras and microphones together with programs and systems like a machine-learning system, artificial intelligence, a face-tracking system and natural-language-processing ability, it can assess older adults' performance and engagement and automatically adjust the difficulty of their cognitive exercises (Alnajjar et al., 2019; Mois et al., 2020; Pino et al., 2019). Otake-Matsuura et al. (2021) used the robot Bono-05 to moderate group conversation, which it achieved by rotating its body and arms to invite an older adult to speak. To equally engage every older adult in the intervention, Bono-05 prompted and stopped their utterances based on speech-pattern analysis of total speech time and utterance length.

Benefits of technology-based cognitive interventions

Compared to non-technology-based cognitive interventions, the benefits of technology-based cognitive interventions include the reduced cost of training (Alnajjar et al., 2019), the increased motivation and interest of participants' in the training (Savulich et al., 2017) and the supply of real-time feedback that allows for automatic adjustment of the training level based on a user's performance (Martínez-Alcalá et al., 2018).

Findings on the effects of technology-based cognitive interventions

A growing number of studies and randomized controlled trials (RCTs) have been conducted to address a key question: Are current technology-based interventions effective in maintaining or improving cognition of both cognitively healthy and impaired older adults?

In cognitively healthy older adults

Systematic reviews and meta-analyses that have synthesized the findings of studies examining the effects of computerized cognitive training and non-immersive VR (action video games) on the cognitive function of healthy older adults are summarized in Table 1. Their results suggest that such training has the potential to improve memory, attention, visuospatial ability, processing speed and executive function (Gates et al., 2020; Klimova, 2016a, 2016b; Kueider et al., 2012; Wang et al., 2021). For instance, Monteiro-Junior et al. (2017) found that playing non-immersive VR Nintendo Wii sports games for 30 to 45 min could slightly improve healthy older adults' verbal fluency. Long-term interventions, such as Big Brain Academy or Brain Age interventions delivered for a month (Ackerman et al., 2010; Nouchi et al., 2012), did not improve global cognition in older adults but did improve their executive function and processing speed. In addition, Virtual Week was effective in improving healthy older adults' performance in ecological prospective memory tasks (Rose et al., 2015). Although Bonnechère et al. (2020) reported that attention and visuospatial ability did not improve after technology-based training, this may be due to the inclusion of various types of low-quality studies.

Computerized cognitive training via mobile applications, a relatively new technology, has also been shown to produce positive effects on cognitive function in healthy older adults. For example, Oh et al. (2018) showed that five 15–20-min sessions of SMART per week over 8 weeks resulted in improvements in older adults' working memory performance. Moreover, Martínez-Alcalá et al. (2018) showed that mobile application-based mental exercises for 3 months improved the Mini-Mental State Examination (MMSE) performance of healthy older adults lacking experience of using technology. Furthermore, a large-scale study involving 12,000 healthy older adults found that playing cognitive mobile games improved the processing speed of even the oldest-old adult aged over 80 years (Bonnechère et al., 2021).

Results on the efficacy of robot-based training appears to enhance healthy older adults' cognitive function, but the results in different domains are mixed. Some studies have found that robot-based training leads to improvements in healthy older adults' global cognition (Sawami et al., 2019; Tanaka et al., 2012), while others have reported no improvement (Kim et al., 2015; Otake-Matsuura et al., 2021). In terms of specific cognitive domains, the verbal memory of healthy older adults was improved after 8 weeks' living at home with a humanoid robot (Tanaka et al., 2012), and healthy older adults' delayed memory was improved after 7 weeks' cognitive dance therapy with robots (Sawami et al., 2019) or after 12 weeks' of a conversation intervention moderated by robots (Otake-Matsuura et al., 2021). However, in a 12-week intervention performed by Kim et al. (2015), the robot-assisted training group of healthy older adults only outperformed the human-assisted training group of healthy older adults in executive function, and no between-group difference was found in visual memory or working memory.

A few studies have investigated the long-term (i.e., week- or month-long) effects of technology-based interventions on healthy older adults' cognition. Bacha et al. (2018) found that the improvement in healthy older adults' global cognition induced by VR Adventure games was maintained 4 weeks after the intervention. Toril et al. (2016) revealed that the improvement in working memory, short-term memory, and episodic memory of healthy older adults' induced by training software was maintained 3 months after the intervention. Eggenberger et al. (2015) found that the healthy older adults in both a non-immersive VR video-game dancing group and a treadmill walking with verbal memory-training group were able to maintain improved performance in executive function, memory and processing speed for a year after their respective interventions, which suggests that technology-based interventions can produce similarly positive and persistent effects as traditional interventions.

In cognitively impaired older adults

Several systematic reviews and meta-analyses have been conducted on the effects of technology-based interventions on cognitively impaired older adults (see Table 2). Despite some inconsistent results, the overall findings indicate that such training has the potential to improve the global cognition, memory, attention, processing speed, visuospatial ability, executive function and learning of cognitively impaired older adults. Specifically, the intervention Lumosity administered for approximately 12 weeks led to improved visual sustained attention in MCI patients but no enhancement in their visual memory or executive function (Finn & McDonald, 2011). Mrakic-Sposta et al. (2018) developed three non-immersive virtual environments for physical–cognitive training lasting 6 weeks. Although the authors found improvement in the MMSE performance on cognitively impaired older adults who received this training, this result was not statistically significant. Savulich et al. (2017) developed "Game Show," an iPad-based memory game for older adults with amnestic MCI, and found that the participants exhibited improved episodic memory and visuospatial memory after 4 weeks of game playing. Manera et al. (2015) developed "Kitchen and cooking," a game targeting executive function, and found that 1 week of game playing by 21 MCI and AD patients led to greater improvements in executive function, in particular in MCI patients than the AD patients.

Unlike studies on healthy older adults, which have mostly focused on non-immersive environments, studies on cognitively impaired older adults have tended to focus on fully-immersive VR environments. A single 30-min training session of "harvest and cook" programmed with fully immersive environments displaying rural scenery resulted in non-significant improvements in response times among older adults with MCI and mild dementia (Yun et al., 2020). Liao et al. (2019) compared fully immersive VR IADL-based physical and cognitive training with traditional physical and cognitive training, and found that the VR-trained group showed more improvement in executive function tasks

TABLE 1 Summary of Systematic Reviews and Meta-analyses of the Effectiveness of Technology-Based Cognitive Training in Cognitively Healthy Older Adults

Study	Type of technology	Total number of studies included	Sample size	Domain	Number of studies assessed	Number of participants assessed	Pooled effect size [CI]	Comments/additional information
Abdi et al. (2018)[a]	Robot	2 studies published before 2017	105	Global cognition	2	105	N/A[a]	Improved in 1 out of 2 studies
				General cognitive and visual memory	1	71	N/A[a]	The computer training group had greater improvement than the robot group.
				Executive function	1	71	N/A[a]	Both the robot group and the active control group showed significant improvement, compared with the passive control group.
				Cortical thickness	1	71	N/A[a]	Both the robot group and the active control group showed significant attenuation of cortical thinning.
Alnajjar et al. (2019)[b]	Computerized training	15 RCTs published between 2009 and 2019	3295	Working memory	9	639	N/A[a]	Improved in 3 out of 9 studies
				Processing speed	5	216	N/A[a]	Improved in 4 out of 5 studies
				Attention	6	2638	N/A[a]	Improved in 5 out of 6 studies
				Reasoning	4	2408	N/A[a]	Improved in 2 out of 4 studies
	Robot	3 RCTs published between 2009 and 2019	219	Cognitive function (executive function and verbal memory)	1	34	N/A[a]	Improved
				Cortical thickness	1	85	N/A[a]	Less cortical thinning in the anterior cingulate cortices found in the robot group, compared with the traditional intervention group.
Bonnechère et al. (2020)[c]	Computerized training and non-immersive VR	16 RCTs published before 2019	1543	Executive function	9	582	$g = 0.21$ [0.06, 0.35]	Significantly improved

(Continues)

TABLE 1 (Continued)

Study	Type of technology	Total number of studies included	Sample size	Domain	Number of studies assessed	Number of participants assessed	Pooled effect size [CI]	Comments/additional information
				Working memory	9	917	$g = 0.21$ [0.08, 0.34]	Significantly improved
				Verbal memory	7	907	$g = 0.12$ [0.01–0.24]	Significantly improved
				Processing speed	8	403	$g = 0.40$ [0.20, 0.60]	Significantly improved
				Attention	4	299	$g = 0.06$ [−0.16–0.29]	Not significant
				Visuospatial abilities	4	216	$g = 0.03$ [−0.16, 0.22]	Not significant
Gates et al. (2020)[b]	Computerized training and non-immersive VR	8 RCTs (trials with duration ranging from 12 to 26 weeks) published before 2018	1183	Global cognitive function	2 (compared with active control; intervention duration of 12 weeks)	232	$d = -0.31$ [−0.57, −0.05][d]	May improved slightly compared with active control
				Executive function	3 (compared with active control; intervention duration of 12 to 17 weeks)	230	$d = -0.04$ [−0.61, 0.53][d]	No conclusion due to very low-quality evidence
					2 (compared with passive control; intervention duration of 12 weeks to 6 months)	292	$d = -0.08$ [−0.31, 0.15][d]	Little to no effect compared with passive control
				Verbal fluency	1 (compared with passive control; intervention duration of 6 months)	150	N/A[e]	Little or no effect compared with passive control (MD = −0.11 [−1.58, 1.36])
				Episodic memory	4 (compared with active control; intervention duration of 12 to 17 weeks)	439	$d = 0.06$ [−0.14, 0.26][d]	Little to no effect compared with active control
				Episodic memory	1 (compared with passive control; intervention duration of 6 months)	150	N/A[e]	May have improved slightly compared with passive control (MD = −0.90 [−1.73, −0.07])
				Working memory	3 (compared with active control; intervention duration of 12 to 16 weeks)	392	$d = -0.17$ [−0.36, 0.02][d]	Little to no effectcompared with active control

(Continues)

TABLE 1 (Continued)

Study	Type of technology	Total number of studies included	Sample size	Domain	Number of studies assessed	Number of participants assessed	Pooled effect size [CI]	Comments/additional information
				Working memory	1 (compared with passive control; intervention duration of 16 weeks)	60	N/A[e]	Little to no effect compared with passive control (MD = −0.08 [−0.43, 0.27])
				Processing speed	2 (compared with active control; intervention duration of 12 to 16 weeks)	138	$d = -0.63$ [−1.14, −0.12][d]	No conclusion due to very low-quality evidence
				Processing speed	2 (compared with passive control; intervention duration of 12 to 16 weeks)	204	$d = -0.28$ [−0.82, 0.26][d]	No conclusion due to very low-quality evidence
Kueider et al. (2012)[b]	Computerized training (Classic cognitive training)	21 studies[f] published from 1989 to 2011	1835	Executive function	Not mentioned	Not mentioned	N/A[a]	Improved (range of effect sizes of the included studies: $d = 0.08$ to 6.32; median: 0.39)
				Memory	Not mentioned	Not mentioned	N/A[a]	Improved (range of effect sizes of the included studies: $d = 0.26$ to 0.67; median: 0.52)
				Working memory	Not mentioned	Not mentioned	N/A[a]	Improved (range of effect sizes of the included studies: $d = 0.25$ to 3.92; median: 0.89)
				Processing speed	Not mentioned	Not mentioned	N/A[a]	Improved (range of effect sizes of the included studies: $d = 0.54$ to 3.28; median: 1.30)
				Reaction time	Not mentioned	Not mentioned	N/A[a]	Improved (range of effect sizes of the included studies: $d = 0.22$ to 1.17; median: 0.69)
				Attention	Not mentioned	Not mentioned	N/A[a]	Improved (range of effect sizes of the included studies: $d = 0.20$ to 4.07; median: 0.57)
				Visuospatial ability	Not mentioned	Not mentioned	N/A[a]	Improved (range of effect sizes of the included studies: $d = 0.13$ to 4.09; median: 0.39)

(Continues)

TABLE 1 (Continued)

Study	Type of technology	Total number of studies included	Sample size	Domain	Number of studies assessed	Number of participants assessed	Pooled effect size [CI]	Comments/additional information
Kueider et al. (2012)[b]	Computerized training (Neuropsychological Software)	9 studies[g] published from 1989 to 2011	1043	Memory	Not mentioned	Not mentioned	N/A[a]	Improved (range of effect sizes of the included studies: $d = 0.20$ to 2.92; median: 0.56)
				Working memory	Not mentioned	Not mentioned	N/A[a]	Improved (range of effect sizes of the included studies: $d = 0.23$ to 3.00; median: 0.45)
				Processing speed	Not mentioned	Not mentioned	N/A[a]	Improved (range of effect sizes of the included studies: $d = 0.87$ to 7.14; median: 4.00)
				Visuospatial ability	Not mentioned	Not mentioned	N/A[a]	Improved (range of effect sizes of the included studies: $d = 0.19$ to 1.24; median: 0.59)
Kueider et al. (2012)[b]	Computerized training (Video Games)	8 studies[h] published from 1986 to 2010	327	Global cognition	Not mentioned	Not mentioned	N/A[a]	Improved (range of effect sizes of the included studies: $d = 0.39$ to 0.71; median: 0.69)
				Executive function	Not mentioned	Not mentioned	N/A[a]	Improved (range of effect sizes of the included studies: $d = 0.11$ to 0.42; median: 0.25)
				Processing speed	Not mentioned	Not mentioned	N/A[a]	Improved (range of effect sizes of the included studies: $d = 0.31$ to 0.98; median: 0.72)
				Reaction time	Not mentioned	Not mentioned	N/A[a]	Improved (range of effect sizes of the included studies: $d = 0.33$ to 1.11; median: 0.77)
Klimova (2016a)[b]	Computerized training	6 RCTs published between 2013 and 2016	2443	N/A	N/A	N/A	N/A[a]	Improved in reasoning, short-term memory, working memory, processing speed
Klimova (2016b)[b]	Internet training (including associative studies on digital literacy and cognitive decline)	8 studies published from 2010 to 2015	14,370	N/A	N/A	N/A	N/A[a]	Improved in reasoning, working memory, short-term memory, long-term episodic memory, verbal learning, instrumental activities of daily living

(Continues)

TABLE 1 (Continued)

Study	Type of technology	Total number of studies included	Sample size	Domain	Number of studies assessed	Number of participants assessed	Pooled effect size [CI]	Comments/additional information
Toril et al. (2014)[c]	Computerized training and non-immersive VR	20 studies published from 1986 to 2013	913	Cognitive function	Not mentioned	Not mentioned	$d = 0.38$ [0.13, 0.62]	Significantly improved
				Executive function	Not mentioned	Not mentioned	$d = 0.16$ [−0.10, 0.42]	Not significantly improved
				Memory	Not mentioned	Not mentioned	$d = 0.39$ [0.01, 0.64]	Significantly improved
				Reaction time	Not mentioned	Not mentioned	$d = 0.63$ [0.42, 0.84]	Significantly improved
				Attention	Not mentioned	Not mentioned	$d = 0.37$ [0.17, 0.57]	Significantly improved
Wang et al. (2021)[b]	Computerized training (Game-based brain training)	15 RCTs published before 2019	759	Executive function (shifting)	5	196	$g = 0.21$	No significant improvement
				Executive function (inhibition)	3	160	$g = 0.26$	No significant improvement
				Executive function (updating memory)	1	34	$g = 0.62$	No significant improvement
				Short-term memory	5	167	$g = 0.35$	Significantly improved compared with the control group
				Processing speed	10	437	$g = 0.23$	Significantly improved compared with the control group
				Selective attention	6	226	$g = 0.40$	Significantly improved compared with the control group

Note: CI = confidence interval; VR = virtual reality; RCT = randomized controlled trials; g = Hedges' g; MD = mean difference; d = Cohen's d.
[a]A scoping review.
[b]A systematic review.
[c]A systematic review with meta-analysis.
[d]Pooled effect size was not calculated in the systematic review or scoping review.
[e]Pooled effect size was not calculated because there was only one study assessed this domain.
[f]The authors of this study reported the effect using the term SMD (standard mean difference), which is also known as Cohen's *d*.
[g]21 classic cognitive training: three reaction time training, five processing speed training, five memory training, three executive function training, one attention training, four multiple cognitive domains training.
[h]Nine neuropsychological software: three memory training, six multiple cognitive domains training.
[i]Eight sedentary video games: one game trained processing speed specifically, one game trained attention specifically, six trained multiple cognitive domains.

TABLE 2 Summary of Systematic Reviews and Meta-analyses of the Effectiveness of Technology-Based Cognitive Training in Cognitively Impaired Older Adults

Study	Type of technology	Total number of studies included	Sample size	Clinical condition	Domain	Number of studies assessed	Number of participants assessed	Pooled effect size [CI]	Comments/additional information
Abdi et al. (2018)[a]	Robot	4 studies published before 2017	239	Dementia	Global cognition	3	225	N/A[a]	Improved 2 out of 3 studies
					Cortical neuronal activity	1	14	N/A[a]	Increased activity, especially in participants who like the robot (PARO)
Alnajjar et al. (2019)[b]	Computerized training	8 studies published from 2009 to 2019	300	MCI	Working memory	2	115	N/A[a]	Improved in all the included studies
					Processing speed	3	93	N/A[a]	Improved in 1 out of 3 studies
					Reasoning	1	27	N/A[a]	No improvement
					Attention	4	95	N/A[a]	Improved in 3 out of 4 studies
	Robot	5 studies on published from 2009 to 2019	684	MCI or dementia	Not mentioned	N/A	N/A	N/A[a]	All studies yielded positive outcomes in non-cognitive domains (e.g., quality of life). Cognitive outcomes were not studied.
Coyle et al. (2015)[b]	Computerized training and VR	16 studies on MCI published from 1999 to 2014	664	MCI or dementia	Global cognition	9	331	N/A[a]	Improved (Cohen's *d* reported in the studies varied from 0.26 to 1.23)
					Executive function	7	266	N/A[a]	Inconsistent. (Cohen's *d* reported in the studies varied from 0.47 to 0.89)
					Verbal fluency	4	144	N/A[a]	Inconsistent
					Language	5	210	N/A[a]	No significant improvement
					Attention/working memory	8	307	N/A[a]	Inconsistent (Cohen's *d* reported in the studies varied from 0.24 to 0.85, and η_p^2 was 0.14)
					Verbal memory	8	251	N/A[a]	Inconsistent (Cohen's *d* reported in the studies varied from 0.26 to 1.38)
					Visual memory	9	310	N/A[a]	Inconsistent (Cohen's *d* reported in the studies varied from 1.15 to 1.63, and η_p^2 varied from 0.15 to 0.18)
					Processing speed	5	298	N/A[a]	Inconsistent
					Visuospatial ability	4	95	N/A[a]	Inconsistent

(Continues)

TABLE 2 (Continued)

Study	Type of technology	Total number of studies included	Sample size	Clinical condition	Domain	Number of studies assessed	Number of participants assessed	Pooled effect size [CI]	Comments/additional information
					Activities of daily living	8	302	N/A[a]	No significant improvements or decrement ($d = -0.02$)
Gates et al. (2019b)[b]	Computerized training and non-immersive VR	8 RCTs published before 2018 (trials with duration ranging from 12 weeks to 18 months)	660	MCI	Global cognition	5 (compared with active control; follow-up from 3 months to 2 years)	407	$d = -0.53$ [−1.06, −0.01][c]	No conclusion due to very low-quality evidence
						1 (compared with passive control; follow-up from 12 months)	37	N/A[d]	No conclusion due to very low-quality evidence (MD = −0.36 [−0.30, 1.02])
					Episodic memory	5 (compared with active control; follow-up from 3 months to 2 years)	223	$d = -0.79$ [−1.54, −0.04][c]	No conclusion due to very low-quality evidence
						1 (compared with passive control; follow-up from 12 months)	37	N/A[d]	No conclusion due to very low-quality evidence (MD = −2.70 [−5.00, 0.40])
					Processing speed	2 (compared with active control; follow-up from 3 months to 2 years)	119	$d = 0.20$ [−0.16, 0.56][c]	Little or no effect compared with active control
					Executive function	3 (compared with active control; follow-up from 3 months to 2 years)	150	$d = -0.31$ [−0.90, 0.28][c]	No conclusion due to very low-quality evidence
						1 (compared with passive control; follow-up from 12 months)	37	N/A[d]	No conclusion due to very low-quality evidence (MD = −2.70 [−6.21, 0.81])
					Working memory	3 (compared with active control; follow-up from 3 months to 9 months)	72	$d = -0.88$ [−1.73, −0.03][c]	No conclusion due to very low-quality evidence
					Verbal fluency	3 (compared with active control; follow-up from 3 months to 9 months)	150	$d = -0.16$ [−0.76, 0.44][c]	Little or no effect compared with active control
						1 (compared with passive control; follow-up from 12 months)	37	N/A[d]	No conclusion due to very low-quality evidence (MD = 1.90 [−4.50, 8.30])

(Continues)

TABLE 2 (Continued)

Study	Type of technology	Total number of studies included	Sample size	Clinical condition	Domain	Number of studies assessed	Number of participants assessed	Pooled effect size [CI]	Comments/additional information
Ge et al. (2018)[b]	Computerized software, tablets, gaming consoles, and VR	26 studies published before 2017	1040	MCI	Global cognition	22	Not mentioned	N/A[a]	Significantly improved in 8 out of 22 studies
					Executive function	16	Not mentioned	N/A[a]	Significantly improved in 9 out of 16 studies
					Attention/working memory	18	Not mentioned	N/A[a]	Significantly improved in 8 out of 18 studies
					Memory	19	Not mentioned	N/A[a]	Significantly improved in 16 out of 19 studies
					Activities of daily living	11	Not mentioned	N/A[a]	Significantly improved in 2 out of 9 studies
Hill et al. (2017)[c]	Computerized training and VR	17 RCTs published before 2016	686	MCI	Overall efficacy on cognitive outcomes	17	686	$g = 0.35$ [0.20, 0.51]	Significantly improved
					Global cognition	12	560	$g = 0.38$ [0.14, 0.62]	Significantly improved
					Executive function	13	Not mentioned	$g = 0.20$ [−0.05,0.44]	Not significant
					Verbal learning	11	Not mentioned	$g = 0.39$ [0.14, 0.63]	Significantly improved
					Nonverbal learning	8	Not mentioned	$g = 0.50$ [0.25, 0.76]	Significantly improved
					Language	6	Not mentioned	$g = 0.41$ [−0.10,0.92]	Not significant
					Working memory	9 (with outlier)	Not mentioned	$g = 0.74$ [0.32, 1.15]	Significantly improved
					Working memory	8 (without outlier)	Not mentioned	$g = 0.58$ [0.27, 0.90]	Significantly improved
					Verbal memory	12	Not mentioned	$g = 0.42$ [0.21, 0.63]	Significantly improved
					Nonverbal memory	7	Not mentioned	$g = 0.20$ [−0.03, 0.43]	Not significant
					Processing speed	7	Not mentioned	$g = 0.09$ [−0.17, 0.35]	Not significant
					Attention	6	Not mentioned	$g = 0.44$ [0.20, 0.68]	Significantly improved
					Visuospatial skills	5	Not mentioned	$g = 0.18$ [−0.23,0.60]	Not significant
					Instrumental activities of daily living	6	Not mentioned	$g = 0.21$ [−0.18, 0.61]	Not significant
		12 RCTs published before 2016	389	Dementia	Overall efficacy on cognitive domains	11 (with outliers)	345	$g = 0.26$ [0.01, 0.52]	Significantly improved
						9 (without outliers)	303	$g = 0.08$ [−0.15, 0.31]	Not significant
					Global cognition	7	Not mentioned	$g = 0.31$ [−0.11, 0.72]	Not significant
					Executive function	5	Not mentioned	$g = 0.02$ [−0.46, 0.51]	Not significant

(Continues)

TABLE 2 (Continued)

Study	Type of technology	Total number of studies included	Sample size	Clinical condition	Domain	Number of studies assessed	Number of participants assessed	Pooled effect size [CI]	Comments/additional information
					Verbal learning	4	Not mentioned	$g = 0.42$ [−0.14, 0.97]	Not significant
					Non-verbal learning	2	Not mentioned	$g = 0.23$ [−0.43, 0.90]	Not significant
					Language	4	Not mentioned	$g = 0.08$ [−0.29, 0.44]	Not significant
					Verbal memory	9	Not mentioned	$g = 0.17$ [−0.25, 0.59]	Not significant
					Non-verbal memory	1	Not mentioned	$g = -0.06$ [−0.49, 0.38]	Not significant
					Working memory	4	Not mentioned	$g = 0.22$ [−0.34, 0.78]	Not significant
					Processing speed	2	Not mentioned	$g = 0.11$ [−0.43, 0.66]	Not significant
					Attention	2	Not mentioned	$g = -0.19$ [−0.77, 0.39]	Not significant
					Visuospatial skills	3	Not mentioned	$g = 0.54$ [0.07, 1.01]	Significantly improved
					Activities of Daily Living	2	Not mentioned	$g = 0.06$ [−0.51, 0.64]	Not significant
					Instrumental Activities of Daily Living	6	Not mentioned	$g = -0.24$ [−0.50, 0.02]	Not significant
Wu et al. (2020)[e]	VR	15 RCTs published before 2019	612	MCI	Global cognition	13 RCTs	515	$d = 0.869$ [0.33, 1.41][c]	Significantly improved
					Executive function	6 RCTs	184	$d = 1.08$ [0.13, 2.03][c]	Significantly improved
					Short-term memory	3 RCTs	131	$d = 0.49$ [−0.11, 1.08][c]	Not significantly improved
					Long-term memory	4 (without outlier)	152	$d = 0.34$ [−1.19, 0.86][c]	Not significantly improved
Zhong et al. (2021)[e]	VR	17 RCTs published before 2021	744	MCI	Global cognition (MoCA)	8 (with outliers)	368	$d = 1.17$ [0.93, 1.41][c]	Significantly improved
						3 (without outliers)	120	$d = 0.42$ [0.04, 0.79][c]	Significantly improved
					Global cognition (MMSE)	5 (with outliers)	248	$d = 0.93$ [0.64, 1.22][c]	Not significantly improved
						3 (without outliers)	128	$d = 0.09$ [−0.26, 0.44][c]	Not significantly improved
					Executive function (Trail A)	Seven RCTs	325	$d = -0.58$ [−0.80, −0.35][c]	Significantly improved
					Executive function (Trail B)	8 (with outliers)	403	$d = -0.33$ [−0.54, −0.13][c]	Significantly improved

(Continues)

TABLE 2 (Continued)

Study	Type of technology	Total number of studies included	Sample size	Clinical condition	Domain	Number of studies assessed	Number of participants assessed	Pooled effect size [CI]	Comments/additional information
						5 (without outliers)	262	$d = -0.07$ [−0.31, 0.18][c]	Not significantly improved
					Delayed memory	5	164	$d = 0.31$ [−0.05, 0.68][c]	Not significantly improved
					Immediate memory	7 (with outliers)	303	$d = 0.22$ [−0.01,0.45][c]	Not significantly improved
						4 (without outliers)	194	$d = 0.00$ [−0.28, 0.29][c]	Not significantly improved
					Attention (DSF)	3 (with outlier)	140	$d = 0.60$ [0.25, 0.96][c]	Significantly improved
						2 (without outlier)	62	$d = -0.24$ [−0.75, 0.26][c]	Not significantly improved
					Attention (DSB)	3 (with outlier)	140	$d = 0.78$ [0.42, 1.13][c]	Significantly improved
						2 (without outlier)	62	$d = 0.03$ [−0.47, 0.53][c]	Not significantly improved
					Instrumental activities of daily living	3 (with outlier)	98	$d = -0.01$ [−0.41, 0.39][c]	Not significantly improved
						2 (without outlier)	54	$d = 0.40$ [−0.14,0.94][c]	Not significantly improved

Note: MCI = mild cognitive impairment; CI = confidence interval; VR = virtual reality; RCT = randomized controlled trials; g = Hedges' g; d = Cohen's d; η_p^2 = partial eta-squared; MoCA = Montreal Cognitive Assessment; MMSE = Mini-Mental State Exam; Trail A = Trail Making Test A; Trail B = Trail Making Test B; DSF = Forward Digit Span Test; DSB = Backward Digit Span Test.

[a]A systematic review.

[b]A systematic review with meta-analysis.

[c]Pooled effect size was not calculated in the systematic review or scoping review.

[d]Pooled effect size was not calculated because there was only one study assessed this domain.

[e]The authors of this study reported the effect using the term SMD (standard mean difference), which is also known as Cohen's *d*.

(i.e., divided attention) than the traditionally trained group, probably due to the characteristics and attractiveness of the VR environment. A few interventions using robots have also found positive results on the cognitive function of older adults with MCI. In a small-scale within-subjects study, a 4-week piano-learning intervention led by a Musical Assistive Robot Instructor improved executive function and verbal memory in MCI patients (Mois et al., 2020). In addition, Park et al. (2021) performed an RCT in older adults with MCI or subjective memory complaints, which showed that both the robot-assisted group and the paper–pencil training group had improved global cognition, suggesting that VR is comparable to traditional training.

Cavallo et al. (2016) reported that the beneficial effects of Brainer1 on memory, language, and executive function in AD patients were maintained at 6 months post-training (Cavallo et al., 2016). At a 12-month follow-up, the control participants' cognition had continued to decline below the baseline performance, whereas Brainer1 participants, who had previously benefited from the sustained training effect, had showed a decline that reached the baseline level (Cavallo & Angilletta, 2019). This suggests that computerized training programs can delay the progression of cognitive deterioration in AD patients.

Taken together, these findings indicate that technology-based cognitive interventions have comparable or even better effects than traditional interventions in both the short and long term in older adults. Moreover, the current technologies are useful for cognitively healthy older adults and for those with MCI or dementia. However, this does not suggest that applying technologies to interventions would invariably be useful, as technologies' effects on cognition can be influenced by factors such as their acceptance by older adults' and the content and duration of interventions.

It is essential to understand older adults' perceptions, experiences and acceptance of technology-based cognitive interventions. According to the Technology Acceptance Model, older adults' perceptions of the usefulness and ease of use of a technology influence their decision to using the technology (Venkatesh & Davis, 2000). In general, older adults accept the use of technologies in interventions and they are satisfied with the experience. A systematic review reported that older adults enjoy immersive VR (Clay et al., 2020), and Manca et al. (2021) found that older adults felt that the humanoid robot was their friend and that it helped motivate them to participate in training. However, some older adults have had negative experiences with using technologies. For example, some older adults were frustrated because Brain Age was unable to recognize their speech or handwriting, and marked their responses as wrong (Boot et al., 2013). Another study reported that older adults experienced immersive VR-related cybersickness (Bauer & Andringa, 2020).

WHAT COULD FUTURE STUDIES EXPLORE?

Limitations of previous empirical studies

The first limitation of the reviewed studies is the low quality of their evidence, due to their lack of blinding of the assessors and participants, unclear allocation concealment, and lack of control groups (Bonnechère et al., 2020; Gates, et al. 2019a, 2019b; Wang et al., 2021). The second limitation is a lack of investigation of the long-term effects of such interventions. As only a few studies have assessed intervention effects at 1 year or more after the interventions (Cavallo & Angilletta, 2019; Eggenberger et al., 2015; Hughes et al., 2014), it is unclear how long the effects would last. The third limitation is that most studies have focused on the young-old (i.e., those aged between 60 and 70 years), and thus it remains unclear whether the current technology-based interventions would similarly improve cognition in the old-old (i.e., those aged above 75 years). To address these limitations, future studies should blind the assessors and participants, include active and/or passive control groups for comparison, ensure allocation concealment and conduct one or more follow-ups after the interventions.

Challenges in applying technologies

Overuse of and dependence on technologies, especially VR and robots, are possible. Advances in technology and "real" multisensory interactive experiences have led to the development of highly authentic fully immersive virtual environments. Similarly, humanoid robots can now display and imitate human interactions by expressing human emotions, displaying appropriate body language, and showing empathy to the users. Thus, older adults may be reluctant to leave a realistic virtual world or may become heavily dependent on robots for social interactions. In particular, older adults with cognitive impairment may become confused about what is "real" and unable to discriminate reality from VR (Clay et al., 2020; Vogan et al., 2020). Therefore, researchers and practitioners must use regular follow-up sessions to closely monitor participants' conditions and their dependence on the technologies used, to prevent older adults' losing their sense of reality. Future research should also examine the optimal frequency and duration of VR and robot-assisted interventions for this population to prevent overuse and dependence.

The application of technologies in interventions is also subject to the acceptance by practitioners and caregivers. In one study, the general public and caregivers expressed concerns about human caregiving being replaced with robotic companionship, and refused to participate in the subsequent trials (Yuan et al., 2022). In another study, care centers expressed that their services cannot be replaced by technology-based cognitive interventions (Monteiro-Junior et al., 2017). Cooperation between researchers, practitioners, technology companies, older adults and their family members is important to foster development in this field. Researchers should organize workshops to educate practitioners and caregivers about the rationale and potential benefits of technology-based cognitive interventions, clarifying that the technologies are supplementary to the current practices and not replacements for human communications. Practitioners should also share their concerns and usual practices in care centers, to facilitate the implementation of interventions. Finally, technology companies could design older adult-friendly technological elements for interventions, based on empirical evidence, for example, large font sizes, easy-to-understand designs, and feedback-driven programs.

Future avenues of research

To move the field forward, future research should proceed in the following directions. First, more studies are needed to examine the generalizability of technology-based cognitive interventions. The ultimate objective is to improve the cognitive abilities of older adults that are transferrable to functional independence and everyday activities. Thus, in addition to laboratory-based tasks, future studies should consider adopting ecological tasks like Rose et al. (2015), which could clarify the effectiveness and generalizability of technology-based cognitive interventions.

Second, neuroimaging studies should be conducted to corroborate behavioral evidence and uncover the underlying neural mechanisms of technology-based cognitive interventions. In particular, it remains unclear how the enriched environments and stimulation created by advanced technologies can result in neuroplasticity and whether the induced neuroplasticity remains or diminishes after the termination of interventions. To effectively measure the neural effects of technology-based cognitive interventions, for instance, West et al. (2017) suggested measuring brain-derived neurotrophic factor, a protein involved in neuroplasticity and neuronal survival and growth.

Finally, interventions involving different technologies should be developed and tested. In a recent study (Cohavi & Levi-Tzedek, 2022), participants suggested alternating between a VR environment and a social robot for maintaining engagement and interest over time. Thus, future research should investigate whether including both VR and robot-assisted sessions substantially enhances older adults' cognitive function. Moreover, future research can also examine the potential to conduct technology-based cognitive interventions with non-invasive brain stimulations using transcranial magnetic stimulation (TMS) or transcranial direct current stimulation (tDCS), either simultaneously or in alternating sessions. This would be particularly helpful to examine intervention effects in older adults who are physically and/or cognitively impaired, such as those in wheelchairs and those who are unable to perform upper and lower body movements in VR interventions. Hence, using a combination of brain stimulation techniques, a larger proportion of the older adult population could benefit than is currently possible.

CONCLUSION

Current technology-based interventions, such as computerized cognitive training, VR interventions and robot-assisted interventions, generally enhance cognition in both healthy and clinical populations of older adults. Nevertheless, interventions affect different cognitive domains, which likely depends on an intervention's features and older adults' perceptions and experiences of the technologies used. Researchers should therefore understand the characteristics of a technology and programs, identify the needs and interests of older adults and then prescribe the most suitable "medicine" (technology-based intervention). In studies examining the effectiveness of technology-based interventions, aside from assessing performance in older adults' cognitive tasks, it is also important to assess their perceptions, experiences and acceptance of the technologies being applied. In addition, well-designed large-scale studies with longer follow-ups are warranted, as are studies exploring the effectiveness, generalizability and neural correlates of technology-based interventions. Investigating the potential of alternating between different technologies and platforms is also an exciting future direction for research in this field.

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CONFLICT OF INTEREST

All authors declare no conflicts of interest.

ETHICS STATEMENT

Ethics approval was not required for this review paper.

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