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Computerized Cognitive Rehabilitation of Attention and Executive Function in Acquired Brain Injury: A Systematic Review

Yelena Bogdanova, PhD; Megan K. Yee, MA; Vivian T. Ho, BS; Keith D. Cicerone, PhD

Objective: Comprehensive review of the use of computerized treatment as a rehabilitation tool for attention and executive function in adults (aged 18 years or older) who suffered an acquired brain injury. **Design:** Systematic review of empirical research. **Main Measures:** Two reviewers independently assessed articles using the methodological quality criteria of Cicerone et al. Data extracted included sample size, diagnosis, intervention information, treatment schedule, assessment methods, and outcome measures. **Results:** A literature review (PubMed, EMBASE, Ovid, Cochrane, PsychINFO, CINAHL) generated a total of 4931 publications. Twenty-eight studies using computerized cognitive interventions targeting attention and executive functions were included in this review. In 23 studies, significant improvements in attention and executive function subsequent to training were reported; in the remaining 5, promising trends were observed. **Conclusions:** Preliminary evidence suggests improvements in cognitive function following computerized rehabilitation for acquired brain injury populations including traumatic brain injury and stroke. Further studies are needed to address methodological issues (eg, small sample size, inadequate control groups) and to inform development of guidelines and standardized protocols. **Key words:** *ABI*, *attention*, *cognitive rehabilitation*, *computerized intervention*, *executive function*, *stroke*, *traumatic brain injury*

ACQUIRED BRAIN INJURY (ABI), including traumatic brain injury (TBI) and stroke, presents significant personal and public health concerns. Approximately 1.74 million TBIs requiring a physician visit occur each year in the United States, and an estimated 6.8 million Americans older than 20 years have had a stroke. Some 3.1 million individuals in this country are living with ABI-related lifelong disability, incurring an estimated $76.5 billion dollars in direct medical and indirect costs.[1] Persistent cognitive deficits are common following ABI, particularly in executive functioning, attention, and learning.[2–4] These multiple cognitive deficits, coupled with other frequently associated neuropsychiatric or motor symptoms, have a detrimental effect on functional status and may lead to disability.[5–7] Improvement of executive abilities and attentional capacity also contributes to recovery in other functional domains[8,9] and may significantly reduce disability and improve quality

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Ms Yee is the co-first author.

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Y.B. and M.K.Y. contributed equally to the manuscript. Y.B. and M.K.Y. designed the study and developed the search strategies. M.K.Y., Y.B., and V.T.H. conducted literature searches, assessed the articles, and provided methodological quality ratings and summaries of research findings, with supervision from Y.B. M.KY. and Y.B. wrote the first draft of the manuscript. Y.B., K.D.C., and M.K.Y. completed the review and revised the manuscript. All authors contributed to interpretation of the literature and revision of the manuscript, and all have approved the final manuscript.

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of life in individuals with ABI. However, rehabilitation of patients with executive dysfunction is especially challenging due to poor insight, lack of mental flexibility necessary to adapt to changes, and impoverished planning abilities.[6]

Computerized cognitive programs to train executive functions and attention have gained popularity recently, most notably in aging populations in an effort to stave off cognitive decline and potentially enhance cognitive functioning. A large multisite randomized controlled double-blinded study, the Improvement in Memory with Plasticity-based Adaptive Cognitive Training (IMPACT), compared a brain plasticity-based computerized cognitive training program with a general computerized cognitive stimulation program in healthy, aged participants. Following self-administered at-home training, the brain-plasticity group outperformed the cognitive stimulation group on the primary outcome measure, the Auditory Memory/Attention subtest from the Repeatable Battery for the Assessment of Neuropsychological Status, and on trained and nontrained secondary outcome measures of attention and memory.[10] Greater improvements in secondary outcome measures, including processing speed and working memory, were maintained at a 3-month follow-up.[11]

Similar results have been reported by other studies of computerized cognitive training in healthy older adults. Participants using a personalized cognitive computer training program demonstrated significantly greater improvements compared with participants playing conventional computer games on measures of visuospatial working memory, visuospatial learning, and focused attention, with similar trends in 5 other cognitive domains.[12] Similarly, Nouchi et al[13] showed significantly greater improvements on measures of executive functioning and processing speed in healthy older adults playing Brain Age, a game composed of tasks and exercises aimed to improve cognitive functioning, compared with a conventional low-level Tetris game control group.

Nouchi et al[14] also demonstrated cognitive improvements in young adults using Brain Age on tests of executive function, working memory, and processing speed, compared with a Tetris game control group. Brehmer et al[15] found significant cognitive improvements on tasks of attention and executive functioning following a computerized working memory training program in both young adults and older adults immediately after intervention and 3 months later, compared with an active control group using the same computer program set at a low-task difficulty level. The experimental young adult group demonstrated higher training and transfer gains on Span Board backward, Paced Auditory Serial Addition Test (PASAT), Stroop, Rey Auditory Verbal Learning Test, and Raven Standard Progressive Matrices than the experimental older group, but both age groups improved similarly on Digit Span forward.

Current literature suggests that computerized training can improve cognition in healthy older adults experiencing age-associated cognitive decline and in younger and middle-aged populations who have yet to experience changes associated with aging.[16] It stands to reason that similar training programs could be beneficial for persons with ABI who are experiencing significant deficits and, therefore, have greater potential to improve. However, no standardized computerized rehabilitation tool has been developed, and no comprehensive review has been published on the use of computerized treatment programs as a rehabilitation tool for attention and executive function in ABI. One systematic review and meta-analysis demonstrated promising results for patients poststroke using computer-based cognitive and virtual reality programs. However, the review was limited to 12 articles, with only 2 studies utilizing computer-based training.[17,18] The remaining articles focused on virtual reality interventions and simulator-based programs.[19]

It is important to evaluate the efficacy of computerized cognitive training programs and to provide specific guidelines for computerized methods of rehabilitation in the ABI population, given the potential to reduce cost and increase accessibility of treatment to traditionally underserved populations/areas. To close the gap in the literature, we conducted a systematic review of empirical research on computerized cognitive rehabilitation for attention and executive function in ABI. In addition, recommendations for future research and clinical implications are discussed.

METHODS

Literature search and study selection

A literature search was conducted using PubMed, EMBASE, Ovid, Cochrane, PsychINFO, and CINAHL, identifying articles with the following key terms: "cognitive rehabilitation," "traumatic brain injury," "executive functioning," "attention," "acquired brain injury," "stroke," "computerized cognitive rehabilitation," "cognitive impairments," and "computer assisted rehabilitation." Articles published before or during April 2015 were considered, as no previous reviews have been completed. A detailed flowchart of the literature search is depicted in Figure 1.

Participants are adults (at least 18 years of age) who have experienced an ABI such as TBI or stroke of any severity. Articles using computerized cognitive interventions targeting attention and executive functions were included in this review. Interventions had to be delivered by a computer system and involve interacting and using the program via a computer. Treatments using

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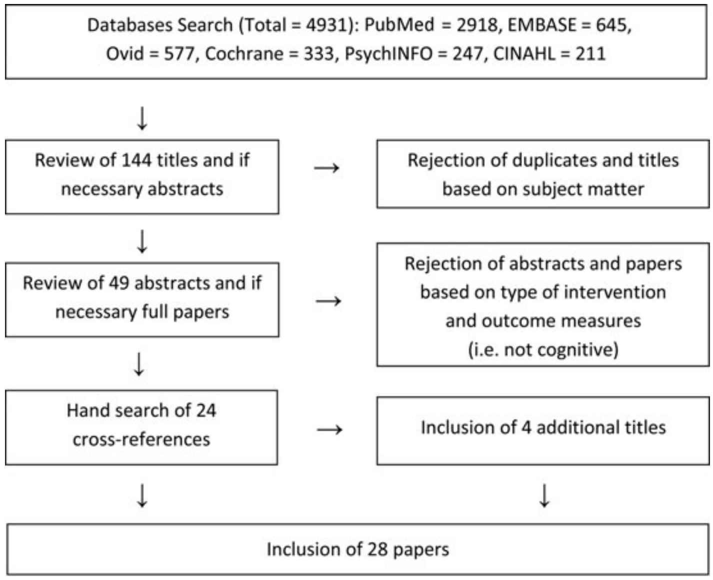

Figure 1. Search process.

computers for online video chat programs (eg, telerehabilitation or teletherapy) were not included, nor were virtual reality interventions or interventions simulating specific real-world situations (reviewed elsewhere).[19,20] Studies utilizing computerized interventions to treat other symptoms following ABI (eg, improving motor function or mobility) were also excluded. There were no exclusion criteria for number of subjects or study design.

The initial search yielded 4931 articles, which was reduced to 144 potential articles after duplicates were removed and articles not related to the topic were rejected. Following further review of titles and abstracts, 49 articles remained. Twenty-four articles remained after full articles were evaluated for intervention type and outcome measures. References for these articles were hand checked, and 4 additional articles were identified for a total of 28 studies in this review.

Quality assessment

The criteria described in the study by Cicerone et al[21] were used to evaluate the quality and methodology of the 28 articles. Two trained assessors independently reviewed each article, and any disagreements were resolved with the help of a third reviewer. Each article was assigned a class depending on the strength of its research design.[22] Class I evidence includes prospective randomized controlled trials. Randomized controlled trials with quasi-randomization of participants are considered class Ia studies. Class II evidence includes prospective nonrandomized cohort studies, retrospective nonrandomized case control studies, and clinical series with controls that are well-designed. Class III evidence includes clinical series without concurrent controls and case studies.

RESULTS

Study characteristics

A total of 28 articles were reviewed (see Table 1). Nine articles met criteria for class I studies, with 3 more qualifying as class Ia. Of those articles, 3 articles addressed TBI, 4 addressed stroke, and 5 involved a mixed population. There were 9 studies that qualified as class II evidence, 5 of which were on TBI, 1 was on stroke, and 3 included mixed populations. The remaining 7 studies were rated as class III evidence. Three of these examined TBI and 4 studied mixed populations.

Patient characteristics

In total, there were 768 participants. Sample size for each study varied widely from 1 to 103 participants. Approximately half of the sample was male (429), but 3 studies did not report on gender. The age range was wide (20s to 70s) as was time since injury (14 days to 7 years).

Interventions

A wide variety of interventions were employed, as most programs were unique to the study. No standardized computerized training protocols were used, with most studies utilizing various attention- and executive function-focused treatment programs specifically created or modified for the study. Only one working memory treatment program, Cogmed QM (originally called RoboMemo, developed by Cogmed Cognitive Medical Systems AB, Stockholm, Sweden), was utilized in multiple (5) studies.[18,23,25,32,36]

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TABLE 1 *Quality criteria ratings*

	Internal Validity								Descriptive					Statistical		
Study	Eligibility criteria specified	Method of randomization described	Treatment allocation concealed	Similarity of baseline characteristics	Treatment and control interventions described	Cointerventions avoided or equivalent	Outcome measures blinded	Outcomes measures relevant	Withdrawal and dropout rates described and acceptable	Short-term outcomes measured	Long-term outcomes measured	Timing of outcome measures equivalent	Sample size described	ITT analysis	Point estimates and variability provided	Statistical comparison of treatment effects
Akerlund et al[23]	X	X		X	X	X		X	X	X		X	X		X	X
Batchelor et al[24]	X							X		X			X		X	X
Bjorkdahl et al[25]	X			X	X			X	X	X	X	X	X		X	
Chen et al[26]	X							X		X			X		X	X
De Luca et al[27]	X			X	X			X	X	X		X	X		X	X
Fernandez et al[28]	X				X			X	X	X		X	X		X	
Gauggel and Niemann[29]	X			X	X			X	X	X		X	X			
Gray and Robertson[30]					X			X	X	X			X			
Gray et al[31]	X	X		X	X			X		X	X		X		X	X
Johansson and Tornmalm[32]	X				X	X		X	X	X	X	X	X		X	
Kim et al[33]	X			X	X			X		X		X	X		X	X
Lebowitz et al[34]	X				X			X	X	X		X	X		X	
Li et al[35]	X				X			X	X	X			X		X	
Lundqvist et al[36]	X	X		X	X			X	X	X	X	X	X		X	
Man et al[37]	X		X	X	X		X	X	X	X		X	X		X	X
Middleton et al[38]					X	X		X		X		X			X	X
Niemann et al[39]	X			X	X			X	X	X		X	X		X	X
Park et al[40]				X	X	X	X	X		X			X		X	X
Ponsford and Kinsella[41]	X			X	X			X	X	X		X	X			X
Prokopenko et al[42]	X	X	X	X	X	X	X	X	X	X		X	X		X	X
Ruff et al[43]	X			X	X			X	X	X		X	X		X	X
Ruff et al[44]	X				X			X	X	X			X		X	
Serino et al[45]	X			X	X		X	X		X		X	X		X	
Sohlberg[46]				X	X			X	X	X			X			
Sturm and Willmes[17]					X			X	X	X		X	X		X	
Westerberg et al[18]	X	X		X	X			X	X	X		X	X		X	X
Wood and Fussey[47]	X			X	X	X		X	X	X		X	X		X	X
Zickefoose et al[48]	X				X			X		X		X	X		X	

Abbreviation: ITT, intent-to-treat.

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TABLE 2 *Study and participant characteristics*

First author	Class	*N*	Etiology and time since injury	Mean age (y)	Intervention type	Control condition	Types of outcomes	Follow-up	Results
Akerlund et al[23]	I	45	Mixed 27.8 wk	51.9	CogMed QM	Conventional rehabilitation	Standard NP measures, self-report rating	3 mo	Significant differences on measures of attention and working memory, neuropsychological impairment, depression
Batchelor et al[24]	Ia	34	TBI 84.5 d	24.4	Remediation of deficits in memory, attention/ speed, high cognitive functioning	Conventional rehabilitation	Standard NP measures	None	Both groups improved significantly on NP measures (no differences between groups)
Bjorkdahl et al[25]	II	38	Mixed 27 wk	51	CogMed QM	Conventional rehabilitation	Standard NP measures, self-report ratings	3 mo	Significant improvements in attention, executive functioning, working memory, fatigue
Chen et al[26]	II	40	TBI 8.6 mo	28.2	Hierarchical computer-assisted cognitive rehabilitation	Conventional rehabilitation	Standard NP measures	None	The CACR group improved on more measures compared with control (15 vs 7 measures)
De Luca et al[27]	II	35	Mixed 3-6 mo	35.3	Training in memory, executive functions, abilities of thinking	Conventional rehabilitation	Standard NP measures, self-report ratings	None	Experimental group improved significantly more than the control group on all NP measures and self-reports
Fernandez et al[28]	III	50	Mixed >50% sample 1-5 y	68% aged 20-39 y	RehaCom	None	Standard NP measures	None	Significant improvements on WMS scales

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TABLE 2 *Study and participant characteristics* (Continued)

First author	Class	*N*	Etiology and time since injury	Mean age (y)	Intervention type	Control condition	Types of outcomes	Follow-up	Results
Gauggel and Niemann[29]	III	4	Mixed 1.5 mo	47.5	Computer-assisted training program	None	Standard NP measures, self-report ratings	None	Improvement trends were seen on attention and memory tests
Gray and Robertson[30]	III	3	TBI Unknown	23	Microcomputer training	None	Standard NP measures	None	Two patients improved on all NP measures by at least 1 SD
Gray et al[31]	I	31	Mixed 81.3 wk	29.8	5 computer training programs: reaction time, rapid number comparison, digit symbol transfer, alternation Stroop programme, divided attention task	Nontraining computer games/tasks	Standard NP measures	6 mo	The experimental group performed better on auditory verbal working memory and attention at 6 mo follow-up
Johansson and Tornmalm[32]	III	18	Mixed 7 y	47.5	CogMed QM	None	Cognitive measures, self-report ratings, clinician ratings	6 mo	Significant improvements on self-report measures of cognition after treatment and at follow-up
Kim et al[33]	I	28	Stroke 20.9 d	64.4	Computer-assisted rehabilitation and virtual reality training	Computer-assisted training alone	Standard NP measures, self-report ratings	None	Both groups improved, but the combined performed better on some NP measures

(*continues*)

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TABLE 2 *Study and participant characteristics* (Continued)

First author	Class	*N*	Etiology and time since injury	Mean age (y)	Intervention type	Control condition	Types of outcomes	Follow-up	Results
Lebowitz et al[34]	III	10	TBI 9.4 y	46.3	Brain plasticity-based cognitive training	None	Standard NP measures, self-report ratings	None	Significant changes on attention measures and on self-reported cognition
Li et al[35]	III	11	Mixed 21.27 mo	49.45	Attention and memory programs from Parrot software	None	Standard NP measures	None	Significant improvements on attention and memory measures
Lundqvist et al[36]	II	21	Mixed 46.4 mo	43.3	CogMed QM	Waitlist	Standard NP measures, self-report ratings	20 wk	Significant improvements on nontrained working memory tasks, self-reported cognition, and health after treatment and at follow-up
Man et al[37]	I	103	Mixed 4.0 y	44.8	Computer-assisted training program administered online or supplemented by support from therapist	No treatment or therapist-administered training	Standard NP measures, self-report ratings	None	Both groups significantly improved on problem-solving abilities and self-reported functional abilities
Middleton et al[38]	III	36	Mixed 3.0 y	27	Attention and memory training software or reasoning and logical thinking software	None	Standard NP measures	None	Both groups demonstrated similar significant improvements on NP measures posttesting
Niemann et al[39]	I	26	TBI 39.1 mo	31.6	Attentional training program	Memory training program	Standard NP measures	None	Attention group performed significantly better on measures of attention (memory group did not perform better on memory measures)

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TABLE 2 *Study and participant characteristics* (Continued)

First author	Class	*N*	Etiology and time since injury	Mean age (y)	Intervention type	Control condition	Types of outcomes	Follow-up	Results
Park et al[40]	I	11	Stroke 27.3 d	65.6	Korean computer-assisted cognitive rehabilitation with real tDCS	Korean computer-assisted cognitive rehabilitation with sham tDCS	Standard NP measures	None	Significant differences on auditory and visual measures of attention and executive functioning
Ponsford and Kinsella[41]	II	26	TBI ≤9 mo	25.3	Computer programs: react, search, red square/green square, spot the letter, evens and fives	Not specified	Standard NP measures, cognitive measures, clinician ratings	None	Improvements were seen in memory, but they could not be directly attributed to the training program
Prokopenko et al[42]	I	43	Stroke ≤14 d	63.2	Computer programs for attention and visual and spatial gnosis	Conventional rehabilitation	Standard NP measures, self-report ratings, clinician ratings	None	Significantly better performance in attention and self-reported cognition
Ruff et al[43]	I	40	TBI 45.3 d	30.8	Computer training: attention, spatial integration, memory, problem solving	Psychosocial adjustment, leisure, and activities of daily living	Standard NP measures	None	Trends suggesting experimental group had greater improvement in memory and attention
Ruff et al[44]	II	15	TBI > 6 mo	26.9	THINKable computer program	None	Standard NP measures, self-report ratings	None	Small significant improvements on training tasks and NP measures
Serino et al[45]	II	9	TBI 28 mo	34	Working memory training program based on PASAT	General stimulation training	Standard NP measures, self-report ratings	None	Significant improvements on working memory, divided attention, executive functions, long-term memory, and questionnaire measures; the control group did not improve

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TABLE 2 *Study and participant characteristics* (Continued)

First author	Class	*N*	Etiology and time since injury	Mean age (y)	Intervention type	Control condition	Types of outcomes	Follow-up	Results
Sohlberg and Mateer[46]	II	4	Mixed 36.5 mo	28	Program for 5 levels of attention: focused, sustained, selective, alternation, divided	None	Standard NP measures, self-report ratings	None	All participants improved on measures of attention, but not all were statistically significant
Sturm and Willmes[17]	II	35	Stroke 14.7 mo	50.7	WDG and Cognitrone	None	Cognitive measures	6 wk	Significant improvements on measures of attention
Westerberg et al[18]	I	18	Stroke 20.1 mo	54	RoboMemo software	No treatment	Standard NP measures, self-report ratings	None	Significantly better on measures of attention and executive functioning
Wood and Fussey[47]	II	30	TBI Unknown	28.3	Computer training with visual scanning, perceptual discrimination, judgment and anticipation, motor response	No treatment and conventional rehabilitation	Cognitive measures, behavior recordings	Unknown	Significant changes on behavioral measures between baseline and posttesting, and changes on choice reaction test seen at follow-up
Zickefoose et al[48]	III	4	TBI ≥3 y	42.75	Attention training (APT-3 or Lumosity games)	None	Standard NP measures, self-report ratings	None	Improvements on difficulty level of task and general improvement on attention, but large variability between participants

Abbreviations: APT-3, Attention Process Training; CACR, computer-assisted cognitive rehabilitation; NP, neuropsychological; PASAT, Paced Auditory Serial Addition Test; SD, standard deviation; TBI, traumatic brain injury; tDCS, transcranial direct-current stimulation; WDG, Wiener Determinationsgerat; WMS, Wechsler Memory Scale.

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Outcome measures

Common outcome measures included standardized neuropsychological tests and behavioral questionnaires. Most measures focused on attention, executive function, activities of daily living, and self-efficacy, but assessment batteries varied greatly between studies. Change in performance on treatment tasks was also used as an outcome measure for some studies. A summary of study and participant characteristics is presented in Table 2.

Traumatic brain injury

Acute TBI

Two class Ia studies met the criteria for an acute TBI (time post-TBI <6 months).[24,43] Ruff et al[43] trained participants in attention, spatial integration, memory, and problem solving and compared them with a psychoeducational treatment group. The experimental group demonstrated improvements in encoding of verbal information and more consistency in retrieval, as well as improvement on a visual-spatial memory task (Rey-Osterrieth Complex Figure Test) and differential gains in accuracy of selective attention. In a second study, participants were trained in verbal and nonverbal recent memory, attention/speed, and higher cognitive functioning either on a computer or conventional rehabilitation. Trainings included activities specifically designed to promote organization, planning, flexibility, concept formation, reasoning, and problem solving. The groups performed comparably, but within-groups analyses revealed significant improvements on measures of attention, memory, and executive functioning.[24]

Chronic TBI

One class I study, 4 class II studies, and 2 class III studies met criteria for chronic TBI (time post-TBI >6 months).[26,34,39,41,44,45,48] A class I study compared computerized attention training with a paper-and-pencil memory training control group. The computerized attention training program focused on visual, auditory, and divided attention, with task difficulty varying depending on number of stimuli, similarity between targets and distractors, and interstimulus intervals. Compared with the memory training group, the attention training group improved significantly more on attention measures such as Trail Making B.[39]

Ruff et al[44] administered attention and memory training with the THINKable program utilizing a crossover-type design and found significant improvements on tasks of attention and memory such as Digit Symbol, Corsi Block, and on the Rey Auditory Verbal Learning Test. In another class II study, participants improved on 15 measures of attention, visuospatial functioning, memory, and problem solving subsequent to computer training compared with a conventional rehabilitation group. The training program–computer-assisted cognitive rehabilitation–arranged the trainings in a hierarchical manner with tasks increasing in complexity over time.[26] Similarly, Serino et al[45] demonstrated significant improvements in working memory, divided attention, and executive function compared with a general stimulation control group following a training program based on the PASAT. Ponsford and Kinsella[41] also utilized a computer program composed of tasks that measure both accuracy and speed of responses over time. They noted steady improvements in attention but felt that they could not attribute it directly to the treatment program.

In a class III study, participants were trained on a computer program resembling computer games that increased in speed and complexity as the user's performance improved. There was no control group, but within-group analysis revealed small effect sizes in simple reaction time, matching to sample (a measure of spatial processing and visuospatial working memory), code substitution (a measure of encoding and memory), scores on the Frontal Systems Behaviour Scale, and scores on the Cognitive Failures Questionnaire.[34] Zickefoose et al[48] compared 2 computer training programs, Attention Process Training-3 and Lumosity, in a crossover trial. Attention Process Training-3 is a hierarchy-based program increasing in difficulty level that trains 5 types of attention: sustained, selective, working, suppression, and alternating. Lumosity, available on the Internet, provides games that adjust in complexity on the basis of performance and are designed to improve cognitive processing speed, flexibility, attention, memory, and problem-solving skills. Following a month of treatment, a generalization in improvement of attention as well as an increase in task difficulty was seen in all participants regardless of which training program they received initially.

Unspecified TBI

One class II study and 1 class III study did not specify chronicity of TBI.[30,47] A class II study utilized a computer training program that incorporated visual scanning, perceptual discrimination, judgment and anticipation, and motor response, compared with both conventional rehabilitation controls and a no-treatment control group. Significant improvements were noted on behavioral measures of attention in the computer training group as well as improvements on the choice-reaction test, although the authors questioned its significance.[47] Gray and Robertson,[30] in a class III study, reported 3 cases each of whom received an individualized computer treatment program. They found that 2 of the 3 cases demonstrated improvement

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of at least 1 standard deviation on outcome measures of attention and executive function such as Wisconsin Card Sorting Test, PASAT, and Digit Span.

Stroke

Acute stroke

Three studies, all rated class I, met the criteria for acute stroke (time poststroke <6 months).[33,40,42] One study investigated the effects of a computerized cognitive rehabilitation program in comparison with a conventional rehabilitation group intervention. The program focused on attention, visual and spatial gnosis, and visual and spatial memory using Schulte's tables, figure background tasks, and grid memory tasks. Participants in both treatment and control groups improved on general measures of cognition such as the Montreal Cognitive Assessment and on Schulte test. However, the experimental group also demonstrated within-group changes on the Mini-Mental Status Exam, the Frontal Assessment Battery, and the Clock Drawing Test. Furthermore, the experimental group improved significantly more than the control group on the Frontal Assessment Battery, the Clock Drawing Test, and Schulte's tables.[42]

Two studies evaluated the effectiveness of computerized cognitive rehabilitation in conjunction with other treatment modalities, virtual reality, and neuromodulation. Kim et al[33] compared a computerized rehabilitation program alone with a combination of the computerized rehabilitation program and a virtual reality program. The computerized rehabilitation program focused on attention and memory and increased in difficulty as the training level advanced. Following training, both groups improved on the Korean- Mini-Mental Status Exam and on measures from the Computerized Neurocognitive Testing. However, the group receiving the combined programs performed significantly better on 2 measures of the Computerized Neurocognitive Testing than those who received only the computerized rehabilitation. Park et al[40] combined computerized training for attention and memory with real or sham neuromodulation intervention, transcranial direct-current stimulation. The group receiving real transcranial direct-current stimulation had significantly higher scores on 2 measures of the Computerized Neurocognitive Testing, auditory and visual Continuous Performance Test, than the sham transcranial direct-current stimulation group.

Chronic stroke

Two studies, 1 class I and 1 class II, met criteria for chronic stroke (time poststroke >6 months).[17,18] One class I study compared a no-treatment control group with an experimental group using the RoboMemo software (now known as CogMed QM). The program included a multitude of tasks requiring the maintenance of attention to multiple stimuli, short delays where stimuli had to be held in working memory, and unique sequencing of stimuli in each trial. The difficulty level of tasks changed according to individual performance. Subsequent to training, the working memory group performed significantly better than the control group on tests of attention, specifically on span board, Digit Span, PASAT, and RUFF 2&7 Selective Attention Test, and reported significantly fewer cognitive failures on the Cognitive Failures Questionnaire.[18] Sturm and Willmes,[17] in a class II study, also reported some improvements in attention tasks following computerized training with another adaptive program that allowed for variations in complexity of stimuli.

Mixed injuries

Acute mixed injuries

One class III study met criteria for acute mixed injuries (time post injury <6 months).[29] Gauggel and Niemann[29] were unable to detect significant training effects in their 4 subjects who participated in a training program focused on alertness and reaction time, vigilance, interference suppression, and selective and divided attention. However, trends toward significance suggested improvements on tests of attention and memory.

Chronic mixed injuries

Four class I studies, 1 class Ia study, 2 class II studies, and 4 class III studies met criteria for chronic mixed injuries (time postinjury >6 months).[23,25,27,28,31,32,35,36,37,38,46] One intervention program, Cogmed QM, was evaluated by 2 class I studies, 1 class Ia study, and a class III study. Cogmed QM, a working memory training program, incorporates visual and verbal/auditory tasks, adjusting difficulty level according to individual performances. In class I studies, Akerlund et al[23] and Lundqvist et al[36] compared experimental groups with a conventional rehabilitation control group and a wait list control group, respectively. Bjorkdahl et al,[25] in a class Ia study, administered CogMed QM in conjunction with a conventional rehabilitation program and noted significant improvements on the Digit Span Reverse and the Fatigue Impact Scale immediately following treatment, compared with the conventional rehabilitation control group whose members did not improve. Improvements remained at the 3-month follow-up on Digit Span Reverse, and an additional improvement not originally present was found on the Working Memory Questionnaire. Johansson and Tornnmalm,[32] in a class III study, did not utilize a control group but demonstrated changes on the Cognitive

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Failures Questionnaire and the Canadian Occupational Performance Measures immediately following treatment and 6 months later. Both Akerlund et al[23] and Lundqvist et al[36] found significantly better performance by the experimental group than that by the controls on measures of attention, working memory, and executive function immediately after treatment and at 4-week follow-up, respectively. Lundqvist et al[36] demonstrated maintenance of effects 20 weeks posttraining on working memory tasks as well as increased satisfaction.

The remaining 2 class I studies and 1 class II study investigated various training programs with mixed results. Gray et al[31] used a training program focusing on reaction time, rapid number comparison, Digit Symbol transfer, Stroop tasks, and divided attention tasks, and compared its participants with an active computer games control group. No significant differences were seen immediately following treatment, but the experimental group performed significantly better at the 6-month follow-up on measures of auditory verbal working memory. Man et al[37] used a problem-solving training program administered either online or on the computer with a therapist and also utilized a conventional rehabilitation control group and a no treatment control group. The 3 treatment groups performed equally well on tests of problem solving and reported similar results on instrumental activities of daily living questionnaires. Sohlberg and Mateer[46] tested an attentional program in 4 subjects and found increased PASAT scores throughout training, but differences failed to reach statistical significance.

Three class III studies found improvements on standardized neuropsychological tests following computer training. Li et al[35] used 8 programs for attention and memory taken from Parrot Software, which were intended to focus on perceptual speed and accuracy as well as cognitive demand. Following treatment, which varied from 2 to 8 weeks, significant improvements on attention and memory scores from the Cognistat Assessment System were reported. Middleton et al[38] compared an attention and memory training program with a reasoning and logical thinking program and found that members of both groups demonstrated similar improvements following treatments on neuropsychological measures of attention, memory, and reasoning. Fernandez et al[28] tested the RehaCom program, which includes various training modules that increase in difficulty as the participant successfully completes easier levels, and found that participant performance improved significantly on Wechsler Memory Scale Subtests.

Unspecified mixed injuries

One class II study, which did not specify chronicity of injury[27] compared conventional rehabilitation with conventional rehabilitation combined with computerized rehabilitation focusing on executive functions, thinking abilities (categorization, identification, problem solving, etc), and memory. Following treatment, the combined group improved on all measures, while the conventional rehabilitation group improved only on functional measures. Between-group analysis revealed that the combined group improved significantly more than the control group.[27]

Adverse effects

One study reported transient adverse effects of training among 50 participants with TBI or stroke. Adverse effects attributable to the therapy included mental fatigue in 14% of patients and headache in 6% during the first 6 sessions. Symptoms resolved in all patients as they progressed with therapy and became more familiar with the procedures.[28] No other studies reported any negative effects of training or decreases in performance following treatment.

CONCLUSION

The results of this systematic review provide encouraging evidence that computerized cognitive rehabilitation can improve attention and executive functioning in survivors of ABI. Eight of 11 studies reported significant gains on outcome measures following treatment in TBI patients, with the 3 remaining studies reporting trends toward significance. Similarly, 10 of 12 mixed-population studies observed significant improvements on outcome measures, with the remaining 2 studies reporting positive trends. The remaining 5 studies all reported significant improvements subsequent to treatment for stroke patients. Overall, most studies support computerized cognitive rehabilitation for attention and executive function in ABI. Although these preliminary results are promising, there are multiple methodological issues that need to be addressed in future studies to further advance the development and utilization of computerized treatment programs in ABI.

A variety of limitations and methodological issues should be noted in many of the studies reviewed, as these may account for the range of the results. A large majority of the studies included small sample sizes, with 26 of the 28 studies having fewer than 50 participants. Some studies had as few as 1 to 4 participants. Small sample studies often lack the power to detect significance, which may account for reported trends and small effect sizes.

It is also important to distinguish between severity of injury and chronicity. Most studies did not specify severity, which significantly reduces the applicability and replicability of their findings, as there are large differences in the treatment goals and learning abilities of patients along the spectrum of ABI severity. This becomes

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particularly problematic when samples combine patients with mild to severe injury in the same group, greatly increasing variance within the sample and thus making it more difficult to interpret the results and to capture clinically and statistically meaningful treatment outcomes. Similarly, efficacy may vary according to chronicity, as the manifestation and severity of symptoms can differ in acute versus chronic stages of an injury.

Differences in control groups, outcome measures, and treatment programs could also account for the variability of the study outcomes. Approximately one-third of the studies (11) did not utilize a control group and compared only changes within subjects. Only 17 studies directly compared experimental treatment effects with a control group outcome. The most common comparators were "no treatment" or "conventional rehabilitation" control groups. Arguably, the best control groups are those using low-level active computer programs (eg, playing nontraining games or doing crosswords on the computer), as they simulate computerized rehabilitation activity without providing targeted treatment. However, only a few studies utilized this type of control.[28,44] Furthermore, only 5 studies using control groups adequately described the method of randomization, and only 4 studies reported masked investigators or study personnel.

Twenty of the 28 studies reported withdrawal and dropout rates, with none having high rates of attrition. No studies reported intent-to-treat analysis. However, it should be noted that an intent-to-treat analysis was not applicable for studies reporting 100% retention rates. Lack of long-term follow-up assessments, relatively short training periods, and inpatient rehabilitation settings likely account for the consistent high retention rates. Still, high retention rates are not synonymous with adherence to protocols, especially when programs are self-administered without supervision. No study reported adherence to protocol rate; this may be an important variable to consider in future studies, as it could significantly affect treatment outcome.

A large variety of outcome measures were used, each testing different aspects of neurocognition. Sixteen studies used both objective and subjective (self-report) measures. Ten studies utilized only objective outcome measures, and the remaining 2 studies used only self-report measures. Some measures may be more sensitive to change, which would make it easier to detect statistically significant outcomes, while others may be unable to capture subtle but functionally significant changes. While the use of standardized neuropsychological measures typically administered in a structured environment such as testing room or an office may provide valuable information, measures reflecting patient functioning within the context of daily life are also important. The development and inclusion of ecologically valid outcome measures is critical for the evaluation and tracking of real-life changes associated with the treatment of ABI.

Another important factor to consider is the role of supervision in the administration of computerized treatment. Previous systematic reviews have suggested that computerized cognitive training should be administered under the supervision of a qualified therapist.[8,22,49] Nine of the 28 studies clearly stated the presence and support of a therapist, 5 of which were the studies utilizing the program Cogmed QM. No study explicitly detailed the exact amount of involvement or interaction that occurred between the therapist and the participant. Future studies should not only evaluate whether the presence of a trained therapist is necessary but also determine other critical aspects of the "therapist-patient-computer program" interaction, such as optimal timing and amount of therapist-guided training.

Another key issue to address in future studies is long-term outcome, as only 4 studies completed the long-term follow-up evaluations, a necessity for determining the durability of the treatment effects.[25,31,32,36] Only 1 treatment program, CogMed QM, was tested by multiple studies,[18,23,25,32,36] while other studies utilized their own individualized programs, using different treatment doses (number and length of treatment sessions) and frequencies. The intensity of training programs (eg, massed vs distributed training) has been shown to influence the extent of improvement in cognitive performance among healthy participants[50] but has not been evaluated in clinical populations. Finally, age of participants and familiarity with computers and computer games may impact rate of improvement. These factors, as well as various statistical issues that fall outside the scope of this review, may affect study outcomes and are important for the interpretation of the results.

The recommendations developed by a consensus study evaluating the effectiveness of cognitive rehabilitation in TBI suggest that further research is needed to define, standardize, and assess outcome measures.[51] Manualized standardized treatment programs and guidelines need to be developed to ensure consistency and accessibility of treatment. These recommendations are directly applicable to computerized cognitive rehabilitation in ABI and should guide future studies and computerized treatment development.

In conclusion, there is evidence that computerized cognitive rehabilitation interventions have beneficial effects on attention and executive functioning in ABI. However, no standardized protocols or guidelines have yet been developed. Further studies, such as controlled randomized clinical trials and long-term follow-up studies, are needed to address multiple methodological issues identified in this review and to develop guidelines and standardized

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protocols. Once developed, it would be important to further assess the effectiveness of home-based treatment delivery, which would greatly increase accessibility to those in need, especially for patients with limited mobility and those residing in rural areas. Systematic research of innovative interventions and methods of treatment delivery targeting specific functional goals and evaluating most optimal and lasting treatment outcomes is needed to provide an evidence base and to inform clinical recommendations for persons with ABI and other neurologically impaired populations.

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