Computer-Based Cognitive Rehabilitation for Individuals With Traumatic Brain Injury: A Systematic Review

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Abstract

Purpose: *The purpose of this review is to evaluate the efficacy of computer-based cognitive rehabilitation (CCR) for improving cognitive and cognitive-communication skills in individuals with traumatic brain injury (TBI).*

Method: *A systematic search using key words related to CCR and TBI was conducted in 11 databases. Studies investigating CCR in children, adolescents, and adults with TBI were identified using a set of predetermined clinical questions, inclusion/exclusion criteria, and search parameters. Studies were evaluated for methodological quality according to American Academy of Neurology guidelines (AAN, 2011).*

Results: *Thirteen studies were included in this review. One study was classified as AAN Class II and 12 were rated as AAN Class III. Results across studies were inconsistent. In addition, studies contained a range of limitations that reduced the confidence of the reported findings.*

Conclusion: *At this time, there is insufficient evidence to support or refute the efficacy of CCR in improving the cognitive or cognitive-communication skills of individuals with TBI. Additional, high-quality research is needed to determine if individuals with TBI will benefit from CCR. Until this occurs, clinicians are encouraged to review existing expert recommendations and engage in practice-based evidence to determine if CCR is appropriate for their individual clients with TBI.*

Traumatic brain injury (TBI) is a major public health problem in the United States, affecting nearly 2.5 million children, adolescents, and adults each year (Faul, Xu, Wald, & Coronado, 2010).

The resulting economic costs are staggering—an estimated $60 billion in direct and indirect medical costs annually (Finkelstein, Corso, & Miller, 2006). When factoring in mental health costs and lost income for caregivers (Bayen et al., 2013), that total is likely much higher.

Among the sequelae of TBI, impairments in cognitive function are one of the most disabling and stressful for an individual with TBI and their family. Deficits in attention, memory, executive functioning, processing speed, social cognition, and cognitive-communication frequently lead to reduced independence and social participation in academic, vocational, and community settings (Zaloshnja, Miller, Langlois, & Selassie, 2005), especially among individuals with more severe injuries.

Encouragingly, cognitive rehabilitation has been shown to be effective for treatment of several types of cognitive deficits resulting from TBI (Cicerone et al., 2011). Practice guidelines generated from systematic reviews (Cicerone et al., 2011) and expert panels (Bayley et al., 2014) detail a number of cognitive rehabilitation practices that are well-supported by evidence from empirical studies.

Unfortunately, individuals with TBI are frequently unable to benefit from these practices due to a lack of access to cognitive rehabilitation services. This lack of access is likely due to several factors, including limited insurance coverage for outpatient rehabilitation therapy, difficulty traveling to and attending outpatient therapy sessions, and lack of cognitive rehabilitation providers in rural communities (Burrows, Suh, & Hamann, 2012).

One potential solution to this lack of access is computer-based cognitive rehabilitation (CCR)[1]. Computer-based cognitive rehabilitation (CCR) refers to the use of specially-designed software programs to improve cognitive functions through structured practice of cognitive tasks. These programs are available on computers and many other electronic devices, such as smartphones, tablets, and gaming systems. Many CCR programs can be used and monitored by a clinician remotely, allowing cognitive rehabilitation to transcend the therapy room. These programs allow individuals with TBI to participate in cognitive rehabilitation anywhere they have computer or electronic device access, including in their home.

In addition to improved access to services, CCR has several other potential advantages over traditional cognitive rehabilitation. Treatment in CCR can be delivered with a greater intensity than is possible with traditional cognitive rehabilitation (e.g., 60 minutes, two times per day, every day) if clinicians are monitoring an individual's practice rather than initiating it. Cost of treatment may be reduced, if a clinician's direct involvement is not needed every time an individual uses their CCR program. Computer-based cognitive rehabilitation (CCR) programs can potentially be designed to capture large amounts of data regarding an individual's performance that would be too difficult to capture during face-to-face tasks. This includes data such as reaction times, eye gaze, and speech samples, in addition to measures of task accuracy. These data may provide a more comprehensive view of individuals' performance and skills and may lead to more tailored and effective treatment targets. Treatment stimuli in CCR programs can also be manipulated more precisely, as stimuli are not dependent upon the actions of human therapists. As a result, specific cognitive processes may be able to be targeted with greater precision. Lastly, CCR can be highly engaging when presented in a game format and with multimedia stimuli, allowing individuals to enjoy therapy activities and feel proud of in-game accomplishments.

Computer-based cognitive rehabilitation (CCR) may also be uniquely suited to take advantage of neuroplasticity in the brain. By increasing the intensity, specificity, and salience

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[1]For the purposes of this review, the phrase "computer-based cognitive rehabilitation" does not refer to other uses of computers or electronic devices in cognitive rehabilitation activities, such as cognitive orthotics or prosthetics (e.g., electronic memory aids, web-based organizational assistants). In addition, CCR is considered to be synonymous with the phrase "computerized cognitive training."

19

of treatment, CCR may increase experience-dependent neuroplasticity (Kleim & Jones, 2008). Beneficial neural changes resulting from treatment may then underlie improvements in cognitive and functional outcomes. Though there is considerable excitement regarding this possibility, as well as considerable marketing by commercial software companies, the potential for CCR to improve cognitive function by inducing neuroplasticity has not yet been established.

In light of the many potential benefits of CCR, an increasing number of studies have examined the effects of CCR on aspects of cognitive function. Gontkovsky, McDonald, Clark, and Ruwe (2002) reviewed CCR studies conducted between 1983 and 1997. Studies ranged in quality from uncontrolled pilot studies to randomized controlled trials. Based upon their review, Gontkovsky and colleagues (2002) concluded:

> Investigations examining the efficacy of computer-assisted cognitive rehabilitation have yielded mixed findings, although a positive trend has been demonstrated suggesting that such forms of treatment are, at minimum, equivalent to traditional modes of intervention. As noted previously, research in this area is limited and marked by methodological flaws, including lack of adequate controls for comparison, designs which are based on archival data as opposed to those developed to attain data in a prospective fashion, and inconsistencies with respect to various study procedures that limit meaningful comparisons across studies. Additional empirical research clearly is needed to address the aforementioned numerous shortcomings. (p. 198)

Since the publication of the Gontkovsky et al. (2002) article, many more CCR programs have been developed both by researchers and commercial software companies, leveraging advances in computer technology, and increases in the rate of computer use (File & Ryan, 2014). Recent cognitive rehabilitation systematic reviews and evidence-based practice guidelines have reviewed CCR studies, but in the context of the larger body of cognitive rehabilitation research. Computer-based cognitive rehabilitation (CCR) studies have typically been evaluated together with studies of traditional, non-computer-based cognitive rehabilitation interventions targeting specific cognitive domains (e.g., attention, memory, executive functioning, and processing speed). To the authors' knowledge, no recent review has synthesized the findings solely for CCR.

To address this gap in knowledge, this article provides a systematic review of the literature employing CCR with children, adolescents, and adults with TBI. Given the importance of determining if CCR is an efficacious option for individuals with TBI, this review will address the following two clinical questions:

1. Does computer-based cognitive rehabilitation improve cognitive or cognitive-communication skills in children and adolescents with TBI?

2. Does computer-based cognitive rehabilitation improve cognitive or cognitive-communication skills in adults with TBI?

Method

Literature Search

The authors conducted a systematic literature search between March and May 2015 to identify studies for this review. The search was limited to peer-reviewed journals in English, with no restrictions regarding date of publication. Individual searches were conducted in 11 electronic databases: ASHAWire; CINAHL via EBSCOhost; Cochrane Library; ERIC; Google Scholar; Library of Congress; MEDLINE via PubMed; psychBITE; PsycInfo; speechBITE; and Web of Science. Searches used combinations of the keywords listed in Table 1.

Table 1. Literature Search Concepts and Keywords.

Population	Treatment		
Brain Injury	Computer	Brain	Rehabilitation
Head injury	Computer-based	Cognitive	Remediation
Closed-head injury	Computer-assisted	Cognition	Retraining
Concussion	Computerized	Attention	Training
		Executive Function	Game
		Memory	Games
		Processing Speed	

Article Screening and Eligibility

Articles identified in the literature search were screened by the authors according to predetermined inclusion and exclusion criteria. Studies were included in the review if they:

1. Included participants diagnosed with cognitive or cognitive-communication deficits as a result of TBI.

2. Used group comparison designs with control groups or conditions (e.g., randomized controlled trials, non-randomized controlled trials); or used single-case experimental designs in which participants acted as their own controls (e.g., multiple baseline designs, withdrawal/reversal designs, alternative treatment designs).

3. Included treatments administered on a computer or other electronic device, targeting global cognitive function, specific cognitive skills (e.g., attention, memory, executive functioning, processing speed, social cognition), or cognitive-communication skills at the body functions and structures or activities and participation levels (WHO, 2001).

Studies were excluded if they:

1. Included individuals with aphasia.

2. Contained mixed populations (e.g., participants with TBI and participants with brain tumor), unless data could be separated for analysis.

3. Combined computer-based treatment with other types of treatments (e.g., pen and paper tasks, cognitive behavioral therapy, and pharmaceutical intervention) but did not allow for the analysis of the effect of computer-based treatments alone.

4. Included interventions that used virtual reality, immersive video games (e.g., first-person shooters), or cognitive orthotics/prosthetics (e.g., computer-based memory aids, web-based scheduling programs).

After discarding duplicate articles, the authors independently screened the remaining articles. If article abstracts appeared appropriate for the review based on the criteria above, the full-text of each article was obtained and examined. Review of the citations for these articles resulted in inclusion of additional articles not identified in the database searches. Articles were ultimately included in the systematic review if both authors selected them for inclusion. Disagreements regarding inclusion of articles occurred in 6/54 instances (11%) and were resolved through consensus.
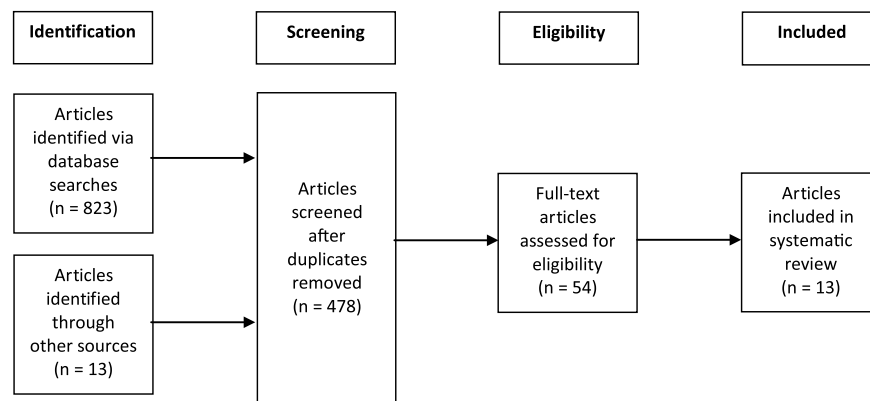
Evaluation of Level of Evidence

The level of evidence of each study was evaluated using the Clinical Practice Guidelines of the American Academy of Neurology (AAN, 2011). The level of evidence represents the classification

21

of the risk of bias of a study. According to the AAN, bias is "…the study's tendency to measure the intervention's effect on the outcome inaccurately. It is not possible to measure the bias of a study directly…However, using well-established principles of good study design, we can estimate a study's risk of bias" (AAN, 2011, p. 8). The AAN uses a four-tiered classification scheme to judge a study's risk of bias (see Appendix A). Class I studies have a low risk of bias; Class II have a moderate risk of bias; Class III have a moderately high risk of bias; and Class IV studies have a very high risk of bias. Two independent raters classified the risk of bias of each study included in the review. Interrater reliability was 92% (12/13), with disagreement solved by consensus using a third rater.

Results

The number of articles included at each stage of the review process is shown in Figure 1. Thirteen studies were included in the systematic review–1 study of an adolescent population and 12 studies of adult populations. No studies with children (ages 5–11) were included. In total, 465 studies were excluded. The majority of these studies were excluded because they: (a) were not treatment studies; (b) were not cognitive or cognitive-communication treatment studies; (c) did not administer treatment via computer; (d) included mixed populations (typically stroke); and (e) did not include a control group or condition.

Figure 1. Flow Chart of Literature Search.

Identification	Screening	Eligibility	Included

Articles identified via database searches (n = 823) →

Articles identified through other sources (n = 13) →

Articles screened after duplicates removed (n = 478) →

Full-text articles assessed for eligibility (n = 54) →

Articles included in systematic review (n = 13)

Appendix B summarizes the study characteristics, participant information, intervention details, outcome measures, and findings for the 13 intervention studies included in the review.

Participant Characteristics

Overall, 241 participants with TBI were included across the 13 studies. For the groups that specified the gender of participants with TBI, the ratio of males to females was approximately 2:1. In the treatment groups, the studies varied in sample size from 2 to 20 participants with TBI (mean = 9.5, median = 10, 25th percentile = 6, 75th percentile = 13). Education was not consistently reported across studies, but ranged from 6–18 years in the studies of adult populations. Injury severity was also not specified by all studies, but ranged from mild to severe.

Interventions

All studies used computer-based cognitive rehabilitation software programs. The majority of programs were created by researchers and not available for use by clinicians. Currently, four of the programs are available for purchase commercially (ComCog; MaxMedica Company; PSSCogRehab, Psychological Software Services; APT-3, Lash & Associates Publishing/Training, Inc.; Lumosity™; Lumos Labs).

Outcome Variables

Outcome measures generally consisted of: standardized neuropsychological or language assessments; experimental cognitive assessments, including computerized assessment tasks based on specific computer-based interventions; and behavioral rating scales. Functional outcomes were assessed in several studies (Ponsford & Kinsella, 1988; Schoenberg et al., 2008; Tam et al., 2003), and one study each looked at cost of treatments (Schoenberg et al., 2008) and task-related fMRI BOLD activation (Kim et al., 2009).

Levels of Evidence

No studies in this review qualified for an AAN Class I rating, the highest level of evidence, representing randomized controlled trials with a low risk of bias. The three randomized, controlled trials included in this review (Thomas-Stonell, Johnson, Schuller, & Jutai, 1994; Niemann, Ruff, & Baser, 1990; Ruff et al., 1994) did not qualify for a Class I rating because they did not report using concealed allocation. Concealed allocation refers to blinding of study investigator(s) who randomize participants into treatment and comparison groups. It is important in reducing bias because it prevents study investigators from manipulating treatment assignments, which has been demonstrated to reduce a study's accuracy (AAN, 2011).

The studies included in this review were all classified as AAN Class II or Class III studies (see Appendix B). One randomized controlled trial (Niemann et al., 1990) was classified as AAN Class II. The remaining 12/13 (92%) studies were classified as Class III. No studies were classified as Class IV, likely in large part due to the inclusion criteria for this review requiring studies to include a control group or condition.

Study Summaries and Findings

Adolescents. One Class III study of adolescents with TBI was included in the review. Thomas-Stonell et al. (1994) conducted a randomized controlled trial of TEACHware™ (Johnson, Thomas-Stonell, & Shein, 1994), a computer-based program for the remediation of cognitive-communication skills. The study employed an A-A'-B within-subject and between-group design. Twelve participants with TBI, ages 12–21, were randomly assigned to a remediation group or a control group. All participants were administered pretest baseline measures, including a battery of standardized of language and cognitive measures and a screening module from the TEACHware™ program. These measures were repeated after four weeks, in order to "determine the subject's rate of improvement due to the combination of spontaneous recovery, learning effect, and traditional rehabilitation methods" (Thomas-Stonell et al., 1994, p. 29). Participants in the remediation group then received intervention using TEACHware™ an average of two sessions per week for 8 weeks. The control group did not receive TEACHware™ intervention, but continued with their traditional therapy and community school programs. At the conclusion of the 8-week period, both groups were assessed using the same battery of standardized assessments and the TEACHware™ screening module administered at baseline and after 4 weeks. The authors found that the remediation group performed significantly better than the control group on several of the standardized assessment measures (all p-values < .05). These included the Expressive One-Word Picture Vocabulary Test (EOWPVT)-Upper Extension; the Word Associations and Recalling Sentences subtests of the Clinical Evaluation of Language Fundamentals-Revised (CELF-R); Task A-Brand Names, Task C-Signs of the Time, and the total test score of the Adolescent Word Test; and the Understanding Ambiguous Sentences subtest and total test score of the Test of Language Competence (TLC). In addition, there was a significant difference in scores on the TEACHware™ screening module over the final two test sessions (p < .05), controlling for performance in the baseline test session. Participants in the remediation group improved significantly more (16.5%, SE = 2.65) than the control group (6.3%, SE = 2.65) on the screening module. Based on these results, the authors concluded that the TEACHware™ program is an "effective enhancement to traditional rehabilitation and special education programs" (Thomas-Stonell et al., 1994, p. 35). Limitations of the study were not discussed by the authors, but included: the small sample size, participants' stage of recovery varied greatly

23

(between 3 months to 4 years), and participants in both groups varied in the amount of therapy and school services they received outside of the study.

Adults. Of the 12 studies with adult populations included in this review, one study was rated as Class II (Niemann et al., 1990) and the remaining 11 studies were rated as Class III. 7/12 studies (58%) employed group comparison designs, and the remaining five studies had single-case experimental designs.

Group Comparison Design Studies

Niemann et al. (1990) conducted a randomized controlled trial of a computerized program to improve deficits in attention skills after TBI. The study sample consisted of 29 community-dwelling participants with moderate-to-severe TBI who were at least one-year post-injury. Training focused on three aspects of attention: visual, auditory, and divided. All tasks were presented hierarchically. An active control group participated in a memory training program that included both internal and external strategy training. Participants were randomly assigned to groups and were seen for 9 weeks total, with two 2-hour sessions per week. A selection of neuropsychological assessments was administered at 7-to-9 day intervals several times before, during, and after completion of the training. A second set of neuropsychological measures was given before and after training to assess generalization effects. No functional outcome measures were included. A significant difference was found between pre- and post-treatment performance on the Trail Making Test B ($p < .015$). However, this finding did not meet the alpha level adjusted for multiple comparisons (0.13) calculated by the authors. No other significant differences were found within or between groups.

Ruff et al. (1994) evaluated the efficacy of THINKable, an attention and memory retraining program incorporating realistic pictures, speech recognition, and touch-screen technology. THINKable was designed to be customizable for the needs of individuals with severe TBI. Participants in this study were 15 individuals between the ages of 16 and 50 with severe TBI. Participants had minimal scores of 70 on the Galveston Orientation and Amneisa Test (GOAT), but sufficient cognitive functioning as determined by the Dementia Rating Scale (DRS). The authors conducted a randomized controlled trial with repeated measures. Fifteen participants with severe TBI were randomized into two groups: one completing attention training then memory training, and the other completing memory training prior to attention training. Groups did not differ in scores on cognitive screening measures, but information regarding differences in age, education, severity, and time post injury were not reported. Outcome measures included performance on the THINKable assessments of attention and memory, a selection of neuropsychological assessment, and behavioral measures of attention and memory (rated by both the participants and outside observers). Results indicated the participants made small but significant gains on all THINKable attention tasks ($p = 0.03$) and on 1/3 of memory tasks ($p = 0.021$). Mixed findings were observed on neuropsychological assessments of attention and memory. Significant improvements were noted on other-reported behavioral ratings of attention ($p = 0.04$) and self- and other-reported ratings of memory ($p = 0.04$, $p < 0.001$).

Tam and Man (2004) conducted a non-randomized control study to explore the efficacy of their computer-assisted memory re-training package in participants with TBI. The participants in the experimental group were randomly assigned to one of four treatment groups formed around specific treatment strategies: Self-Pacing, Feedback, Personalization, and Visual Presentation. A control group, also individuals with brain injury, did not receive any specific memory training. Participants attended 10 sessions, each 20–30 minutes in length, which increased in level of difficulty. Outcome measures included computer quizzes based on the training tasks, the Rivermead Behavioral Memory Test (RBMT), and a self-efficacy measure that was designed and validated by the authors to measure participants' feelings regarding their own abilities in the training program. The authors reported significant improvement in all groups on computer-based quizzes. While the Visual Presentation group demonstrated percentage improvement on the RBMT, no statistical improvement was noted across groups on the RBMT. On ratings of self-efficacy, the Feedback group was the only treatment group to show significant improvement ($p < .05$) when compared to

24

the control group and other training groups. One important limitation of this study reported by the authors was the significant heterogeneity between groups. The authors attributed this to failure to analyze confounding variables such as IQ, education, and etiology of brain injury.

The remaining five group comparison design studies were non-randomized control studies. Wood and Fussey (1987) aimed to determine the effect of a microcomputer cognitive rehabilitation intervention on measures of attention and speed of information processing. The study used a multiple baseline design as well as a pre-test/post-test group comparison. The intervention was administered to two experimental groups and one healthy control group. Individuals participating in the study had been clinically diagnosed with attention deficits and described as having problems with the "amount of information they could handle" (p. 149). Ten individuals with TBI (7 females and 3 males) were trained on visually scanning targets on a screen. Their accuracy and speed on accomplishing this task was calculated using a hit ratio. Outcome measures included: experimental and standardized neuropsychological measures of psychomotor function and vigilance, a fixed interval attention to task recording, and an attention rating scale completed by nursing and therapy staff. A significant difference between groups on pre-test vs. post-test scores was observed on the attention to task recording. No significant differences were found on measures of psychomotor function and vigilance or the attention rating scale.

Chen et al. (1997) conducted a study using a retrospective semi-archival design to examine if individuals with TBI benefitted from a CCR program (The Bracy Process Approach; Bracy, 1995). Two groups of individuals with TBI were selected from medical records. The experimental group received CCR while the control group received typical rehabilitation therapies. Participants were matched for injury criteria such as chronicity, time between neuropsychological testing, and length of coma. Primary outcome measures included neuropsychological tests of attention, visual spatial ability, and memory and problem solving tasks. Both groups improved significantly at post-testing, but there was no significant difference between groups ($p < 0.05$, Bonferroni-corrected for multiple comparisons). The authors noted that one limitation of the study was the variability in injury severity between the experimental and control groups.

Dou and colleagues (2006) developed their own computer assisted memory rehabilitation program to specifically target memory deficits post-TBI. Given the evidence in the area of errorless learning after TBI, the authors sought to create a program that combined this technique with an enriched environment through computer training, allowing for sufficient practice along a continuum of difficulty levels. The training program was made up of four parts: (a) basic memory, (b) working and semantic memories, (c) mnemonic strategies, and (d) application of strategies in "daily life situations." This pilot study examined the performance of three groups at pre-test and post-test: a Computer-Assisted Memory Training group (CAMG), a Therapist-Administered Memory Training group (TAMG), and a control group (CG). The sample was made up of Chinese patients between 18–55 years old, who had a history of TBI, were at least 3 months out from the post-operative stage of intervention, and obtained a score of 6 or more on the Everyday Attention Questionnaire, Abbreviated Version. The experimental groups participated in one month (20 sessions, 5 days per week) of training with a follow-up assessment one month after the last session. Primary outcome measures included the Neurobehavioral Cognitive Status Examination (NCSE), the Cantonese Version of the RBMT, and the Hong Kong List Learning Test (HKLLT). Results are difficult to interpret due to conflicting information presented in Dou et al. (2006). The authors report in discussion that the CAMG showed "better results" compared to TAMG or the control group, on "…encoding, storage and retrieval in random and blocked conditions have been shown by HKLLT, in the memory sub-test of NCSE–memory, as well as in sub-tests of RBMT–story (immediate and delay recall), face, etc." (p. 222). Based on these findings, the authors conclude that "errorless learning and an enriched environment, as provided by computers in CAMG, seem to support better results in memory training" (p. 223).

In 2008, Schoenberg and colleagues used a telemedicine-based CCR program to compare functional outcomes and treatment cost in individuals with TBI. The study sample included

individuals with moderate-severe TBI who were consecutively admitted for treatment at a large rehabilitation hospital. Participants selected for the teletherapy (TELE) group participated in CCR in their homes. The face-to-face comparison group were also individuals with moderate-to-severe TBI who were matched to TELE participants on age, education, gender, hand dominance, and level of functioning. The CCR program used in this study was Cog Rehab Version 95, based on the Brady Process Approach employed by Chen et al. (1996). This program emphasized hierarchical training in many cognitive domains including attention, reaction time, visuospatial skills, learning and memory, and problem solving. Participants accessed the program in their homes after an initial training session with a therapist. The therapist monitored progress via the internet and could tailor the program according to the needs of individual participants. Dosage was calculated differently for each group. The TELE participants self-reported treatment time, with an average of 95.84 hours over 24.4 weeks. In comparison, the face-to-face participants' treatment time was tallied via documentation of medical records, with an average of 27.05 hours over 9.8 weeks. The first outcome measure of interest was cost of treatment, calculated by the overall cost of services and equipment divided by the hours of therapy received. The second dependent variable of interest was functional outcome, which the authors operationally defined as independent living, independent driving, and return to work or school. Results of this study revealed a greater cost per hour for face-to-face therapy compared to teletherapy ($103.74 vs. $58.85). However, when overall costs were tabulated (taking into account the frequency of therapy and computer and internet costs), teletherapy was more expensive ($3,672 per TELE participant vs. $2,610 per face-to-face participant). After removing one participant who used teletherapy for an extended period of time, the cost of teletherapy was comparable to face-to-face therapy ($2619 per participant). At the end of treatment, no significant differences were found between groups in the proportion of participants living independently, driving independently, or returning to work or school. Significant within-group improvements from pre-treatment to post-treatment were for all functional outcomes was found for both groups (all p < 0.01). However, the authors noted that the groups differed significantly in time since injury, and this was not taken into account during analysis of functional outcomes.

Lastly, Kim and colleagues (2009) used functional magnetic resonance imaging (fMRI) to examine differences in plasticity in attentional networks pre- and post-cognitive training. This study compared performance between participants with TBI and non-injured comparison participants on an fMRI visual attention task (VAT) before and after participants with TBI received 4 weeks of CCR using ComCog software. ComCog trains users on ten different attention tasks, across levels of attention and modalities (i.e., visual and auditory attention, vigilance, divided attention, and persistence). Outcome measures included behavioral measures of VAT accuracy and response time, as well as fMRI activation of the visuospatial attentional network. On the behavioral VAT measures, participants in the TBI group showed significantly greater accuracy and decreased response time after training (p < 0.05). Analysis of fMRI data revealed that the comparison group displayed more activation in the bilateral anterior cingulate cortex (ACC) and supplementary motor area (SMA), while the TBI group exhibited more activation in the right frontal (middle and inferior frontal gyri), insular, and left temporal lobe. In addition, there was a significant relationship between fMRI activation and response time at post-training in the TBI group, such that the faster the reaction time, the higher the individual brain response in the ACC.

Single-Case Experimental Design Studies

Ponsford and Kinsella (1988) used a multiple baseline across subjects design to evaluate the efficacy of a computerized program targeting speed of information processing deficits after TBI, compared to computer and therapist feedback and training. Training tasks for this study were developed partially by the first author, with others based on the work of Gianutsos and Klitzner (1981). These tasks targeted reaction time and accuracy for visually presented information. Outcome measures included a four-choice reaction time task, The Symbol Digit Modalities Test a two-letter cancellation task, and the WAIS/NHAIS Similarities subtest. In addition, a rating

26

scale of attentional behaviors was completed by the participants' occupational therapist, and a video taken of the participant performing a clerical task was evaluated and scored by a rater based on percentage of time devoted to the task. Overall, the training was deemed as contributing to gradual improvement across time on the neuropsychological and subjective measures; however, because of limitations in the sampling, this improvement was attributed as being due to spontaneous recovery from the injury event, not as a result of the intervention. The authors concluded that participants showed "few significant changes" and that the "majority of the significant results failed to provide support for the hypotheses" (Ponsford & Kinsella, 1988, p. 704).

Gray and Robertson (1989) employed a multiple baselines across behavior design to assess the efficacy of attention training delivered via microcomputers to three young males with severe TBI. The authors used Cognitive Rehabilitation Software, designed by Braun et al. (1985), to target attention and concentration. Exercises reportedly simulate the design of traditional neuropsychological measures of attention and information processing skills, such as the PASAT and the Stroop tests. Training on this program included adaptive levels of cueing, error feedback, and use of verbal regulation. The authors reported a significant improvement on the training tasks from the baseline period to the intervention period across all three participants. In their attempt to determine the underlying mechanism for improvement during the intervention phase, Case 1 was further analyzed in a qualitative fashion. After this analysis, the authors determined that is was not the computerized therapy itself that was contributing to the change, but rather the participant's improved use of metacognitive strategies (i.e., verbal rehearsal).

The ability to customize computerized tasks to benefit an individual patient was developed further by Tam et al. (2003) in a study which used telemedicine equipment to deliver computerized treatment in individuals' homes. Two-thirds participants in this single case experimental (A-B-A reversal design) study had incurred a TBI. The first case, T. M., experienced deficits in word recognition and word retrieval that impacted his daily functioning and eventually led to unemployment. T. M. was unable to carry on a conversation or complete tasks such as reading the newspaper. His cognitive abilities were relatively intact; therefore, his therapy program was customized to address word recognition. T. M. completed six sessions of word-recognition training "tailor-made" for his learning style and preferences. Baseline phase assessments were compared to those during the intervention and reversal phases, and positive changes were observed during the training phase. After the treatment was withdrawn, however, the positive change did not persist. Subjectively, T. M. reported a high degree of satisfaction with the training program and increased confidence in his cognitive abilities after the training period. The second participant in this study with TBI, K. W., endorsed severe memory difficulties as a result of his injury. He reported poor prospective memory skills which compromised his ability to make future plans and disrupted his daily living. He participated in six training sessions, consisting of five timed computerized tasks that were randomly generated and targeted typing and word-guessing skills. These customized tasks were designed to maximize his enjoyment and participation. Results of this study indicated that K. W. made significant gains in correct responses during the training phase of treatment, however, performance scores dropped when treatment was withdrawn. K. W. reported he had gained confidence in his cognitive abilities after completion of the program, and only wished the program was longer in duration. In both cases, the outcome measures used was the slope of the line fitting the data points for word recognition accuracy (T. M.) and prospective memory performance (K. W.). These slopes were determined by visual inspection of plots of word recognition and prospective memory performance.

Zickefoose, Hux, Brown, and Wulf (2013) used a single-case experimental design to study two cognitive training programs, Attention Process Training-3 (APT-3) and Lumosity™. This study used an A-B-A-C-A design to compare the efficacy of these two programs for four adults with severe TBI. Each participant in this study received APT-3 and Lumosity™ during the course of two, 1-month intervention phases. Neuropsychological outcome measures included the Test of Everyday Attention (TEA), as well as repeatable probe measures adapted from the Neurological Assessment Battery (NAB) Numbers and Letters Test. In addition, participants completed rating scales to

measure their perceived enjoyment and willingness to continue using both training programs. Results indicated significant improvements for all participants on all APT-3 tasks ($p < .01$ for all tasks) and all Lumosity™ tasks ($p < .05$ for all tasks) except Rotation Matrix (only 1/4 participants with significant improvement, $p < .05$). On the untrained neuropsychological outcome measures, evidence of generalization was mixed. On the TEA, 1/4 participants demonstrated improved performance on several subtests, but the performance of the remaining 3/4 participants across subtests was varied. Similarly, high levels of variability across and within participants was seen on the probe measures adapted from the NAB. Finally, on the self-rating scales, participants generally reported more enjoyment and willingness to continue with Lumosity™ than APT-3.

Discussion

The purpose of this systematic review was to examine the efficacy of CCR for improving cognitive and cognitive-communication skills in children, adolescents, and adults with TBI. A literature search of 11 databases yielded 13 intervention studies that met study inclusion criteria. Studies were reviewed and the quality of evidence was classified according to the AAN (2011, 2015).

Results of this review provide insufficient evidence to support or refute the efficacy of CCR in improving the cognitive or cognitive-communication skills of individuals with TBI. For children with TBI, no studies of CCR satisfied eligibility criteria for inclusion in this review. For adolescents and adults with TBI, findings were generally mixed, both across studies and for studies targeting a particular cognitive skill (e.g., attention). Nearly all studies (12/13, 92%) were rated as AAN Class III, indicating a moderately high risk of bias. The only Class II study, a randomized controlled trial conducted by Niemann et al. (1990), found conflicting evidence for improvement in attention skills following CCR.

Several methodological practices observed in the studies reviewed potentially undermine the validity of many of the reported findings. For example, the majority of group comparison studies used a passive control group. This raises the possibility that improvements observed on outcome measures were due to nonspecific factors[2], rather than to the interventions being examined (Boot, Simons, Stothart, & Stutts, 2013; Donovan, Kwekkeboom, Rosenzweig, & Ward, 2009). Most studies also had small sample sizes, with 10 or fewer subjects in the majority of treatment groups (11/17, 65%). These studies were likely underpowered, limiting their ability to identify a true effect[3]. For studies with multiple outcome measures or post-hoc comparisons, some significant results may have been false positives, due to the lack of alpha-level correction for multiple comparisons (Hochberg & Benjamini, 1990). Lastly, nearly all of the studies did not specify confidence intervals or effect size estimates[4]. As a result, the magnitude of treatment effects was not known and treatments could not adequately be compared.

Clinical and Research Implications

Results of this review are generally in accordance with previous practice guidelines regarding CCR. Ponsford et al. (2014), representing the INCOG expert panel, provided the following recommendation regarding CCR for attention: "Reliance on repeated exposure and practice on de-contextualized computer-based attentional tasks is NOT recommended due to lack of demonstrated impact on everyday attentional functions" (Ponsford, 2014, p. 326). Similarly, Velikonja et al. (2014) from the INCOG panel made this recommendation regarding CCR for memory:

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[2]Examples of effects of non-specific factors include the subject-expectancy effect and the Hawthorne effect.
[3]No power calculations (a priori or post hoc) were reported for any study in this review.
[4]In the case of Chen et al. (1994), the effect size estimate was reported, but not in sufficient detail to be informative.

Restorative techniques such as computer-based training show no evidence in enhancing sustained memory performance. Guidelines in using such techniques indicate that it should only be considered to develop adjunct memory rehabilitation strategies with evidence-based instructional and compensatory strategies, and only if developed in conjunction with a therapist with a focus on strategy development and transfer to functional tasks. (p. 377)

In both of these practice guidelines, there is an appeal to shift the focus of CCR tasks from the body structures and functions level to the activities and participation level. This appears to be in recognition that the "active ingredients" (Hart et al., 2014) of computer-based attention and memory training programs are not decontextualized cognitive training tasks. Rather, the active ingredients may be use of compensatory and metacognitive strategies in conjunction with structured practice on functional tasks, following validated instructional techniques. It remains for future studies to demonstrate empirically whether this is indeed correct.

Future research should also seek to address the limitations of studies included in this review. Study participants in group comparison design studies should be randomized to treatment and comparison groups, to ensure that important baseline variables (e.g., age, education, severity, and years post-injury) are comparable across groups. Randomization should be concealed from study investigators so that treatment allocation is not manipulated. Investigators should conduct a priori power calculations in order to determine sufficient sample sizes for their studies. Whenever possible, active control groups should be used in order to determine if improvements on outcome measures are due to the studied interventions rather than other factors. Functional outcome measures should always be included, in order to determine if performance on training tasks generalizes to everyday activities. Finally, good statistical practices should be used, including correcting for multiple comparisons when indicated and reporting confidence interval and effects size estimates (preferably standardized estimates) for statistical tests.

For now, clinicians are directed to existing expert recommendations (e.g., Ponsford et al. 2014; Velikonja et al. 2014) for guidance regarding clinical practice. Clinicians are also encouraged to engage in practice-based evidence (PBE; Lemoncello & Ness 2013) to guide their treatment decisions regarding CCR. Practice-based evidence (PBE) refers to clinicians generating their own evidence, by "gathering good-quality data from routine practice" (Margison et al., 2000). This approach complements traditional evidence-based practice (EBP), and is especially useful when there is a dearth of high-quality research evidence available. By conducting PBE in conjunction with EBP for CCR, "SLPs can continue to provide ethical, rational, theoretical, individualized interventions to promote high quality care and advocate for our services while continuing to add to the growing evidence to support or refute our practices" (Lemoncello & Ness, 2013).

Acknowledgements

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31

Appendix A. American Academy of Neurology Narrative Classification of Evidence Scheme for Therapeutic Studies.

Class I:

- Randomized, controlled clinical trial (RCT) in a representative population.

- Masked or objective outcome assessment

- Relevant baseline characteristics are presented and substantially equivalent among treatment groups, or there is appropriate statistical adjustment for differences.

- Also required:

    a. Concealed allocation

    b. No more than two primary outcomes specified

    c. Exclusion/inclusion criteria clearly defined

    d. Adequate accounting for drop-outs (with at least 80 percent of enrolled subjects completing the study) and cross-overs with numbers sufficiently low to have minimal potential for bias.

    e. For noninferiority or equivalence trials claiming to prove efficacy for one or both drugs, the following are also required*

        1. The authors explicitly state the clinically meaningful difference to be excluded by defining the threshold for equivalence or non-inferiority.

        2. The standard treatment used in the study is substantially similar to that used in previous studies establishing efficacy of the standard treatment. (e.g. for a drug, the mode of administration, dose and dosage adjustments are similar to those previously shown to be effective).

        3. The inclusion and exclusion criteria for patient selection and the outcomes of patients on the standard treatment are comparable to those of previous studies establishing efficacy of the standard treatment.

        4. The interpretation of the results of the study is based upon a per protocol analysis that takes into account dropouts or crossovers.

    f. For crossover trials, both period and carryover effects examined and statistical adjustment performed, if appropriate

Class II:

- An RCT that lacks one or two criteria a–e (see Class I) or a cohort study meeting criteria b–e (see Class I)

- Randomized, crossover trial missing one of the following two criteria:

    a. Period and carryover effects described

    b. Baseline characteristics of treatment order groups presented

- All relevant baseline characteristics are presented and substantially equivalent among treatment groups, or there is appropriate statistical adjustment for differences

- Masked or objective outcome assessment

(Continued)

32

Class III:

- Controlled studies (including studies with external controls such as well-defined natural history controls)
- Crossover trial missing both of the following two criteria

    a. Period and carryover effects

    b. Baseline characteristics presented

- A description of major confounding differences between treatment groups that could affect outcome**
- Outcome assessment masked, objective, or performed by someone who is not a member of the treatment team

Class IV:

- Did not include patients with the disease
- Did not include patients receiving different interventions
- Undefined or unaccepted interventions or outcome measures
- No measures of effectiveness or statistical precision presented or calculable

* Note that numbers 1-3 in Class Ie are required for Class II in equivalence trials. If any one of the three are missing, the class is automatically downgraded to Class III.

**Objective outcome measurement: an outcome measure that is unlikely to be affected by an observer's (patient, treating physician, investigator) expectation or bias (e.g., blood tests, administrative outcome data).

Source. American Academy of Neurology. (2015). *Amendments to the 2011 American Academy of Neurology Clinical Practice Guideline Process* Manual. St Paul, MN: Author.

Appendix B. Study Characteristics, Participant Information, Intervention Details, Outcome Measures, and Findings for the 13 Studies in the Review.

Study	Design	AAN Class	N	Age (yrs.)	Intervention(s)	Targeted Domain(s)	Outcome Measure(s)	Reported Findings
Chen et al. (1997)	Group Comparison Design Retrospective, non-randomized control study	III	Experimental: 20 (8 female) Comparison: 20 (5 female)	Experimental: Mean = 30.45 SD = NR Range = NR Comparison: Mean = 26.0 SD = NR Range = NR	Experimental: Computer-assisted cognitive rehabilitation software using the Bracy Process Approach (Bracy, 1985). Tasks organized hierarchically and designed to target underlying 'basic processes' associated with functional skills deficits. Comparison: traditional neurorehabilitation Treatment schedule: Not reported.	Attention Visual-Spatial Skills Memory Problem Solving	Comprehensive neuropsychological assessment battery	Both groups improved significantly at post-testing (p < 0.004). However, no substantial differences between CACR and traditional neurorehabilitation treatment on gains in neuropsychological test scores were obtained (p = 0.38, ES = 0.182; specific effect size estimate (e.g., η_p^2) was not listed).

(Continued)

34

| Dou et al. (2006) | Group Comparison Design

Non-randomized control study | III | 37 (10 female)

Computerized Assisted Memory Training Group (CAMG):
13 (4 female)

Therapist Assisted Memory Training Group (TAMG):
11 (3 female)

Control group (CG):
13 (3 female) | Range = 21–55

CAMG:
Mean = 39.46
SD = 11.92
Range = NR

TAMG:
Mean = 37.64
SD = 13.82
Range = NR

CG:
Mean = 36.69
SD = 12.65
Range = NR | Computer Assisted Memory Rehabilitation program developed by authors that emphasized three principles to improve memory function: errorless learning, using an enriched training environment, and practicing at gradable levels of difficulty.

Therapist Assisted Memory Rehabilitation program that consisted of the same content as CAMR, but was converted to a picture album and delivered via therapist face-to-face with participant.

Treatment schedule:
One-month training period, with 20 days total of training, 6 days per week for ~45 minutes per training session. | Memory
Working Memory
Semantic Memory | Cognitive screening measure of language, spatial skills, memory, calculations, and reasoning (Neurobehavioral Cognitive Status Examination (NCSE), now known as the Cognistat Paper test).

Standardized neuropsychological assessments of memory: Rivermead Behavioral Memory Test (RBMT); Honk Kong List Learning Test (HKLLT), a Chinese variant of the California Verbal Learning Test (CVLT). | The authors report that the CAMG showed "better results" compared to TAMG or the control group, on "…encoding, storage and retrieval in random and blocked conditions have been shown by HKLLT, in the memory sub-test of NCSE–memory, as well as in sub-tests of RBMT–story (immediate and delay recall), face, etc." (Dou et al., p. 220). |

| Gray & Robertson (1989) | Single-Case Experimental Design Multiple baselines across behavior design | III | 3 (0 female) | Case 1: 20 Case 2: 30 Case 3: 19 | Case 1: The Rapid Number Comparison and Digit Symbol Transfer tasks from Cognitive Rehabilitation Software (Braun et al., 1985) were used for attention training. Both programs involve visual scanning and information processing under time pressure. Case 2: The Alternating Stroop program was used for attention training. The program is modified from the Stroop test administered via computer, and includes fading cues. Case 3: The Alternating Stroop Program, Digit Symbol Transfer were sued for attention training. The video game "Breakout" was used to target psychomotor speed and visuo-motor coordination. Treatment schedule: Case 1–8 sessions; Case 2– 6 sessions; Case 3–7 sessions. No other information reported. | Attention | Standardized neuropsychological measures of attention, working memory, and executive functioning: Paced Auditory Serial Addition Test (PASAT); Wechsler Adult Intelligence Scale (WAIS) Digit Span; Wisconsin Card Sorting Test (WCST). | Case 1: During treatment phase, significant improvement observed on target measure (WAIS Digit Span) ($p < 0.05$), but not on reaction time control task ($p > 0.05$). No improvements noted on either task in baseline phase. Case 2: During treatment phase, significant improvement observed on target measure (WAIS Digit Span) ($p < 0.05$), but not on memory control task ($p > 0.05$). No improvements noted on either task in baseline phase. WCST improved by > +1SD between pre- and post-training. Case 3: No significant improvements noted on either task during baseline or treatment phases. PASAT improved by > +1SD between pre- and post-training. |

(Continued)

| Kim et al. (2009) | Group Comparison Design

Non-randomized control study

Controlled before-and-after study | III | Experimental: 10 (3 female)

Normal Control: 15 (5 female) | Experimental: Mean = 30.1 SD = 9.6 Range = NR

Comparison: Mean = 25.1 SD = 3.1 Range = NR | ComCog software (MaxMedica Company) comprised of 10 different attention tasks to train visual and auditory attention, vigilance, divided attention, and persistence. Each task had several subtasks with varied levels of difficulty.

Treatment schedule: 4 weeks total; 3 sessions per week; 30 minutes per session | Attention | Researcher developed visual attention task (VAT):

Behavioral: Accuracy, response time

fMRI: Activation | Behavioral: Participants in the TBI group showed significantly greater accuracy and decreased response time after training (p < 0.05).

fMRI: The control group displayed more activation in the bilateral ACC and SMA. The TBI group exhibited more activation in the right frontal, insular, and left temporal lobe. In the TBI group, faster the reaction time, the higher the individual brain response in the ACC. |

Niemann et al. (1990)	Group Comparison Design Randomized controlled trial Multiple baseline design and pre-test and post-test group comparison	II	Experimental: 13 (gender not specified) Control: 13 (gender not specified)	Experimental: Mean = 28.9 SD = 8.2 Range = NR Control: Mean = 34.3 SD = 12.0 Range = NR	Computer-based attention training targeting three major components: visual, auditory, and divided attention. Components subdivided into focused and alternating attention tasks. Task difficulty varied systematically and ranged in duration from 5 to 10 minutes. Control group participated in memory training with external and internal memory aids using paper-and-pencil tasks and software programs. Treatment schedule: 9 weeks total; 2 sessions per week; six 2-hour sessions per component, with 30-40 minutes per session for tasks, with remaining time spent on feedback and strategy training.	Attention	Baseline: Standardized neuropsychological measures of attention, processing speed, memory, and learning: Paced Auditory Serial Addition Test (PASAT); Test d2; Divided Attention Test; Trail Making Test B; Rey Auditory Verbal Learning Test (RAVLT); Block Span Learning Test (BSLT). Generalization: Standardized neuropsychological measures of attention, memory, and learning: Ruff 2 & 7 test; Wechsler Memory Scale (WMC) Logical Memory; and Ruff-Light Trail Learning Test (RLTLT).	Baseline: Significant difference only on Trail Making Test B (p < .015) for attention training group. However, this finding did not meet the alpha level adjusted for multiple comparisons (0.13) calculated by the authors. Generalization: No significant findings.

(Continued)

| Ponsford & Kinsella (1988) | Single-Case Experimental Design

Multiple baselines across subjects (A-B-BC-A) | III | Experimental: 10 (6 female)

Normal Control: 16 (3 female) | Experimental: Mean = 24.4 SD = 8.7 Range = 17-38

Control: Mean = 25.8 SD = 7.8 Range = NR | React and Search tasks (Gianutsos and Klitzner, 1981) that targeted reaction time and visual search skills, as well as three selective attention tasks designed by the first author.

Treatment schedule: 3 weeks; 5 sessions per week; 30 minutes per session. | Attention | Psychometric measures of speed and processing: Four-choice reaction time task (as used by Van Zomeren, 1981); Symbol Digit Modalities Test (Smith, 1973); Two-letter cancellation task.

Rating Scale of Attentional Behaviors, rated by participant's Occupational Therapist.

30-minute video of participant completing clerical task designed to measure effects on distractibility and sustained attention during functional activities.

Control: Wechsler Adult Intelligence Scale/Naylor-Harwood Adult Intelligence Scale (WAIS/NHAIS) Similarities subtest. | When controlling for spontaneous recovery, no conclusive evidence that participants showed significant improvements as a result of remedial intervention via computer-based attentional training. |

(Continued)

| Ruff et al. (1994) | Group Comparison Design

Randomized controlled trial with repeated measures | III | 15 (gender not specified)

Group A: 7 (Received attention training first, the memory training)

Group B: 8 (Received memory training first) | Mean = 26.9 SD = NR Range = 17-47 | THINKable (IBM), an attention and memory training program. Modules were created specifically for study with multiple levels of difficulty; clinicians could make minor adjustments to difficulty for each participant.

Treatment schedule: Training terminated after 20 hours were completed or 90% scores achieved on the most advance program. Treatments were subdivided into one 2-hour session per day. | Attention Memory | Computer-based assessments of attention and memory

Standardized neuropsychological assessments of attention and memory. One set was administered pre- and post-treatment. A second set of measures was administered during treatment

Behavioral questionnaires regarding attention and memory function in everyday life (self- and other-reported) | Small but significant gains noted on computer-based assessment of attention (p = 0.03) and on 1/3 computer-based assessments of memory (p = 0.021).

Mixed findings on neuropsychological assessments of attention and memory.

Significant improvements noted on other-reported behavioral ratings of attention (p = 0.04) and self- and other-reported ratings of memory (p = 0.04, p < 0.001). |

(Continued)

| Schoenberg et al. (2008) | Group Comparison Design

Non-randomized control study | III | Experimental (TELE):
19 (1 female)

Reference (FTF):
20 (5 females) | Experimental:
Mean = 27.4
SD = 9.08
Range = NR

Reference:
Mean = 33.1
SD = 16.38
Range = NR | Teletherapy (TELE): Psychological Software Services PSS CogRehab Version 95 (Chen et al., 1997), targeting attention, reaction time, visuospatial skills, learning, memory, and problem solving. Training Software installed on participants' personal computers. Participant first met with therapist in-person for a tutorial, then logged on from home to complete computerized training. Data then save to server for therapist review.

Face-to-Face (FTF): Participants seen by speech-language pathologist at a community-based outpatient clinic as part of their individualized rehabilitation treatment plan of care.
Treatment schedule: TELE: Participants would log on at their convenience. Based on self-report, average total hours of therapy was 95.84. FTF: Individualized treatment plan, schedule not reported. Based on review of medical records, average total hours of therapy was 27.0 | Attention Reaction Time Visuospatial Skills Learning & Memory Problem Solving | Cost of Treatment: billed costs of treatment for each individual participant divided by the hours of therapy

Functional Outcomes: Independent living: participant not requiring in-home care.

Independent driving: participant passing driving course or written examination administered by the Department of Public Safety for the State of Oklahoma.

Return to work or school: participant engaging in 31 or more hours of work (paid or volunteer) or school class time | No significant difference between mean cost of the TELE and FTF groups (p = 0.228).

Significant difference between the average cost per hour of the TELE and FTF groups (p = 0.003).

No significant differences between experimental and reference groups on functional outcomes (p = 0.368 – 0.512).

Significant within-group improvements from pre-treatment to post-treatment were for all functional outcomes was found for both groups (all p <0.01). |

(Continued)

| Tam & Man (2004) | Group Comparison Design

Non-randomized control study | III | Experimental: 26 (10 females)

Self-Paced: 7 (2 female)

Feedback: 7 (2 female)

Personalized: 6 (3 female)

Visual Presentation: 6 (3 female)

Control: 8 (4 females) | Range: 18-55

Self-Paced: Mean = 40.5
SD = NR
Range = 18-55

Feedback: Mean = 33.3
SD = SD

Range = 15-41
Personalized: Mean = 32.6
SD = NR
Range = 26-49

Visual Presentation: Mean = 39.8
SD = NR
Range = 35-45

Control: Mean = 45
SD = NR
Range = 19-63 | Computer-assisted memory re-training packages developed by authors with four different treatment emphases: Self-Paced, Feedback, Personalized, and Visual Presentation. Tasks in each group were graded in difficulty and related to: remembering people's faces and names, remembering to do something, remembering what people tell, remembering where to put something.

Treatment schedule: 10 sessions; 20-30 minutes per session. No other information reported. | Memory | Computer-based quizzes derived from treatment tasks

Rivermead Behavioral Memory Test (RBMT)

Self-efficacy rating scale | Significant improvements in all experimental groups on computer-based quizzes derived from treatment tasks ($p < 0.05$).

No significant improvements within in any experimental group, nor between experimental groups and control group on the RBMT.

Significant improvement in self-efficacy for Feedback Group ($p < 0.05$), but not for other experimental groups. |

(Continued)

| Tam et al. (2003) | Single-Case Experimental Design

Reversal/ withdrawal design (A-B-A) | III | 2 participants with TBI (0 female)

1 participant with stroke due to AVM (not included in this review) | Case 1: 37
Case 2: 20 | On-line tele-cognitive rehabilitation tasks developed by authors targeting word recognition and memory skill retraining.

Treatment software was customized in each case.
Treatment schedule: 6 sessions. No other information reported. | Memory | Correct responses on individualized training tasks

Self-efficacy questionnaire | Case 1: During treatment phase, there was an increase in the slope of line fitting word recognition accuracy scores increased from +0.3 to +0.42), that then declined after treatment phase to -0.3. Based on self-efficacy questionnaire, participant "stated that he had been more confident and was motivated to relearn" after training.

Case 2: During treatment phase, there was an increase in the slope of line fitting scores of prospective memory function (not specified) from -0.06 to +0.37, that then declined after treatment phase from +0.14 to -0.43). Based on self-efficacy questionnaire, participant "showed more confidence in his prospective memory and felt less impact from cognitive deficits" after training. |

(Continued)

Thomas-Stonell et al. (1994)	Group Comparison Design Randomized controlled trial A-A'-B within subject and between group design	III	Remediation: 6 (4 female) Control: 6 (5 female)	Remediation: Mean = 17.33 SD = 2.50 Range = 16-21 Control: Mean = 16.17 SD = 2.64 Range = 12-18	TEACH$_{WARE}^{TM}$ program designed to remediate higher-level cognitive-communication deficits. Includes a screening module and six interlinked training modules. Treatment schedule: 8 weeks total; average of 2 sessions per week; 1 hour per session.	Attention Memory/Word Retrieval Comprehension of Abstract Language Organization Reasoning/ Problem Solving	Standardized assessments of cognitive-communication and language skills. TEACH$_{WARE}^{TM}$ screening module	Significant group differences (p < 0.05) found on several of the standardized assessment battery test scores and for the screening module. Skill improvements for individuals in the remediation group were not instrument specific (i.e., only noted on screening module scores), but generalized to noncomputer-based activities as measured by the standardized assessment battery.

(Continued)

| Wood & Fussey (1987) | Group Comparison Design

Non-randomized control study

Multiple baseline procedure and pre- and post group comparison | III | Experimental: 10 (7 female)

Patient Control: 10 (0 female)

Normal Control: 10 (5 female) | Experimental: Mean = 28.4 SD = 8.7 Range = NR

Patient Control: Mean = 27.2 SD = 9.9 Range = NR

Normal Control: Mean = 29.4 SD = 10.3 Range = NR | Computer-based task developed by authors that required visual scanning, perceptual discrimination, judgment and anticipation, and motor response.

Treatment schedule: 4 weeks; 5 sessions per week; 1 hour per session. | Attention Visual Processing Speed | Experimental and standardized neuropsychological measures of psychomotor function and vigilance: Psychomotor function: pursuit rotor; Wechsler Adult Intelligence Scale (WAIS) digit symbol; choice reaction time (CRT) x100; and simple reaction time (SRT). Vigilance: visual vigilance; and CRT (20 minutes).

Behavior recordings completed by therapy staff that rated presence of attention (attention to task) and quality of attention (attention rating). | A significant difference between groups on pre-test vs. post-test scores was observed on the attention to task recording ($p < 0.05$). No significant differences were found on measures of psychomotor function and vigilance or the attention rating scale. |

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Zickefoose et al. (2013)	Single-Case Experimental Design Multiple baseline phases, two treatment phases (A-B-A-C-A)	III	4 (0 female)	Case 1: 36 Case 2: 50 Case 3: 36 Case 4: 49	Attention Processing Training-3 (APT-3) targeting skills across all attention domains including: sustained attention, selective attention, working attention, suppression, and alternating attention. Lumosity™ games targeting: cognitive processing speed, flexibility, attention, memory, and problem-solving skills. Treatment schedule: Two 1-month intervention phases; 20 sessions per phase; 30 minutes per session.	Attention Processing Speed Flexibility Memory Problem Solving	Performance across sessions on APT-3 tasks. Performance across sessions on Lumosity™ games: Birdwatching, Monster Garden, Playing Koi, Rotation Matrix, and Top Chimp. Test of Everyday Attention (TEA) Four researcher-developed repeatable probe measures, based on the Neurological Assessment Batter (NAB) Numbers and Letters Tests Parts B, C and D. Self-rating scales of enjoyment of and willingness to continue with tasks	Significant improvements for all participants on all APT-3 tasks (p < .01 for all tasks). Significant improvements for all participants on all Lumosity™ tasks (p < .05 for all tasks), except Rotation Matrix (only 1/4 participants with significant improvement, p < .05). On the TEA, findings were mixed. 1/4 participants appeared to generalize his improved attention to several TEA subtests. TEA subtests of 3/4 participants were too inconsistent to warrant any claim of generalization. On research developed probes, high levels of variability across and within participants. 1/4 participants demonstrated significant improvement (p < .05) for probes #2 and #4. Self-rating scales: Participants reported more enjoyment and willingness to continue with Lumosity™ tasks vs. APT-3.

46